ECOLOGICAL STUDIES ON RIVER POLLUTION CONTROL

VOL I

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SUMMARY

This collection of papers records a series of studies, carried out over a period of some 50 years, on two aspects of river pollution control - the prevention of pollution by sewage biological filtration and the monitoring of river pollution by biological surveillance.

The earlier studies were carried out to develop methods of controlling flies which bred in the filters and caused serious nuisance and possible public health hazard, when they dispersed to surrounding villages. Although the application of insecticides proved effective as an alleviative measure, because it resulted in only a temporary disturbance of the ecological balance, it was considered ecologically unsound as a long-term solution. Subsequent investigations showed that the fly populations in filters were largely determined by the amount of food available to the grazing larval stage in the form of filter film. It was also established that the winter deterioration in filter performance was due to the excessive accumulation of film. Subsequent investigations were therefore carried out to determine the factors responsible for the accumulation of film in different types of filter. Methods of filtration which were considered to control film accumulation by increasing the flushing action of the sewage, were found to control fungal film by creating nutrient limiting conditions. In some filters increasing the hydraulic flushing reduced the grazing fauna population in the surface layers and resulted in an increase in film. The results of these investigations were successfully applied in modifying filters and in the design of a Double Filtration process. These studies on biological filters lead to the conclusion that they should be designed and operated as ecological systems and not merely as hydraulic ones.

Studies on the effects of sewage effluents on Birmingham streams confirmed the findings of earlier workers justifying their claim for using biological methods for detecting and assessing river pollution. Further ecological studies showed the sensitivity of benthic riffle communities to organic pollution. Using experimental channels and laboratory studies the different environmental conditions associated with organic pollution were investigated. The degree and duration of the oxygen depletion during the dark hours were found to be a critical factor. The relative tolerance of different taxa to other pollutants, such as ammonia, differed. Although colonisation samplers proved of value in sampling difficult sites, the invertebrate data generated were not suitable for processing as any of the commonly used biotic indexes.

Several of the papers, which were written by request for presentation at conferences etc., presented the biological viewpoint on river pollution and water quality issues at the time and advocated the use of biological methods. The information and experiences gained in these investigations was used as the "domain expert" in the development of artificial intelligence systems for use in the biological surveillance of river water quality.

ACKNOWLEDGEMENTS

In retrospect I appreciate that my work over the years has been influenced by numerous individuals. Amongst such I would like to record my sincere thanks to the following:-

To Dr Ll.Lloyd, Reader in Entomology, Leeds University, who first introduced me to the inhabitants of his bacteria beds at Knostrop sewage works, and to the subject of sewage biology, which was to become the field of study in which I was able to apply my somewhat academic degree in botany and zoology.

To Dr. S.H. Jenkins, Chemist, Birmingham Tame and Rea District Drainage Board, whose foresight in realizing the importance of biology in the future developments of water pollution control, had established a post of biologist on his staff. His guidance and encouragement in the earlier stages of my studies, both on biological filters and polluted streams, were important in giving direction to my research. His continued support over the 14 years I spent at the Drainage Board facilitated my later extensive studies on different filters on the Board's several sewage treatment works.

To my civil engineer and other colleagues, first at the Drainage Board and later in consultancy, on working parties and in education, for the interdisciplinary discussions which influenced my thinking.

To a succession of research students and individuals of research teams, with whom I worked for a period of over 20 years in the Applied Hydrology Section at Aston University, for their co-operation in much of the later investigations reported in the papers submitted.

To the Department of Civil Engineering which, following the closure of the Department of Biological Sciences, afforded me a niche as a visiting honorary member, enabling me to continue my research interests as a member of Bill Walley's research team, working on the application of A.I. to biological surveillance.

To Professor R.J. Kettle, for him agreeing to me registering for a higher degree as a Visiting Fellow in the Division of Civil and Mechanical Engineering, School of Engineering and Applied Science. Also for the use of facilities and secretarial assistance in preparing the submission.

To Dr. Peter Hedges, who was appointed my advisor to provide guidance in the preparation of the submission, a role in which he far exceeded any perfunctory requirements by interpreting new regulations with little by the way of precedence. Attempting to achieve the high standards of presentation he obviously expected was a challenging exercise. However with his guidance and the capable secretarial assistance of Mrs Joan Domone, the miscellaneous collection of reprints was transformed into a presentable document.

Finally, to my wife Joan, who over the years has sacrificed much to enable me to pursue my research interests without being able to share my professional rewards, for her insistence without which I would never have made this submission.

CONTENTS

Page

VOLUME I

Preface 5

Synopsis - The Ecology of Sewage Biological Filters 6

List of Publications by H.A. Hawkes on The Ecology of Sewage Biological Filters. Presented in the Thesis. 9

Statements on Contributions to Joint Publications. The Ecology of Sewage Biological Filters. 10

15 Selected Papers on The Ecology of Sewage Biological Filters. 11

VOLUME II

Contents of Volume II

Synopsis - The Ecology of River Pollution and Biological Surveillance. 3

List of Publications by H.A. Hawkes on The Ecology of River Pollution and Biological Surveillance presented in the Thesis. 6

Statements on Contributions to Joint Publications. The Ecology of River Pollution and Biological Surveillance. 8

24 Selected Papers on The Ecology of River Pollution and Biological Surveillance. 10

Appendix Curriculum Vitae and Comprehensive List of Publications by H. A. Hawkes. i - xiii

PREFACE

The two lines of research reported in the accompanying papers both relate to applied biological aspects of river pollution control - biological sewage treatment and biological surveillance of river water quality. The earlier phases of both lines of research (1948 - 62) were carried out as personal research as the sole biologist with the Birmingham Tame and Rea District Drainage Board which later became part of Severn Trent Water Authority, now Severn Trent plc.

The studies in both fields were continued and developed as research topics in the Applied Hydrobiology Section which I established at the University of Aston. This later research was supported by studentships and research contracts and involved a succession of students, and resulted in a series of publications of joint authorship. Only those in which I made a significant contribution have been included in the ones submitted. The two lines of research, although both concerned with water pollution control, were developed separately and the resultant publications are best considered chronologically arranged under two titles -

1. The Ecology of Sewage Biological Filters.
2. The Ecology of River Pollution and Biological Surveillance.

SYNOPSIS - THE ECOLOGY OF SEWAGE BIOLOGICAL FILTERS

The original problem, justifying the appointment of a biologist at Birmingham sewage works, was the need to control the fly *Anisopus fenestralis* which bred in the sewage filters at Minworth and dispersed in large numbers to cause nuisance and possible public health hazard in the surrounding villages. My initial work was the continuation of investigations in progress on the chemical control of the fly using the newly developed synthetic insecticides DDT and BHC. Investigating the methods of assessing the fly populations being used at the time I found them to be unreliable (Publications 1 and 2).

To use the insecticides most effectively and to minimise any adverse environmental impact, studies were undertaken on the ecology of the insects in the filters. Methods were developed for sampling the different stages of the insect, determining the amounts of the microbial film within the filter and the aerial density of the adult flies above the filters. Using these methods the distribution of the different stages and their seasonal incidence was established (3). Frequent - weekly - sampling of one filter revealed the rhythmic incidence of the fly involving a succession of generations throughout the year. The suppression of the spring peak of larvae by a single application of insecticide, although reducing the fly population, delayed the spring unloading of the filter which occurred in a untreated control filter, and as a result the fly population was greater later in the year. This indicated that control by insecticides, although necessary in the short term, was ecologically unsound and control by limiting the insect's food supply (i.e. the microbial film) would be a sounder method. The results of this early study influenced the direction of subsequent work.

To determine the conditions under which the flies emerged from the filters in large numbers to cause nuisance, an intensive study was carried out involving hourly catches over the filters for a period of one year (4). Nuisance to the public was only caused when the flies dispersed from the works. Factors affecting the dispersal of the fly were therefore also investigated, and the results are included in Chapter 3, pp 251 - 258 of the book edited by Curds & Hawkes, submitted separately.

The possibility of controlling the fly by insecticide treatment raises the question of the role of insects in controlling the film. At the time there was a difference in opinion regarding the role of insects in the filters. Generally British workers considered insect grazing was essential in controlling the microbial film and preventing ponding, others in America considered the insects were incidental and played a minor role, if any, in the economy of the filter. To resolve the difference, ecological studies were carried out on a series of filters operating under different conditions. These distinguished for the first time the differences in the roles of insects in controlling bacterial and fungal dominated films, thus reconciling the opposing views (5).

These investigations also showed that the different populations of the fly present in the different filters were related to the amounts of film present. The winter deterioration in efficiency, a common feature of filters, was found to be caused by excessive accumulations of film rather than by direct effects of low temperatures on the metabolic activity. Thus the two problems associated with filters-fly nuisance and filter ponding with consequent deterioration in performance, were both caused by the degree of film accumulation. An ecological approach to these problems was advocated in an award-winning paper presented to the Institute of Sewage Purification Annual Conference 1960 (6). Modified methods of filter operation which had proved successful in practice in controlling film accumulation were explained in ecological terms of microbial growth rates as opposed to the mechanistic hydraulic concepts commonly held at the time.

Having established the importance of film control in filter operation, field and laboratory studies were directed at establishing the environmental and operational conditions affecting the accumulation of film, both fungal and bacterial.

Seasonal fluctuations in fungal film were found to be related to seasonal changes in nutritional conditions - sewage strength - and to temperature (7). The effect of medium size was investigated using purposely designed filters (8 & 9). Using a modified distributor arm the effect of the type and spacing of the jets on the fungal film and fauna was investigated (10). The most marked effect on the amount of fungal film and the associated fly population was found to be the frequency at which the sewage was applied to the filter as determined by the rate of rotation of the distributor (11). This made possible the control of film and fly populations by regulating the dosing frequency.

Applying this control method to the primary stage of the double filtration process made possible the development of this method of filtration, which had previously been limited by the ponding of the primary stage during the winter (12). The results of these investigations were later successfully applied to the process design of the filtration stage of the sewage treatment works for Warwick and Leamington where a nitrified effluent was required. This research was recognised by the European Water Pollution Control Association in the award of the Dunbar Medal (1964) for "outstanding contribution in the field of sewage treatment by applying results of his ecological research on biological film and grazing fauna to the practice of engineering design and operation of trickling filter installations".

To investigate factors affecting the accumulation of bacterial film, studies were carried out on newly constructed filters treating a purely domestic sewage. These included a study to investigate the effect of dosing frequency on a bacterial film (13). Perforated shafts incorporated in the filters enabled studies to be carried out on conditions throughout the filters (14). These studies proved the importance of grazing activities of insects and worms in bringing about the spring unloading of the filters. The cause of the winter accumulation of solids to cause ponding was, however, less evident. To investigate the effect of temperature on solid accumulation in filters studies were carried out using bench-scale filters under environmentally controlled conditions (15). These investigations indicated the importance of the differential effects of temperature changes on the relative rates of BOD removal by physical adsorption and the bio-chemical oxidation by the microbial film.

A more detailed summary of these ecological investigations together with the results of other previously unpublished work on the ecology of high-rate biolocal filters, is presented in Sections VII and VIII of Chapter 3 (pp 228 - 333) of the book "Ecological Aspects of Used-Water Treatment", submitted separately.

List of Publications by H.A. Hawkes on The Ecology of Sewage Biological Filters presented in the Thesis.

1. Jenkins, S.H., Baines, S. and Hawkes, H.A., 1949. The Control of *Anisopus fenestralis* and factors influencing the numbers of *Anisopus* caught in surface traps. J.Inst.Sew.Purif. (2), 178-87.

2. Hawkes, H.A., 1951, A study of the biology and control of *Anisopus fenestralis*, a fly associated with sewage filters. Ann. appl. Biol. *38*, 592-605.

3. Hawkes, H.A., 1952, The ecology of *Anisopus fenestralis* (Scop.) (Diptera) in sewage bacteria beds. Ann. appl. Biol. *39*, 181-192.

4. Hawkes, H.A., 1961, Fluctuations in the aerial density of *Anisopus fenestralis* (Scop) (Diptera) above sewage bacteria beds. Ann. appl. Biol. *49*, 66-75

5. Hawkes, H.A., 1957, Film accumulation and grazing activity in the sewage filters at Birmingham. J.Inst.Sew.Pur., 88-112

6. Hawkes, H.A., 1961, An ecological approach to some bacteria bed problems. J.Inst.Sew.Purif. (2) 105-132.

7. Hawkes, H.A., Factors influencing the seasonal incidence of fungal growths in sewage bacteria beds. Int.J.Air.Wat.Poll. 9, 693-714

8. Hawkes, H.A., and Jenkins, S.H., 1955, Comparison of four grades of sewage percolating filter media in relation to purification, film accumulation and fauna. J.Inst.Sew.Purif., 88-112

9. Hawkes, H.A. and Jenkins, S.H., 1958, Comparison of four grades of media in relation to purification, film accumulation and fauna in sewage percolating filters operating on alternate double filtration. J.Inst.Sew.Purif., 221-5

10. Hawkes, H.A., 1959, The effects of methods of sewage application on the ecology of bacteria beds. Ann. appl. Biol. *47*, 339-49

11. Hawkes, H.A., 1955, The effects of periodicity of dosing on the amounts of film and numbers of insects and worms in the alternating double filters at Minworth, J.Inst.Sew.Purif. (1), 48-50.

12. Hawkes, H.A. and Jenkins, S.H. 1964, Comparison of double filtration and alternating double filtration of an industrial sewage using beds having controlled frequency of dosing. Scientific paper from Institute of Chemical Technology, Prague, Technology of Water, 8(1) 87-119

13. Hawkes, H.A. and Shephard, M.R.N., 1970. The seasonal accumulation of solids in percolating filters and attempted control at low frequency dosing. Proc. 5th Int.Wat.Pollut.Res.Conf., 11, 11/1-11/8

14. Hawkes, H.A. and Shephard, M.R.N., 1972, The effect of dosing frequency on the seasonal fluctuations and vertical distribution of solids and grazing fauna in sewage percolating filters. Wat. Res. *6*, 721-730.

15. Shephard M.R.N., and Hawkes, H.A. 1976, Laboratory studies on the effects of temperature on the accumulation of solids in sewage percolating filters.
Wat. Pollut. Control, *75*, 58-72

Book (submitted separately) Ecological Aspects of Used-Water Treatment. Curds, C. & Hawkes, H.A. (Editors) Academic Press, London.
Vol. 3, The Processes and their Ecology (1983)
Chapter 1 Biological Filters (A.M.Bruce & H.A. Hawkes) 1-111.
Chapter 3 Applied significance of Ecological Studies of Aerobic Processes. (H.A.Hawkes) 173-333.

STATEMENTS ON CONTRIBUTIONS TO JOINT PUBLICATIONS

The Ecology of Sewage Biological Filters.

1. Dr S J Jenkins was Chemist in charge of the laboratory and scientific staff of the Board. He was overall director of the research. S. Baines was my predecessor I continued his work on chemical control by comparing the use of emulsion and dispersible powder - reported on p4. I was critical of the trapping method and investigated factors affecting its efficiency pp.5-7. Conclusions 5-10 resulted from my part in the investigation.

8 & 9 Two related investigations jointly planned with SHJ supervised by HAH, SHJ responsible for chemical analytic work HAH for biological work. I wrote the papers.

12 This investigation was the result of my suggestion that "Two-stage Filtration....... would provide a more nutrified effluent than ADF or Recirculation" (Publication II). It was therefore a continuation of my line of investigations on filters. Dr Jenkins supported my proposals for these large scale investigations involving a team of plant operators. He was also responsible for the chemical analytical work carried out in his laboratory. HAH operated the plant, was responsible for the sampling and the biological work. HAH processed the data, using statistical methods advised by SHJ and wrote the paper.

13,14 & 15 MRN Shephard was appointed by Research Assistant 1964-67. During this period he assisted he with the long-term studies on the Langley Filters (Publication 21). For a two-year period, with his assistance, a more intensive study on the vertical distribution of film was carried out (Publication 22). In the laboratory he constructed and operated laboratory-scale filters which I had previously planned. The work was reported in his thesis which he successfully submitted for a Masters Degree. Based on the results in his thesis I wrote the joint papers after he had left.

Paper No. 1

The control of *Anisopus fenestralis* and factors influencing the numbers of *Anisopus* caught in surface traps.

Jenkins, S.H., Baines, S and Hawkes, H.A.
J.Inst.Sew.Purif. (2), 178-87, 1949

The Control of *Anisopus Fenestralis*, and Factors Influencing the Numbers of *Anisopus* Caught in Surface Traps

By S. H. Jenkins, D.Sc., F.R.I.C. (Fellow), S. Baines, B.Sc. Hons. (*Formerly Biologist, Birmingham Tame & Rea District Drainage Board*), H. A. Hawkes, B.Sc., Hons. (*Biologist, Birmingham Tame and Rea District Drainage Board*).

Anisopus fenestralis is a useful filter scavenger in its larval stage but the adult fly may become a nuisance in spring and summer by congregating in damp or shady parts of houses. Tomlinson and Jenkins[1] described large scale experiments carried out in 1945 and 1946 at Minworth Works, Birmingham, when Gammexane and DDT were found to be the most effective of a number of chemicals tried. Tomlinson and Muirden[2] found these two chemicals were highly satisfactory in controlling species of *Psychoda*.

This paper records the results of further experimental work at Minworth on 21 acres of filters in 1947 using different amounts of Gammexane and DDT, and on 41 acres in 1948, when Gammexane alone was used: the dispersible powder form of Gammexane was also compared with the emulsion. A preliminary report is made of observations on several factors which affect the number of *Anisopus* caught in dark trays placed on the surface of a filter.

EXPERIMENTS IN 1947 WITH GAMMEXANE AND DDT.

Thirteen acres of filters which receive bio-flocculation plant effluent from travelling distributors were divided into plots of about 1/6th acre. Gammexane D.929 containing 13 per cent. gamma isomer, of which about 90 per cent. is extracted with solvent naphtha, was applied once at a rate equivalent to 5, 10, 20 and 40 lbs. D.929 per acre: DDT was applied at the rate of 15, 30, 60 and 120 lbs. per acre. Each treatment was replicated five times and five untreated plots were used as controls. The insecticide emulsion was fed into the distributor supply channels over a period of one hour, thus allowing sewage containing insecticide to flow over each part of the filter four times. The filters were rested for 18 hours after treatment.

The emulsions used were: DDT 15 lbs. dissolved in 3½ gallons 90/190 solvent naphtha by gently heating in a metal tub on an electric hot plate: 0.63 gallons oleine added, followed by ¾ lb. caustic soda in ½ gallon water; less caustic soda is used if curd formation occurs: 0.17 gallon of Teepol X is added and the volume made up to 10 gallons. Much practice is required to obtain satisfactory results. A better 15 per cent. emulsion is obtained by the method given below, substituting DDT for Gammexane.

Gammexane. 20 lbs. Gammexane D.929 is heated in 5 gallons of warm solvent naphtha until no further solution occurs. This takes 30-60 minutes. The temperature may be raised to 160°F. The mixture is allowed to stand, preferably overnight, the clear liquid decanted and made up to 5 gallons with solvent naphtha. To the extract are added 2 gallons 50 per cent. N sulphonated castor oil and ½ gallon cresylic acid. The viscous emulsion produced is stable for at least six months.

Three shallow trays, 1 ft. square, were inverted and placed at random on the surface of each plot. The *Anisopus* found in the trays were counted twice a week, and the numbers taken as a measure of the flies in the filter. The counts were started several weeks before applying insecticide. From these initial counts, the plots were divided into five groups and the insecticide was applied so that each treatment and one control occurred in each group. In three of the groups the treatment was given a second time.

On another block of 8 acres of filter, sewage partially treated by activated sludge is distributed from fixed spray jets. The nearest point of application of the Gammexane used was ¼ mile away from the filters. Preliminary tests with fluoresceine having shown how long it took for the colour to reach the filters, the insecticide emulsion was added at a constant rate to the sewage over a period of one hour: the filters were dosed with sewage for a further half hour and then rested for 18 hours. A portion of the filter was treated with insecticide applied by hand from a watering can.

The first application of insecticide was made in April, when *Anisopus* larvae and adults were plentiful; the second application to some of the filters was made in June.

In Figures 1, 2 and 3 the results of treatment of filters with a low initial *Anisopus* count are given on the left ; those with a high count are shown on the right.

Figure 1. DDT at 15 lbs. per acre reduced the number of *Anisopus* for a few weeks in the filter with a low initial count but was ineffective in the one with a high count. With 30 lbs. per acre, little control was exercised. DDT at 60 lbs. per acre gave a considerable reduction in numbers, the control being maintained for 5 or 6 weeks. With 120 lbs. DDT a reduction lasting for many weeks was effected in one case. The filter with the high initial count responded to 120 lbs. DDT but the effect was delayed. The reaction which occurred immediately following the application represents the killing of adults ; the increase which follows is probably due to the emergence of adults from pupae and the subsequent fall to the killing of larvae. The above results indicated that an application of 60 lbs. of DDT per acre would be required to effect control of *Anisopus.*

Figure 2. The Gammexane extracted from 5 lbs. D.929 per acre reduced the numbers of *Anisopus* in the filter having a high initial count. 10 lbs. of D.929 also effected some reduction in numbers. With 20 lbs. the numbers were also reduced, by comparison with those obtained from the control filter. With 40 lbs. D.929 only partial control was effected on the filter with a low initial count, but the control was very good with the filter having a high count before the treatment.

Figure 3. The results showed that with all the applications—5, 10 and 20 lbs. of D.929 per acre, the numbers of *Anisopus* caught in trays were reduced. Comparisons were made on all the filters between application by hand and in the feed liquor. With an occasional exception, hand application gave more consistent results, although the reduction in numbers effected by the two methods of application was of the same order.

Experiments with Gammexane in 1948.

On the results obtained in previous years it was decided to dose the 41 acres of filters at Minworth with Gammexane at the rate of 10 lbs. D.929 per acre. The abundance of *Anisopus* larvae in the filters was used to decide when to apply the insecticide. Some of the blocks of filters required treatment four times between January and June : one block of 7 acres was not treated at all because few larvae were present. Many *Anisopus* larvae were found in some filters in July and August but these filters were not treated since it has previously been observed at Minworth that relatively few adults reach maturity from the larvae present in July and August.

Tray counts of *Anisopus* were made ; as before the filtration area was arbitrarily divided up into plots which gave high and low counts before treatment.

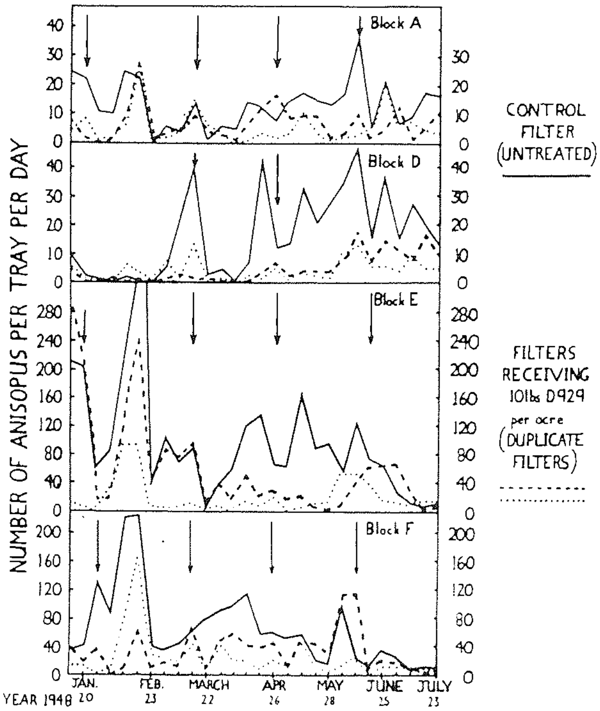

Fig. 4. Control of *Anisopus* effected by the application of 10 lbs. of Gammexane D929 per acre.

The results are given in Figure 4. They show that the treatment caused an immediate reduction in the numbers of adults. This was generally followed by an increase, the magnitude of which it should be possible to anticipate by making a pupal count, followed by a further reduction. From about the middle of January to the end of July the average percentage reduction of *Anisopus* achieved by four applications of Gammexane was 56, 62 and 55 per cent. on Blocks A, E and F and by two applications on Block D, 74 per cent. It may be a coincidence, but 1948 was the first time for many years that not a single complaint of fly nuisance was received.

In 1948 the cost of the chemicals used for applying the Gammexane at 10 lbs. of D.929 per acre was £222 : the cost of the labour for making up the emulsion, transporting and applying it was £46.13.0d. The cost of the treatment, spread over 41 acres of filters was therefore £6.11.0d. per acre. As already stated, some filters received more frequent treatment than others. The overall cost of treatment per acre per application of 10 lbs. of D.929 per acre was £2.11.0d. in 1948.

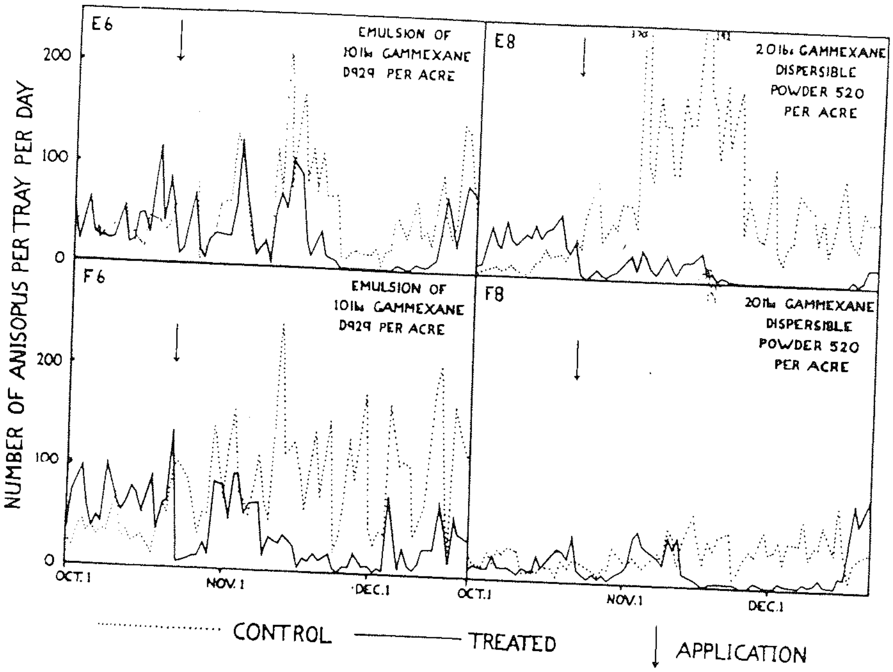

Fig. 5. Comparison between results obtained with Gammexane emulsion applied at the rate of 10 lbs. D929 per acre and Gammexane dispersible powder applied at the rate of 20 lbs. DP520 per acre.

COMPARISON BETWEEN GAMMEXANE APPLIED AS EMULSION AND POWDER.

In the autumn of 1948 a single application of Gammexane to a block of 13 acres of rectangular filters dosed from travelling distributors was made because of the presence of many *Anisopus* larvae and adults. Comparisons were made between Gammexane dispersible powder, which was reported upon favourably in the discussion of the paper by Tomlinson & Muirden,[2] and Gammexane emulsion. For each acre of filter the emulsion obtained from 10 lbs. of D.929 was used, *i.e.*, about 1.2 lbs. gamma isomer per acre: this was compared with 20 lbs. of dispersible powder DP.520, *i.e.*, 1.3 lbs. gamma isomer per acre. The filters were drained for 6 hours before treatment with insecticide and not dosed with sewage for 16 hours after treatment.

The average results of three daily counts of *Anisopus* found in trays are shown in Fig. 5 during the period of 3 weeks before to 8 weeks after treatment.

The graphs show that both with emulsion and dispersible powder an immediate reduction in numbers occurred after treatment, persisting for about a week. This was followed by an increase in numbers, lasting for about three weeks, due probably to the emergence of adults from pupae unaffected by the insecticide. A later reduction in numbers resulted from the action of the insecticide on the larvae: this effect persisted for 3-6 weeks. On one occasion during insecticide treatment of Block E, Figure 5, when many adult *Anisopus* were outside the filter, a subsequent sharp increase in the flies caught on an adjacent control filter was probably due to the repellant effect of the Gammexane, deterring flies from re-entering the treated filter. Such an increase on the control filters did not occur when few flies were about during treatment of Block F (Figure 5).

The conclusion drawn from the results given in Figure 5 and others not included in this paper is that Gammexane dispersible powder is at least as effective as the emulsion used at comparable rates. This conclusion supports the results reported by Tomlinson and Muirden[2] regarding Psychoda control.

The average number of *Anisopus* caught daily per square foot tray was 75 for the control filters used with the emulsion: the D.929 emulsion reduced the numbers by 61.5 per cent. The corresponding figures with the dispersible powder were 63 and 73.5 per cent.

FACTORS WHICH AFFECT THE NUMBERS OF ANISOPUS CAUGHT IN TRAYS.

The numbers of *Anisopus* found in surface trays sometimes bear little relationship to the observed numbers in the immediate vicinity of the filter. An attempt was made to measure the numbers of *Anisopus* leaving the filters by supporting sticky sheets of perspex 2 ins. or 3 ins. above the filter medium. Lower counts were obtained in this way but to some extent this resulted from the preparation failing to remain sticky owing to condensation.

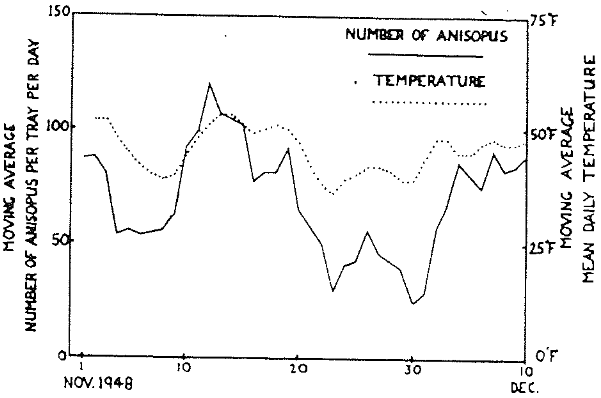

Fig. 6. Relationship between the numbers of *Anisopus* found in surface trays and the average of the minimum and maximum daily temperature.

EFFECT OF TEMPERATURE.

Fig. 6 shows the relationship between the daily average of the minimum and maximum temperatures and the average number of *Anisopus* in 18 trays on the various control filters. Day to day irregularities have been smoothed out by using a three day moving average. The results show a close correlation between air temperature and the numbers of flies entering the trays.

EFFECT OF LIGHT.

Preliminary observations showed that light played an important part in determining the numbers of *Anisopus* found in a tray placed on the surface of the medium. The effect of light on *Anisopus* has also been referred to by Khalsa.[3]

An experiment was therefore carried out on three separate occasions, when hourly counts over a period of 24 hours were made in triplicate of the *Anisopus* found in trays of three types. The first type was an inverted metal tray, one foot square, as used in the fly control work; the second was an inverted metal tray with a 4 in. perspex square replacing part of the metal; with the third type the 12 in. square top was made entirely of perspex. The three separate experiments gave similar results and only one experiment will be described.

In one set of the three different trays, which were closely grouped together on the filter surface, the flies were counted hourly and the trays returned to their original position, still leaving the flies in the trays. At the end of 24 hours, 22 flies were found in the metal tray, 12 in the one with the 4 in. perspex square and 0 in the one with the 12 in. perspex square, showing that admission of light had reduced the numbers found at the end of 24 hours. However, the numbers of flies present at hourly intervals, given in Figure 7, show that *Anisopus* had entered all the trays during the period of darkness. Since more flies were found in the trays with perspex windows during darkness than at daylight, this proves that the flies had left the trays for the filters under the influence of light.

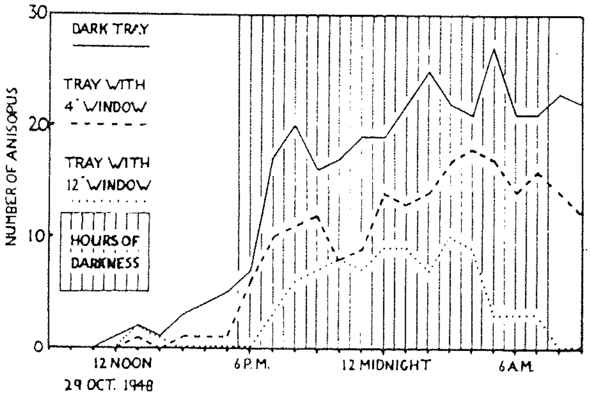

Fig. 7. Numbers of *Anisopus* found hourly in three different types of tray. The *Anisopus* found in the trays were left undisturbed and the trays returned to their original positions.

With the two other sets of the three different kinds of tray the insects which were found at each hour were removed hourly, and the trays returned

TABLE I.

Counts of Anisopus *in three different types of tray, found after a period of 24 hours, and found hourly.*

Numbers of *Anisopus*	Type of Tray		
	All metal	With 4" perspex window	With 12" perspex window
Found at the end of 24 hours in trays from which the flies **were not** removed hourly	22	12	0
The sum of 24 separate hourly counts in trays from which the flies **were** removed hourly after counting ..	57	58	27

to their original positions. Table 1 gives the results, which show that the sum of the 24 separate hourly counts is greater than the count found after 24 hours.

The individual hourly counts for the three types of tray are shown in Figure 8, a, b and c. In every case a very marked increase in the numbers in the trays occurred at about dusk, *i.e.*, between 6 and 7 p.m. The numbers entering the trays hourly declined during the hours of darkness and were at a minimum at daylight.

The increase in numbers observed at dusk, and the decrease throughout the night, are not due to temperature variations. The temperatures given in Figure 8, a, b and c show that from dusk to dawn the temperature did not vary by more than 2°C. During the daylight counts, however, a temperature rise between 11 a.m. and 1. p.m. coincided with a sudden increase in the numbers in the dark trays.

In Figure 8 (a) an increase at dusk is also shown in the all-metal trays which were permanently dark and, which might not be expected to show a response to light and dark if they only trapped the flies leaving one square foot of filter. One possible explanation is that during daylight the dark trays attract flies from adjacent areas to

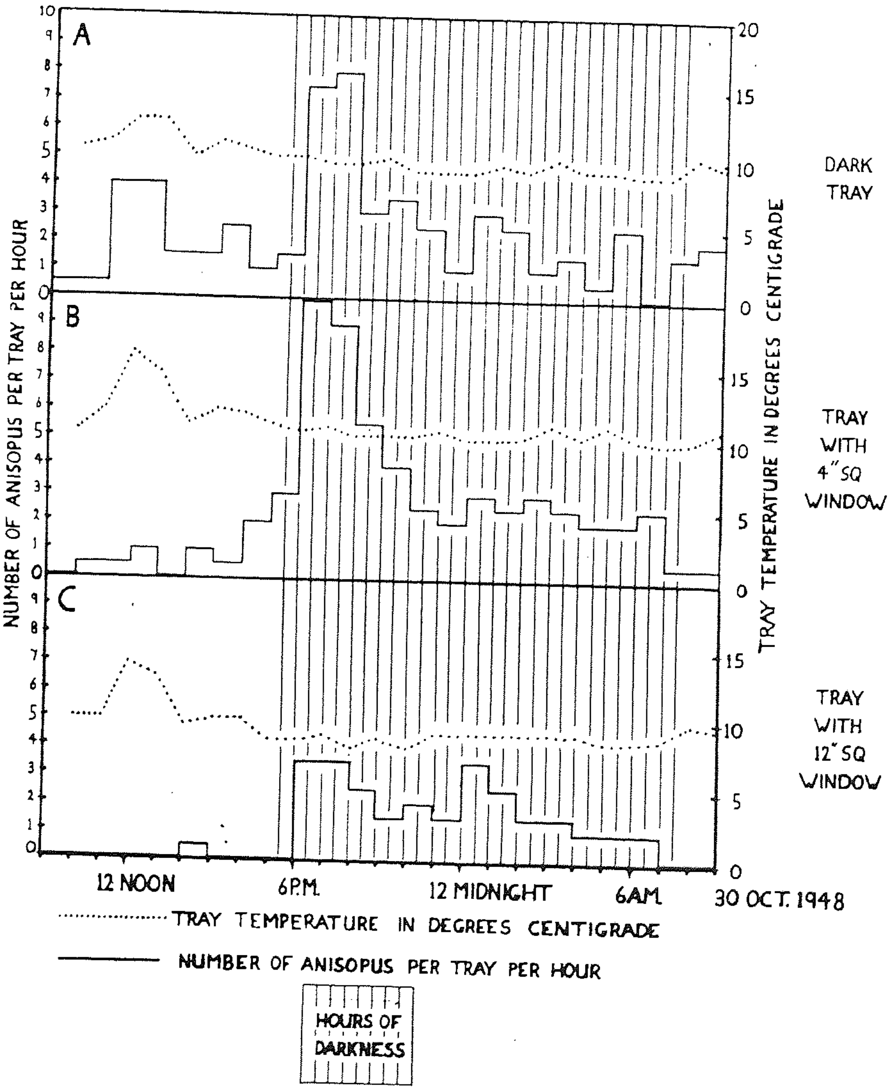

Fig. 8. A, B and C. Number of *Anisopus* found hourly in three different types of trays. The *Anisopus* found in the trays were removed at hourly intervals immediately after counting and the trays returned to their original positions.

powder at the rate of 20 lbs. D.P.520 per acre (6.5 per cent. gamma isomer) gave results at least as good as 10 lbs. of D.929 per acre (13 per cent. gamma isomer) applied as an emulsion.

6. During mild or cold weather the effect of a temperature increase is to cause a rise in the numbers of *Anisopus* found in dark trays. The effect of temperature during warm weather has not yet been studied.

7. Light exerts a repellant influence on the entry of flies into a surface tray. At dusk there is a marked increase in the numbers of *Anisopus* leaving the filters. In surface trays fitted with a window the flies return to the filters at dawn.

8. A dark tray on the surface of a filter attracts *Anisopus* from a greater area than it covers. The results obtained justify the hypothesis that at dusk, the absence of the repelling influence of light causes more flies to be present nearer the surface : those flies seek the shelter of the trays. Dark trays therefore also show an increase in numbers at dusk.

9. In blocks of surface trays, the outer trays collected more *Anisopus* than the inner trays. This is held to support the view that the trays attract *Anisopus* from a greater area than that covered by the tray.

10. Observation and experiment support the conclusion that dark trays do not measure the numbers of *Anisopus* leaving the filters, because the flies are attracted to a dark tray.

11. Although several factors influence the numbers of *Anisopus* found in a dark tray it is thought that such a trap provides a useful and practical measure of the *Anisopus* population of a filter.

ACKNOWLEDGMENTS.

This paper is published by kind permission of Mr. F. C. Vokes, Engineer to the Birmingham Tame and Rea District Drainage Board. The authors are indebted to members of the Works staff for assistance in the large scale experimental work ; to Miss B. M. Wesley for carrying out fly counts and Mr. A. M. Whiteley for assistance in observations on the larval population of the filters.

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The foregoing paper was presented at a meeting of the Midland Branch held in Birmingham on Thursday, 21st April, 1949.

DISCUSSION.

In proposing the vote of thanks to the authors, MR. T. G. TOMLINSON (Water Pollution Research Laboratory) remarked that a striking thing which emerged from a study of the literature on the biology of percolating filters and the control of flies breeding in filters was, that until very recently, *Anisopus* was not mentioned at all; *Psychoda*, "the sprinkling filter fly" as it was called as though there was no other, completely dominated the attention of these investigators. The inference was, that *Anisopus* was not present in sufficient numbers to make it worth while to find a name for it.

And far as his information went, Mr. Tomlinson considered that *Anisopus* was present at some time in the majority of filters. The situation at the Minworth Works of the Birmingham Drainage Board was unusual in having *Anisopus* as a dominant member of the filter population and in having a problem confined entirely to this one species. He suggested that the intense and prolonged emergence of *Anisopus* from the beds with travelling distributors was due to a large extent to the pre-treatment of the sewage before filtration; the wide spaces between jets, providing an ideal site for pupation, was a contributing factor. It seemed probable that the population balance would change considerably when the Minworth plant was changed over to alternating double filtration; the increased growth of film would support a population of *Psychoda* in the spring which, in competition with *Anisopus*, would have a controlling effect during the late spring and summer. Last year it was noted at one works treating settled sewage in rectangular filters of similar construction to those at Minworth that the emergence of *Anisopus* was confined to March, April and the first week in May and that, after the first week in May, *Psychoda* and *Scatella* were dominant.

Dr. Jenkins had evolved a convenient and effective method of control based on scientific investigations carried out during the past five years. He and his colleagues had improved their technique step by step and had now arrived at a stage when several acres of filters could be treated in one operation by adding a water-dispersible Gammexane powder to the influent sewage. Perhaps they would bring out some apparatus for adding this disagreeable powder directly to the sewage with a minimum of handling.

It would be noticed that the peak after treatment which was so marked in Fig. 2 was absent from Fig. 3. This illustrated how the dry zones between the jets of the travelling distributors harboured both larvae and pupae which were not reached by the insecticide. Dr. Jenkins would remember that, in 1946, some of the plots on Block E were sprayed by hand so that the whole was covered; the curves for these plots showed lower secondary peaks compared with plots dosed through the distributor. It would seem that, where there was complete coverage, Gammexane was almost immediately effective.

It would be interesting to know whether the good correlation shown in Fig. 6 would hold for the whole temperature range experienced throughout the year. An investigation into the activity of *Anisopus* flies at different temperatures gave the following results; below 54°F. there was very little flight, between 54°F. and 59°F. there was some flight, the flies became very active within the range 60°F. to 65°F. and above 72°F. flight became very excited and the flies lived for a comparatively short time.

It would seem from Fig. 7 that *Anisopus* was sensitive to quite small intensities of light. Light would only affect those flies actually on the surface or a few inches below the surface; the increased catch at dusk would seem to be due to flies which had emerged from the filter in the vicinity of the trap entering the trap from the side.

Taking the data in Table 2 as a whole it was clear that more flies were trapped in the outer than in the inner trays. In small samples such as these, however, the size of the sample should be taken into consideration and the "t" test applied. If this was done values for the probability that the differences in column 6 might be obtained by chance are as follows; for the first three experiments 20, 10, and 1 per cent. and for the second three, 10, 30 and less than 1 per cent. Taking values of 5 per cent. and less as indicating significance it would be seen that 2 out of the 6 experiments gave significant differences.

Mr. G. W. Bennett (Coventry) in seconding the vote of thanks said that *Anisopus* appeared to be far more prolific on the Birmingham Works than was generally found. Were all the Drainage Board Works similarly affected ?

Experiments on Fly Control had been carried out on the Finham Works for the last three seasons by the Water Pollution Research Department. The experiments had been controlled and carried out by Mr. Tomlinson, and had proved very successful.

Varying quantities per acre of DDT and Gammexane had been used, together with differing methods of application. The applications of these insecticides had been made either by introduction to the centre bucket of individual distributors, or by addition to the common feed to blocks of filters. In some cases the time of application varied from one to three hours, followed by 18 hours rest, and in others the insecticide had been applied in the minimum time to allow for complete coverage, followed by 18-20 hours rest.

5lbs. of DDT or 1lb. of 'Gammexane' per acre had been found to be an effective control for a period up to one month, and in later experiments, a fortnightly application of 16lbs. of the dispersible powder per acre was found to give almost complete control.

These treatments did not appear to have any adverse effect on the beds; on the other hand, *Achorutes* had increased considerably.

The authors had found that the dispersible powder D.P.520 was a very convenient source of 'Gammexane', because it could very easily be mixed in water and could quite safely be handled by semi-skilled labour; whereas the emulsion must be made up by Technical Staff, transport was not so easy, and in view of the quantities involved application was more difficult.

Care must be exercised when using these insecticides, due to their toxic effect on fish.

Although the authors were dealing with *Anisopus* only, their findings generally confirmed results already published.

The effect of light on *Anisopus* was very interesting. In view of this, could not more effective control be obtained by applying the insecticides during the hours of darkness, when apparently more flies were at rest (Fig. 8) ? The optimum time appeared to be just after darkness had fallen.

Mr. Hewitt (Birmingham) said that he would like to confirm Mr. Tomlinson's remarks on the lack of knowledge of fly life in filters even a few years ago. The name *Psychoda* was used to include everything, since it was the only one which had been mentioned in papers available to sewage works personnel. For many years the only whole-time biologist in the country, primarily interested in sewage purification, was Mr. Haigh Johnson of the West Riding Rivers Board. The papers he published, such as the one on *Psychoda and Achorutes*, made one regret that he did not deal with many more organisms found in bacteria beds.

Turning to *Anisopus Fenestralis*, it seemed a matter of wonder that such a helpless, defenceless type of fly had managed to survive. It was surmised, by one author, that it was originally a nectar feeding insect: it might be that force of circumstances had caused it to turn to sewage purification for a living, as had occurred also with certain other creatures.

The need for biologists was very great but unfortunately sewage purification did not seem able even to retain those who entered the field. Dr. Reynoldson, Dr. Barker and Mr. Baines had all taken up other activities, with consequent loss to the study of the biology of sewage purification processes.

It was difficult to speak on such a specialised problem and he would conclude by indicating that although biologists were doing the work, chemists had supplied the tools.

Mr. J. Hurley (Wolverhampton) noted that the authors stated that "hand application gave slightly more effective control than application of the emulsion in the feed liquor, but the benefit was less than the extra cost involved in hand application." He wondered how the extra benefit of hand application had been assessed in monetary terms. Probably it was felt that the extra expenditure involved in hand application could be more profitably spent on heavier, or more frequent, doses of insecticide. Had the authors considered whether their conclusion would still apply if some other method of hand application, such as a knapsack sprayer, were employed ?

Earlier in the discussion, it had been mentioned that the term "filter fly" had commonly been taken as referring to *Psychoda*, while until recently *Anisopus* had received little mention or attention. This might have been due, in some measure, to the fact that *Psychoda* were readily identified and associated with sewage works, whereas to folk living near sewage works, *Anisopus* were probably "just midges." Thus their presence might not have caused complaints to be made at the sewage works; they might even have been welcomed as a promise of fine weather on the morrow !

It had to be remembered that fly control, if carried out too drastically, might possibly retard the scavenging of the filters, and so ultimately lead to clogging of the beds. The winters of 1947-48 and 1948-49 had not been bad ones from the ponding standpoint, so observations in these years might not be typical of all winters. Possibly *Anisopus* deserved treating with special care, for they became active early in the season, when their help in removing the winter's accumulation of solids was specially valuable. Of course, it was by no means certain that fly control would add to the danger of ponding; it might well be that other forms of life (such as *Lumbricillus* worms and *Achorutes*) would increase sufficiently to take on the work previously done by fly larvae. It was just a point which needed watching.

Mr. Winsor had brought to the meeting a number of *Anisopus* flies in a glass bottle—a sort of Anisopean flea circus. One of these flies had escaped, and after a preliminary flit round the table, it had flown straight towards the nearest window. At first glance, this did not seem to agree with the statement that anisopus liked shade, and swarmed at dusk. However, there were at least two possible explanations of the seemingly inconsistent behaviour of Mr. Winsor's fly. One was that mid-afternoon at Birmingham was about equivalent to dusk elsewhere. Another factor might be the repellent affect of the members of the Branch and of the tobacco which they smoked.

Mr. C. E. Winsor (Birmingham) said that to one who had lived in the village of Minworth for the last ten years, the observations made in the paper were of considerable interest.

For many years past, the inhabitants of Minworth had involuntarily used their houses as fly traps and were well acquainted with the habits of the adult fly. As these were not all mentioned in the paper it might be of interest to describe them.

The fly was very light in weight and easily carried by the prevailing wind. This largely determined the location of possible nuisance. The fly would always be found in daytime on the shady side of the house, under porches, doorways, etc., and, as its name implied, especially on windows. It was very sluggish and would remain motionless for hours. This would easily be tolerated were it not for the females' most objectionable habit of laying slimy masses of eggs on anything moist, such as dish clothes, vegetable salads, etc.

The suggestion that it was originally a nectar feeding insect was amusing in view of the fly's great fondness for vinegar, pickles, mincemeat, beer and alcohol.

The dusk emergence on a large scale had been confirmed on countless occasions. Rooms with open windows or doors free from flies in daylight would be found to swarm with them after dusk. Their removal, incidentally, could be most easily carried out by suction through the hose of a vacuum cleaner.

The fly also appeared to be much influenced by the colour of objects. Very seldom would anyone wearing a white lab. coat outside be found to attract flies, whereas the wearer of a dark suit or dress would be swarming with them.

Finally, as a tribute to the authors of the paper, there was no doubt that the very careful programme of fly control carried out in 1948 had been responsible for the most fly-free year in the experience of Minworth.

Mr. J. H. Spencer (Northampton) asked for information regarding the life cycle of *Anisopus*. He wondered whether it would be possible to arrange to dose the filters with insecticide, and repeat the dose when necessary so as to synchronise with the time when the insect was likely to be in the larval stage. That would be known from the life cycle of the insect. He drew attention to the lack of uniformity of symbols in the graphs which he had found rather confusing. Mr. Spencer wished to know if the insects actually swarmed at dusk, seeing that they came out of the filters in greatest numbers at that period. In a previous paper by Mr. Davies, read before the Institute recently, Mr. Spencer said there had been some reference to the repellent action of insecticides. Would it not be possible to go into that question further? He suggested that the repellent action might be studied by having insecticide-treated and untreated trays on the filters, in order to determine whether the insecticide discouraged the flies from entering the trays. He also asked whether *Achorutes* were affected by 'Gammexane' and whether *Achorutes* in any way affected *Anisopus*.

Mr. N. Salt (Birmingham) asked the authors if harrowing the top stones of a filter (practised at the Yardley works to break up surface growths) would be effective in destroying flies in the larval and pupal stages by crushing them.

Reply to Discussion.

In reply the authors expressed agreement with Mr. Tomlinson's statement that *Anisopus* was present in most filters and that it was dominant in few. That might not always be the position. Comparatively slight alterations in operation might result in conditions becoming favourable to *Anisopus*. For instance, during the past few weeks reports in the public press had referred to a plague of flies, which were known to be at Leeds sewage works at Knostrop, and there had been reports of *Anisopus* from other sources. At Minworth works, the cleanest filters had the biggest adult *Anisopus* population, although some filters which ponded completely in winter contained many *Anisopus* larvae in spring and early summer. The nature of the sewage might be a factor of importance: the size of the medium certainly was. When, at Mr. Tomlinson's suggestion, the 1-2" medium of a clean filter was replaced several years ago with $\frac{3}{4}$" medium to a depth of 6", *Anisopus* ceased to breed in the filter. As regard the suggestion by Mr. Tomlinson that the change over to alternating double filtration would reduce the *Anisopus* and favour *Psychoda* because of the greater amount of filter film, the authors thought that on some filters at Minworth the application of alternating filtration would reduce the degree of winter ponding, which might actually encourage *Anisopus* on those filters. It was hoped that with increasing knowledge it would be possible to control the numbers of *Anisopus* by methods of operation.

The authors recognised, as Mr. Tomlinson pointed out, that drier spaces between jets would be sought out by larvae for pupation, and that once there it would be difficult to attack them by insecticide applied in the feed liquor. That only emphasized the need to apply insecticide when the insects were in the larval stage.

The question of the correlation between temperature and *Anisopus* caught at different times of the year had not yet been investigated.

With regards to the sensitivity of *Anisopus* towards light, it might be that an ascent to the surface would take place at dusk, in addition to any effect caused by shading an area of the filter by dark trays. The entry of flies from the side of a dark tray was also possible;

such flies might be those which had emerged from the filters at dusk.

The authors were interested in the conclusion reached by Mr. Tomlinson that two out of six experiments gave significant results when the "t" test was applied. There seemed to be little doubt that larger counts were obtained in the outer trays of a block of trays, though whether the author's explanation of the fact was the true one or not was as yet open to argument.

With regard to Mr. Bennett's remarks concerning the prevalence of *Anisopus* at Minworth, it was a fact that this fly was dominant at that works in spring and early summer, but not at any other works of the Board, or indeed in the district. The authors agreed that the dispersible powder was more convenient to use than the emulsion, if that had to be prepared; in addition, the dispersible powder was more effective. There might be occasions when an emulsion was required, for instance to spray filter walls or buildings. In that event, unskilled workmen could quickly be taught to make the emulsion.

By applying insecticide just before dusk, not as Mr. Bennett had suggested, during darkness, it would be possible to obtain a larger kill of adults near the surface but the essence of control was to kill the insects in the larval stage. The authors had also failed to notice any deterioration in the quality of the effluent or in the surface appearance of the treated filters.

The authors were of the same opinion as Mr. Hewitt that there was much ignorance of the biology of filter beds. There was a possibility that by knowing more about the distribution, life cycle and habits of the higher organisms which inhabited filters, it would be possible to exercise control over *Anisopus* and *Psychoda* by other means than insecticides.

Mr. Hurley had asked how it was possible to assess the benefits of hand application of insecticide in monetary terms. Hand application, done properly was very expensive in labour. By more frequent application in the feed liquor it ought to be possible to achieve the same results. With filters dosed from fixed jets it was necessary to get good distribution if the application of insecticide was to give results approaching those obtainable by hand application. The authors had satisfied themselves that for an area the size of Minworth, application by hand from a knapsack sprayer was out of the question. They had tried a smoke generator, which covered the area with a mist of insecticide but the success of the method was too much at the mercy of wind and weather. Mr. Hurley's point about achieving fly control at the expense of ponding, due to the elimination of scavenging organisms, had occurred to the authors and they had been on the look out for signs of summer ponding. Apart from an autumn application, some years ago, resulting in rather a lot of film being present, and in a ponded filter failing to clear itself quickly following an application of 'Gammexane', the general experience was that the control of *Anisopus* still permitted other scouring organisms to maintain sufficient activity to prevent ponding.

Mr. Winsor had given them some useful information concerning the habits of *Anisopus*. It was true that the fly was weak on the wing but something more than wind might be needed to account for its presence away from the sewage works, since in very windy weather it was not tempted to come out of the filters. Furthermore, the fly sought shelter out of the wind, as could be proved by placing vertical sheets of perspex coated with a sticky preparation over or near the filters, when it would be found that the side in the path of the wind would have fewer flies than the other side.

There appeared to be a genuine difference of opinion regarding the attraction of *Anisopus* to light and dark clothing. Most people on sewage works wore dark clothing and might therefore feel that that was the reason the flies lighted upon them, but at least one of the authors was prepared to affirm that a white laboratory overall was the reason for his popularity with adult *Anisopus*.

As regards Mr. Salt's question concerning the possibility of harrowing the surface of filters in order to crush the larvae or pupae, the authors considered that that would not be effective. Medium which was forked and dug over quite violently still contained many larvae intact. Such forking, however, usually resulted in many adults being crushed.

In reply to Mr. Spencer's request for information about the life cycle of *Anisopus* the authors gave the following approximate figures for 20°C.; egg stage 4 days, larval stage 20 days, pupal stage 8 days, adults 7 days. These figures depend upon the food and temperature factors. Mr. Tomlinson had already dealt with the effect of temperatures on the life and activity of the adult.

The authors did not think it practicable to predetermine the dosing of the filters to coincide with the calculated life cycle of the insect, because there were generally different generations of the insect in different stages of development and the duration of these stages was subject to such influences as weather, food supply and temperature. Concerning Mr. Spencer's question about the emergence of the insects at dusk, it was likely that swarming would explain the reason for the emergence at dusk. In bright sunlight the adults certainly sought the shade. This demonstrated some years ago by Mr. Tomlinson by placing large shady awnings in different part of a filter. These shady parts collected large numbers of insects, as also did shade traps such as inverted biscuit tins placed over the filters. They would certainly follow up Mr. Spencer's suggestion that the repellent action of the insecticide used might be determined. However, by having some fly traps treated with insecticide and others untreated as he had suggested, flies entering the treated traps could die and be left on the filter surface, not in the trap.

Achorutes were only slightly affected by 'Gammexane' in the concentration employed, as had first been observed by Mr. Tomlinson. The only effect *Achorutes* had on *Anisopus* was as a competitor for food.

MIDLAND BRANCH ANNUAL GENERAL MEETING.

The Branch Annual General Meeting was held in the Chamber of Commerce Buildings, Birmingham, on Thursday, 21st April, 1949.

The minutes of the last Annual Meeting were read and confirmed, and the Honorary Secretary presented his report on the year's work ; he was accorded an enthusiastic vote of thanks for his energetic and efficient work during the year.

The next business was the election of officers for the year 1949-50, the following nominations being approved unanimously :—

The Ecology of Sewage Biological Filters

Paper No. 2

A study of the biological control of *Anisopus fenstralis*, a fly associated with sewage filters.

Hawkes, H.A.
Ann. appl. Biol. 38, 592-605, 1951

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A STUDY OF THE BIOLOGY AND CONTROL OF *ANISOPUS FENESTRALIS* (SCOPOLI, 1763), A FLY ASSOCIATED WITH SEWAGE FILTERS

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(With Plate 15 and 6 Text-figures)

In work on the control of the sewage fly *Anisopus fenestralis* (Scopoli, 1763), it was shown that the larval phase was considerably lengthened by limiting the food supplied. The effects of food supply and temperature are considered in relation to the incidence of the adult fly in the filters. The assessment of the fly population of sewage filters by tray traps, as previously used by other workers, was investigated. Both light and temperature were found to affect the number of *A. fenestralis* entering the trays: it is concluded that although the trays do not accurately assess the *A. fenestralis* population of a bed, nor measure the rate of emergence from the bed, they are of value in assessing the relative effect of different control measures. In the filters the period of maximum abundance was during the spring, followed by a period of reduced numbers throughout the summer, with a recovery in the autumn giving relatively high numbers throughout the winter. Emergence of *A. fenestralis* from the filters is influenced by climatic factors, especially temperature and light; a diurnal variation in the rate of emergence was also observed. Because of this effect of temperature on emergence, the flies were only present above the filters in the warmer periods of the year; and because of the reduced numbers in the filters in the summer, the flies were only abundant above the beds during the spring and early summer and in the autumn. BHC applied as a water-dispersible powder was more effective than in the form of an emulsion. It was also most effective when used against the larval phase.

Introduction

The larva of *Anisopus fenestralis* (Scopoli, 1763) is an active grazer in some sewage filters, where it is beneficial in controlling the amount of bacterial and fungal film on the medium. An excessive amount of such growth is undesirable. Unfortunately the adult flies, because of their shade-seeking habits, enter buildings and dwellings on and near the works causing nuisances. They are attracted to food and have the obnoxious habit of depositing their egg masses in such moist shady places as on tooth-brushes, in sinks and in vegetable salads. On the works the aerial density of the flies at times may make work almost impossible. Because of its close association with sewage and food, *A. fenestralis* must be considered a potential danger to the health of the community besides causing both physical and mental distress, although no connexion between the fly and any disease has ever been proved. Filters as an environment for insects have been discussed by Lloyd (1935). Works treating domestic sewage usually have a balanced fly population consisting of several species of psychodid and chironomid flies. Industrial trade wastes may restrict the fly fauna to few species, as at Huddersfield (Golightly, 1940). The presence of several species of flies results in interspecific competition for food and reduction in numbers of any one species (Lloyd, 1935; Lloyd, Graham & Reynoldson, 1940; Golightly, 1940; Lloyd, 1943*a*, *b*; Khalsa, 1948). The restriction of the fly fauna to few competing species may result in the abundance of one species from which nuisance might result. Complaints have been reported due to *Psychoda* spp. and to *A. fenestralis*. Although *A. fenestralis* is present in sufficient numbers to cause nuisance at several works (Khalsa, 1948), the Minworth Works of the Tame and Rea District Drainage Board is one of the few exceptions in having it as the dominant fly for the greater part of the year. At some sewage works it appears to be a relatively recent invader (Khalsa, 1948), but evidence points to its presence at Minworth for the past 30 years.

The Minworth Sewage Works

The works are situated in the Tame valley, 7 miles east of Birmingham. The three villages, Minworth, Curdworth and Water Orton, are all within the dispersal range of *A. fenestralis* breeding in the filters. The forty-two acres of filters are divided into six blocks having parallelogram-shaped filters and four smaller circular filters. The whole area is surrounded on all sides by trees; these act as a wind-screen and this no doubt favours the presence of *A. fenestralis*. The filters are above ground-level, and for the most part have open stone walls 6–7 ft. in height. The filtering medium varies in size throughout the works, but is mostly of 2–3 in. crushed stone in four of the blocks, and of round gravel of the same size in the other two blocks. Most of the experiments described in this paper were carried out on the last-mentioned blocks. Each of these blocks is divided into ten filters, on each of which the sewage is spread by two machines travelling backwards and forwards, removing sewage by syphon action from a trough running along the middle of the filter. For experimental purposes each filter was thus conveniently divided into four bays.

Only the final stages of treatment are carried out at Minworth, removal of suspended matter by sedimentation having been performed at the Saltley Works, 4½ miles up the Tame valley. On arrival at Minworth a portion of the sedimented sewage receives partial purification with activated sludge before being applied to the filters in three blocks, including the two used in the experiments. The remainder of the sewage, after further sedimentation, is applied to the other three blocks. The sewage treated contains a high proportion of metallic and acid trade wastes, besides gas liquor. On four blocks the sewage is distributed from fixed nozzles projecting from pipes laid on top of the filter. The filter receives a continuous spray of sewage, but for several hours each day, depending upon the flow of sewage, the filters are rested. As already mentioned, the filters used in the experiments received sewage through travelling distributors which provided an intermittent dose on to each part of the filter about every 13 min. On the filters with fixed jets there develops every winter a thick surface fungal growth of *Fusarium* sp., and a fungus referred to by Tomlinson (1941) as a new species of *Sepedonium*. This does not occur on the filters served by travelling distributors. A thin surface growth of unicellular Chlorophyceae appeared on these filters. Besides *A. fenestralis* the following macro-fauna was present in the filters: nematodes, *Lumbricillus lineatus* Mull., *Lumbricus* sp.; spiders and mites, *Achorutes subviaticus* Begn., *Tomoceros minor* Lubb., *Cercyon ustulatus* Preys., *Psychoda alternata* Say., *Psychoda cinerea* Banks., *Psychoda severini* Tonn., *Spaniotoma minima* Mg., *Leptocera fontinalis* Fln., *Spaziphora hydromyzina* Fln. and *Phygadeuon cylindraceus* Ruthe.

THE LIFE CYCLE OF *ANISOPUS FENESTRALIS*

Under optimum food conditions the full life cycle is completed in 121, 73, 50 and 39 days at 9, 13, 18·5 and 21° C. respectively (Tomlinson, 1943). In the filters, however, food may not always be plentiful. The effect of limiting the food supply available to the larvae was therefore investigated.

Culture methods. Nine egg masses of *A. fenestralis* were placed on pieces of filter-paper resting on wetted absorbent cotton-wool in Petri dishes. After hatching, twenty larvae were subcultured into similarly prepared dishes. The food used was activated sludge, a complex of bacteria, fungi and Protozoa, similar in nature to the film upon which the larvae graze in the filters. This food was prepared by centrifuging fresh activated sludge and sterilizing by boiling. The resultant paste was then applied to the filter-paper in the Petri dish. The food was applied frequently; at first in small quantities but increasing as the larvae grew. One set of three cultures was provided with excess food, a second set with half this amount and a third with one-tenth. This was achieved by preparing the sludge paste from the appropriate dilution of the fresh sludge. The pupae and adults were cultured in 2 × 1 in. glass tubes, in the bottoms of which moist wads of absorbent cotton-wool were placed; when required sucrose was added to these tubes. The cultures were incubated at approximately 19° C. and examined daily, the date of eclosion, pupation and emergence being noted. Some adults were provided with sucrose, others received no additional food. To determine the effect of starvation on the size of the pupae five from each set, chosen at random, were measured. The results are summarized in Table 1. The results show that by limiting the food available to the larvae this

TABLE 1. *The effect on the life cycle of limiting the food supplied to the larvae of* Anisopus fenestralis

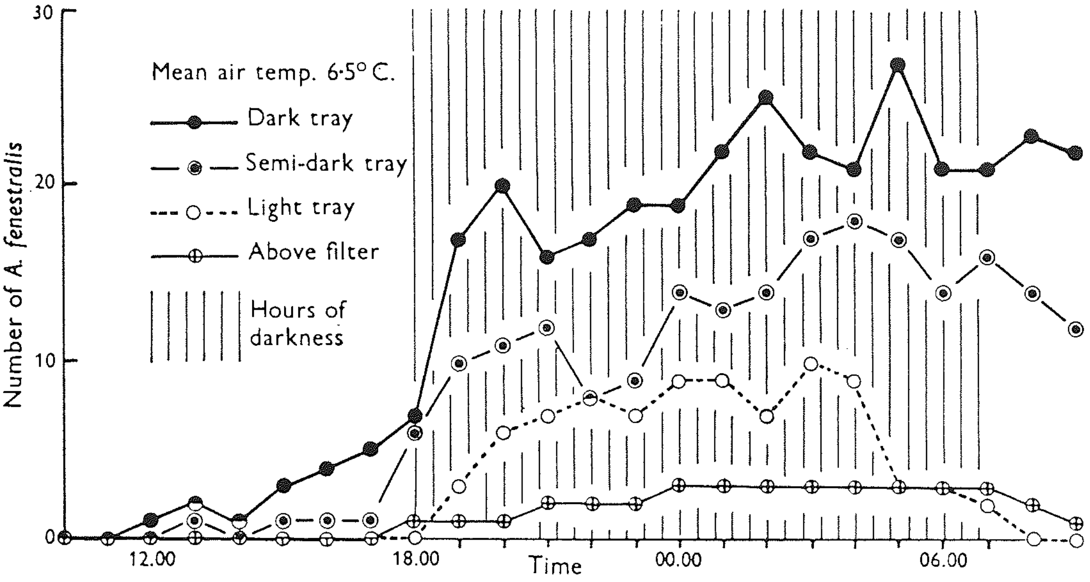
Food provided (units)	10	5	1
Duration of larval phase (days)	30±0·65	34±0·77	69±2·7
Duration of pupal phase (days)	8·6	8·75	8·5
Duration of adult phase (not fed) (days)	9±0·55	7±0·34	5·3±0·44
Duration of adult phase (fed on sucrose) (days)	21	20	47
Average length of pupae (mm.)	8·4	8·6	5·1

phase is lengthened, the mean size of the pupae is reduced and the duration of the adult phase, when not fed, is shortened. The duration of the adult phase is considerably increased by feeding with sucrose. Other work, not reported here, also indicated that the pre-oviposition period was also lengthened when the female adult was allowed to feed on sucrose.

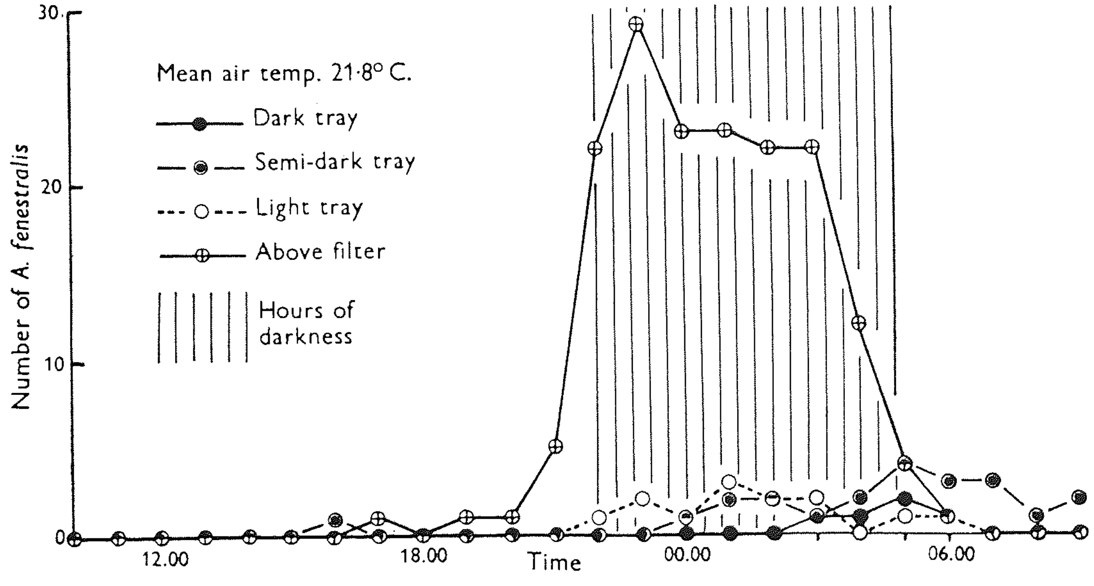
METHODS OF ASSESSING *ANISOPUS FENESTRALIS* POPULATIONS IN AND ABOVE THE FILTERS

Tray traps. These traps were introduced by Tomlinson & Stride (1945) to investigate the fly population of sewage filters. The trap consists of a metal tray 1 ft. square and 2½ in. deep, which is inverted over the filter. Periodically the tray is removed and placed in the inverted lid. The trapped flies are then chloroformed and counted. The tray trap has been widely used in the control experiments, and in assessing *A. fenestralis* populations and incidence (Tomlinson & Stride, 1945; Tomlinson & Jenkins, 1947; Tomlinson & Muirden, 1948; Tomlinson, Grindley, Collett & Muirden, 1949; Khalsa, 1948; McLachlan & Hogg, 1948; Jenkins, Baines & Hawkes, 1949). The exact significance of the numbers of flies found in these trays has never been defined, though reference is made to 'flies which had migrated into the trays' (Tomlinson & Stride, 1945) and 'flies emerging from that part of the filter covered by the trap' (Tomlinson & Jenkins, 1947). Investigation into this method of trapping was therefore considered necessary. Khalsa (1948), working on *A. fenestralis* populations, noted differences between results obtained using tray traps and other trapping methods. McLachlan & Hogg (1948), in work on *Psychoda* spp., found that by modifying the tray by fitting 'a fine gauze top to maintain as far as possible the normal environment by letting in the light and spray' no flies were trapped. If it is intended to measure the emergence of flies from the filter, then the effect of the different environment created over that area of filter covered by the trays should be considered. Experiments were carried out to investigate the effect of light and temperature on the numbers of *A. fenestralis* trapped.

Effect of light. Three types of trays were used: (*a*) the standard tray trap, (*b*) a tray of similar dimensions but having a 4 in. square Perspex window fitted in the bottom and known as the semi-dark tray; and (*c*) a similar tray but having the 1 ft. square bottom made entirely of Perspex and known as the light tray (Pl. 14). These trays were inverted over the filter, and at hourly intervals they were removed in order to count the number of *A. fenestralis* in each tray. The trays were then returned to the filter without disturbing the trapped flies. A measure of the number of *A. fenestralis* above the filter at different times throughout the 24 hr. was obtained by noting hourly the number of flies observed on three 1 sq.ft. areas facing different directions. Hourly readings of the temperature of the three trays and of the air was taken. The numbers of *A. fenestralis* found hourly in three types of tray and on unit area above the filter were plotted together with the air temperature. The experiment was repeated at different times of the year; the results of the October and June experiments, which illustrate the effect of diverse climatic conditions on



Text-fig. 1. Relative numbers of *A. fenestralis* found hourly in three types of tray and on unit area above the filter. October 1948.



Text-fig. 2. Relative numbers of *A. fenestralis* found hourly in three types of tray and on unit area above the filter. June 1949.

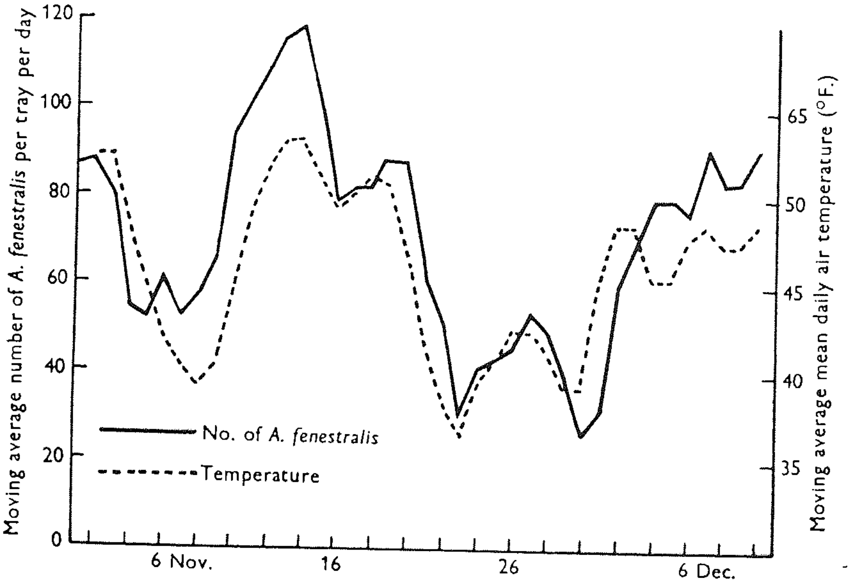
the tray trapping, are shown in Text-figs. 1 and 2. Text-fig. 1 shows that during the hours of daylight in October most flies were trapped in the dark trays and least in the light ones. At dusk there was an increase in the rate of entry of flies into all trays, whereas at dawn the flies were repelled from the light trays. Few flies were observed above the filter and these only in the hours of darkness. By contrast, the results in June (Text-fig. 2) showed that although few flies entered the trays, considerably more were observed above the filter. From these results it is concluded that light tends to inhibit the migration of *A. fenestralis* into the trays. Also the number of *A. fenestralis* trapped into the surface trays is no true measure of the emergence of the fly from the filter. The effect of light on the results obtained with the light and semi-dark trays is understandable, but its effect on the results with the dark trays can only be explained by assuming that *A. fenestralis* entered the trays, seeking shelter, from surrounding areas exposed to light. The difference between the June and October results could be explained by assuming that when conditions were not favourable for emergence the flies took shelter in the trays, but when conditions were favourable they did not seek shelter. To test this hypothesis a square of sixteen trays was arranged on the filter, and the numbers of *A. fenestralis* trapped in the inner trays compared with those trapped in the outer ones. This experiment was made in December when few flies were observed above the filters, and repeated in June when conditions favoured emergence. The results of six sets of counts for each experiment are given in Table 2. In December counts more flies were found in the outer trays in all six experiments, the difference being statistically significant in four out of the six counts. If the tray trapped the flies emerging from 1 sq.ft. of the filter covered by it, then there should be no difference between the numbers trapped in the inner and outer trays. The larger number found in the outer trays indicates that *A. fenestralis* migrates into the trays from surrounding areas when conditions do not favour emergence. The inner trays, being protected by the outer trays, did not have the opportunity of attracting flies from the surrounding area. In the June counts, when conditions favoured emergence,

TABLE 2. *Comparison between the mean number of flies trapped in the inner and outer trays of squares of sixteen trays*

Count in	Exp. no.	Mean count in inner trays	Mean count in outer trays	Difference between mean value for inner and outer trays
December 1948	1	18 ±2·27	25 ±3·25	+ 7 ±3·95
	2	13 ±1·0	19 ±2·3	+ 6 ±2·5
	3	22 ±1·9	37 ±2·5	+15 ±3·15
	4	39 ±3·3	58 ±5·5	+19 ±6·5
	5	31 ±2·0	40 ±5·0	+ 9 ±5·4
	6	20 ±3·4	52 ±3·8	+32 ±5·1
June 1949	1	2·8 ±0·41	2 ±0·36	− 0·8 ±0·55
	2	14·5 ±3·57	14·6 ±1·4	+ 0·1 ±3·85
	3	4·5 ±1·42	5·4 ±0·41	+ 0·9 ±1·47
	4	3·25 ±1·4	3·4 ±0·67	+ 0·15 ±1·56
	5	2 ±0·18	3·4 ±0·66	+ 1·4 ±0·68
	6	2 ±1·2	1·6 ±0·42	− 0·4 ±1·27

in only four out of six cases did the number of flies in the outer trays exceed those in the inner ones, the difference being slight and significant in only one case. It was concluded that *A. fenestralis* only sought shelter of the trays when climatic conditions were adverse to emergence.

Effect of temperature. To investigate the effect of temperature on the migration of *A. fenestralis* into the trays the mean number found daily in eighteen trays was plotted over a period of 40 days in November and December 1948. The mean daily temperature, as measured by the average of the maximum and minimum temperatures for the 24 hr. period, were also plotted; day-to-day irregularities in the sampling being smoothed out by applying a 3-day moving average. From the graphs (Text-fig. 3)



Text-fig. 3. Relationship between numbers of *A. fenestralis* found daily in trays, and the mean daily temperature.

it is seen that for this period there was a close correlation between the number of *A. fenestralis* found in the trays and temperature. By plotting the mean daily temperature and the mean number of *A. fenestralis* found daily in the trays from non-treated areas throughout 1949, it was found that this correlation only held in the colder periods of the year when emergence from the filters was slight.

Discussion on tray traps. The above results suggested that the number of *A. fenestralis* trapped in the trays is a measure of the number at the surface of the filter seeking shelter when climatic conditions discourage emergence. Light and temperature influence the number of flies at the surface; in daylight and in cold weather the flies tend to keep to the warm dark depth of the filter, and therefore only few enter the trays. Increase in temperature and decrease in light intensity results in larger numbers being present at the surface, and consequently the numbers trapped increase. When conditions favour emergence, however, although there may be large numbers at the surface few enter the trays. Trapping by these trays does not therefore give a true measure of emergence nor does it give comparative results for the numbers of flies in the filters at different seasons. The emergence is better measured by the use of traps above the filter, such as the canister trap (Tomlinson & Stride, 1945) or by sticky Perspex cross, as described below; estimates of flies in the filters may be obtained by counting larvae and pupae in the filter. In tests on control measure, however, by careful choice of treated and control areas, comparative counts using tray trapping may be obtained. Other methods of assessing fly populations of filter beds have previously been used. The jar trap, as used by Lloyd (1935), was found difficult to manipulate in large numbers and impracticable on some filters because of the machinery distributing the sewage being too near the surface. Methods employing sticky traps have been used in other fields to study aphis migration (Broadbent, 1948). The use of 1 sq.ft. sheets of sticky Perspex placed immediately over the filters was tried. Although these trapped large numbers of chironomid flies, few *A. fenestralis* were trapped and condensation interfered with the sticky material. To assess the aerial density of *A. fenestralis* above the filters the Perspex 'cross' was designed (Pl. 15). This consists of four vertical sticky sheets of Perspex, each approximately 6 in. square, facing four different directions at right angles to one another. By this arrangement the wind direction, which would influence the flies trapped on a single surface, does not affect the mean number trapped. The cross was mounted 4 ft. above the filter on a post carried on a mechanical distributor.

SEASONAL INCIDENCE OF *ANISOPUS FENESTRALIS* AND SOME FACTORS INFLUENCING EMERGENCE FROM THE FILTERS

In studying the seasonal incidence of *A. fenestralis*, a distinction was made between the incidence in and above the filters. Factors influencing the egress of the flies were also considered. Tray traps were used to assess the incidence in the filter, although it was realized that the results might be influenced by factors previously referred to. The mean of six daily counts on traps set on areas which had not been treated with benzene hexachloride (BHC) was taken as indicating the frequency of *A. fenestralis* in the filter; the average daily temperature in the trays was also found. The mean number of *A. fenestralis* caught daily on the four surfaces of the 'cross' was taken as a measure of the aerial density above the filters; the average daily air temperature above the filter was also noted. The results are shown in Tables 3 and 4. These results of assessment by tray trapping indicate that the period of maximum abundance of *A. fenestralis* in the filter is during the spring. Throughout the summer months the numbers are reduced. An increase occurs in the autumn, and large numbers are found throughout the winter. Above the filter the fly was present in large numbers only during warm periods when the mean temperature exceeded 52° F. Tomlinson (Discussion on Jenkins *et al.* 1949) reported that below 54° F. *A. fenestralis* showed little flight. During the warmer periods there appear to be two periods of abundance, one in June and another in the autumn. The decreased numbers caught on the aerial trap throughout the summer coincided with the reduced numbers found in the tray traps. Emergence of the flies from the filter is influenced by temperature, although other factors such as wind velocity are also considered important. Previous experiments showed that the rate of emergence increased at dusk, which suggests that light is also a contributory factor. This phenomenon might be due to a natural diurnal rhythm of activity, as demonstrated for several mosquitoes (Bates, 1949).

TABLE 3. *The incidence of* Anisopus fenestralis *in the filter as measured by tray trapping*

Month	No. of days each month when mean tray count exceeded				Mean tray temp. (° F.)	Temp. range
	25	50	75	100		
Jan.	15	5	1	0	42	34–49
Feb.	15	5	1	0	44	37–51
Mar.	12	8	3	1	42	34–51
Apr.	18	10	2	1	51	43–63
May	10	1	0	0	57	44–73
June	5	0	0	0	63	53–76
July	0	0	0	0	65	51–77
Aug.	1	0	0	0	62	56–70
Sept.	2	0	0	0	62	58–70
Oct.	6	0	0	0	55	40–68
Nov.	9	1	0	0	46	41–50
Dec.	13	7	2	1	42	38–48

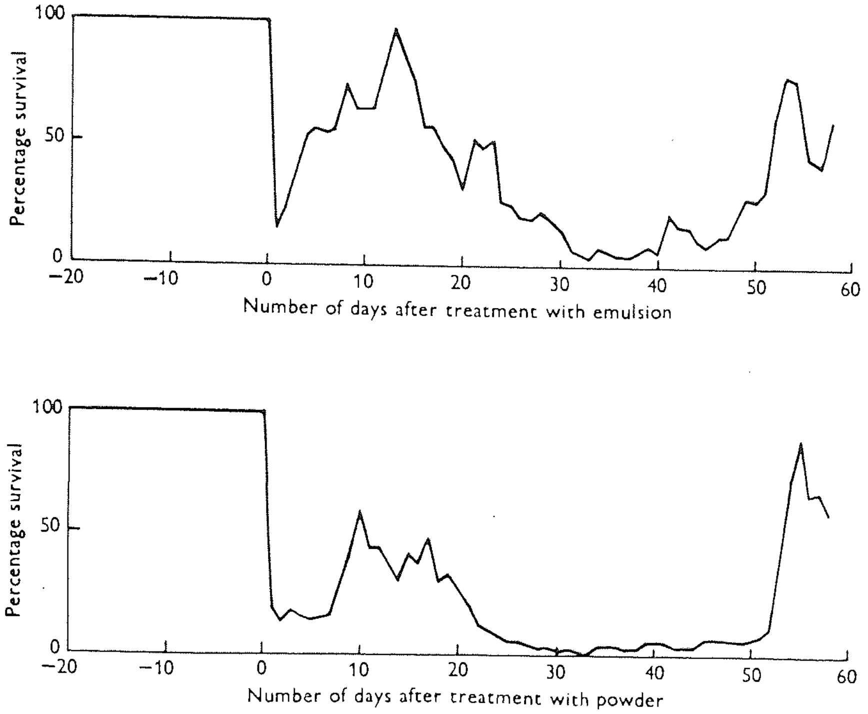
TABLE 4. *The incidence of* Anisopus fenestralis *above the filter as measured by the sticky 'cross' method*

Month	No. of days each month when numbers caught on 'cross' exceeded						Mean air temp. (° F.)	Temp. range
	100	200	400	600	800	1000		
Jan.	0	0	0	0	0	0	42	35–50
Feb.	0	0	0	0	0	0	43	32–51
Mar.	4	3	1	0	0	0	41	34–55
Apr.	7	4	1	1	0	0	50	40–57
May	14	12	5	0	0	0	53	46–58
June	21	16	5	4	2	2	60	53–72
July	12	6	1	0	0	0	64	54–75
Aug.	11	5	0	0	0	0	62	55–70
Sept.	17	11	1	0	0	0	62	56–60
Oct.	11	5	4	0	0	0	55	44–66
Nov.	0	0	0	0	0	0	45	38–50
Dec.	0	0	0	0	0	0	42	35–47

EXPERIMENTS IN CHEMICAL CONTROL

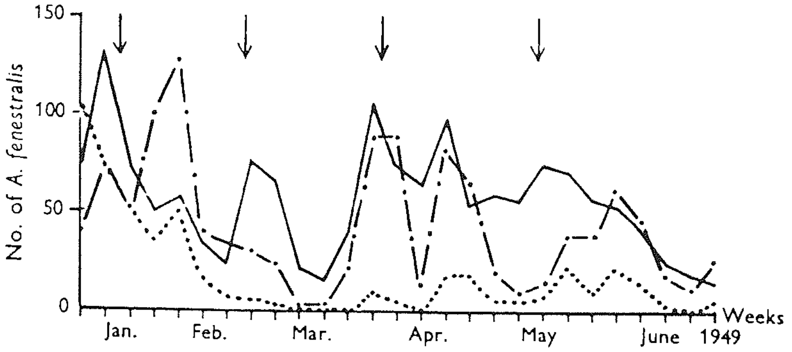
Attempt to control the number of *A. fenestralis* at Minworth was attempted in 1933, when bleaching powder, salt and gas liquor were applied to the filters. Later, the insecticides DDT and BHC were used with success (Tomlinson & Jenkins, 1947; Tomlinson & Muirden, 1948; Tomlinson *et al.* 1949). In continuation of these experiments the effect of BHC, used as a water-dispersible powder and as an emulsion, were compared.

Method of application. The BHC emulsion or dispersible powder required for each filter was diluted with sewage and siphoned for a period of 1 hr. into the sewage being supplied to the filter, which was not dosed with sewage for 6 hr. before treatment and for 17 hr. thereafter. All applications were at the rate of 1·3 lb. of the active γ-isomer per acre. In the autumn of 1948 the effect of a single application to two blocks of filters was studied by tray trapping on four filters, two of which were treated with dispersible powder and two with the emulsion. Half of each of the four filters served as untreated controls. Three tray traps were set on each of the treated and untreated areas. Daily counts of *A. fenestralis* were made on the 20 days before and on the 60 days after the application. The difference between the mean numbers of *A. fenestralis* trapped daily on control and treated filters was expressed as a percentage of the numbers trapped on the control filters. The percentage reduction is shown in Text-fig. 4, which illustrates the effect of the treatment for 60 days following the application of BHC.

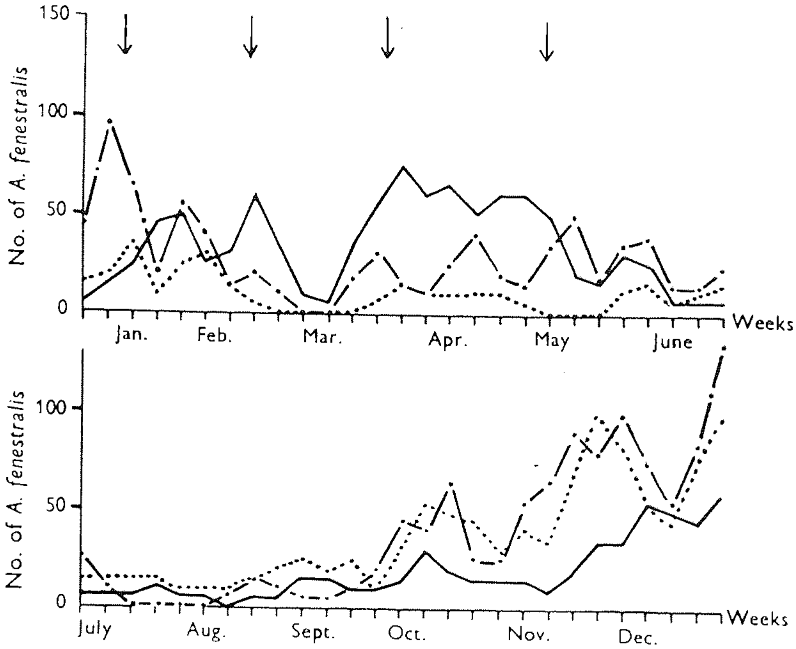


Text-fig. 4. Effect of single application of BHC as an emulsion (above), and as a water-dispersible powder (below).

During the first 6 months of 1949, four applications were made. On each block six tray counts were made daily on untreated control areas and on areas treated with the emulsion and with the dispersible powder. To investigate the possibility of any



Text-fig. 5. Comparative effect of treatment with BHC as an emulsion, and as a water-dispersible powder. January–June 1949. ——, not treated; —·—·, treated with BHC as emulsion; ······, treated with BHC as a water-dispersible powder; ↓, times of treatment.



Text-fig. 6. Comparative effect of treatment with BHC as an emulsion, and as a water-dispersible powder (1949). ——, not treated; —·—·, treated with BHC as emulsion; ······, treated with BHC as a water dispersible powder; ↓, times of treatment.

delayed effect of the treatment the counts on one block were continued throughout the year. The weekly means of the six daily fly counts on each area are shown in Text-figs. 5 and 6. The results of the single applications in 1948 showed that for

60 days following treatment with emulsion a 63% reduction was effected, compared with a figure of 79% for the powder. The results of the four applications in 1949 showed that BHC as an emulsion effected a reduction of only 18·5% over a 6-month period compared with 70% by the powder. The better control effected in the autumn may be explained by the fact that at that time the film was relatively thin compared with the amount present when the applications were made in 1949. This effect has been previously reported (Discussion on Tomlinson *et al.* 1949). The graphs in Text-fig. 6 show that treatment at the rates used did not produce control over a prolonged period. For the second half of the year, when no treatment was given, the areas which had previously been treated had a larger *A. fenestralis* population. A probable explanation is that in the untreated areas the amount of food became limiting, whereas in the treated areas, because of reduced grazing activity, the food material was allowed to accumulate; however, measurements of the amount of film were not made.

The percentage control has been given as the mean for the whole period following treatment, but as shown in the graphs in Text-fig. 4 this varies during the period. The graphs show that there is an immediate reduction due to the death of adult flies in the filter, followed by a recovery period of 15 days due to the emergence of adults from pupae unaffected by the treatment. This immunity of the pupae might be due to their greater resistance or to their ecological position in the drier regions of the filter, where they are least likely to receive the insecticide mixed with the sewage. A second reduction then occurred due to the effect of the insecticide on the larvae in the filters at the time of the treatment. This persisted for approximately 30 days. From these results it is concluded that BHC is most effective when used against the larval stage of *A. fenestralis* and least effective against the pupal stage. The toxicity of BHC on various stages of *A. fenestralis* has been reported by Lloyd (Discussion on Tomlinson *et al.* 1949).

Discussion

The incidence of *A. fenestralis* in the filters can be correlated with temperature and food factors. Culture work has shown that both temperature and food are important in determining the length of the larval phase. In the filters the relative effects of these two factors may vary throughout the year; for in the winter, when food is plentiful, temperature will be the limiting factor, whereas in the summer, due to increased grazing activity, food may become the limiting factor. In the spring, when food is still plentiful and temperatures are rising, conditions are at an optimum for larval development. The shorter the larval phase, the greater the number of generations produced in a given period and hence the larger the adult population. Lloyd (1941, 1943*b*) has demonstrated the effect of temperature on the seasonal rhythm of *Spaniotoma minima* and *Psychoda alternata*. A similar rhythm for *A. fenestralis* was indicated at Minworth, and it is considered that this rhythm would also be influenced by the food factor. On this basis, a spring increase would be expected, followed by a decrease throughout the summer. This is supported by the incidence of *A. fenestralis* at Knostrop Sewage Works (Khalsa, 1948) and the results obtained at Minworth. The effect of food on the incidence of *Psychoda* spp. has previously been reported (Fair, 1934; Golightly, 1940).

The results of the author's experiments on chemical control showed BHC to be most effective as a larvicide. To be used most effectively the treatment should coincide with the larval phase of the rhythm. If the insecticide is applied only when there is an immediate danger of nuisance from adults, it is likely that there will be a large pupal population in the filter which would survive the treatment. Apart from any natural rhythm, an artificial one is induced by the survival of pupae on treatment and by examination of the filters, later applications can be given at the appropriate times. A nuisance is only likely to arise when there are both large numbers of *A. fenestralis* in the filters and climatic conditions favour emergence. Such conditions usually occur in late spring and early summer, and any potential nuisance then should be averted by treatments against the larval phases of these generations in March and April. By this method the beneficial feeding activities of the larvae is retained as long as is compatible with the prevention of nuisance. In assessing the effect of control measures it is considered that tray trapping gives valid results, though, because of interference by climatic changes throughout the year, this method does not give a true measure of the incidence of the fly in or above the filters nor does it measure the rate of emergence of the flies from the filter. A measure of the incidence of the fly is given by counts of larvae and pupae found in the filter, whereas the rate of emergence may be measured by aerial trapping.

This work was carried out in connexion with the fly-control programme of The Birmingham Tame and Rea District Drainage Board, and forms part of a thesis submitted by permission of F. C. Vokes, B.Sc., M.I.C.E., Engineer to the Board, for the degree of M.Sc., of Leeds University. I wish to express my gratitude to Dr S. H. Jenkins, Board's Chemist, for his guidance and interest throughout the experiments, and to thank Prof. E. A. Spaul and Dr Ll. Lloyd for advise and criticism offered. My thanks are also due to members of the Laboratory staff and workmen who assisted me in the daily task of fly counting.

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EXPLANATION OF PLATE 15

Fig. 1. The Perspex 'cross' trap for measuring the incidence of *A. fenestralis* above the filters.

Fig. 2. The three types of tray trap used to determine the effect of light on the trapping of *A. fenestralis* in surface trays.

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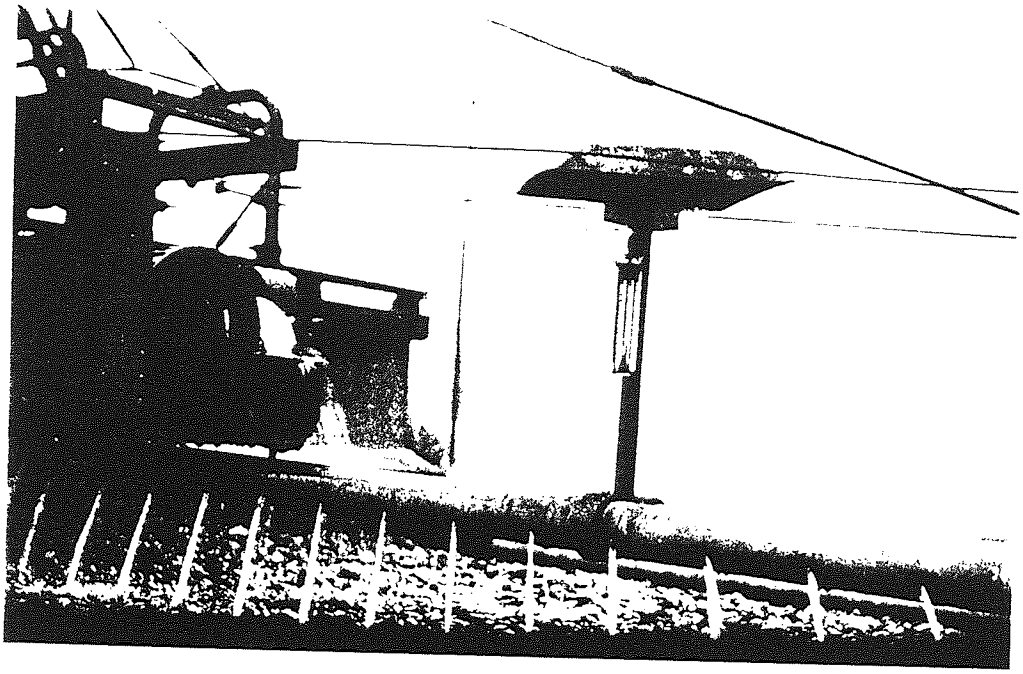

Fig. 1

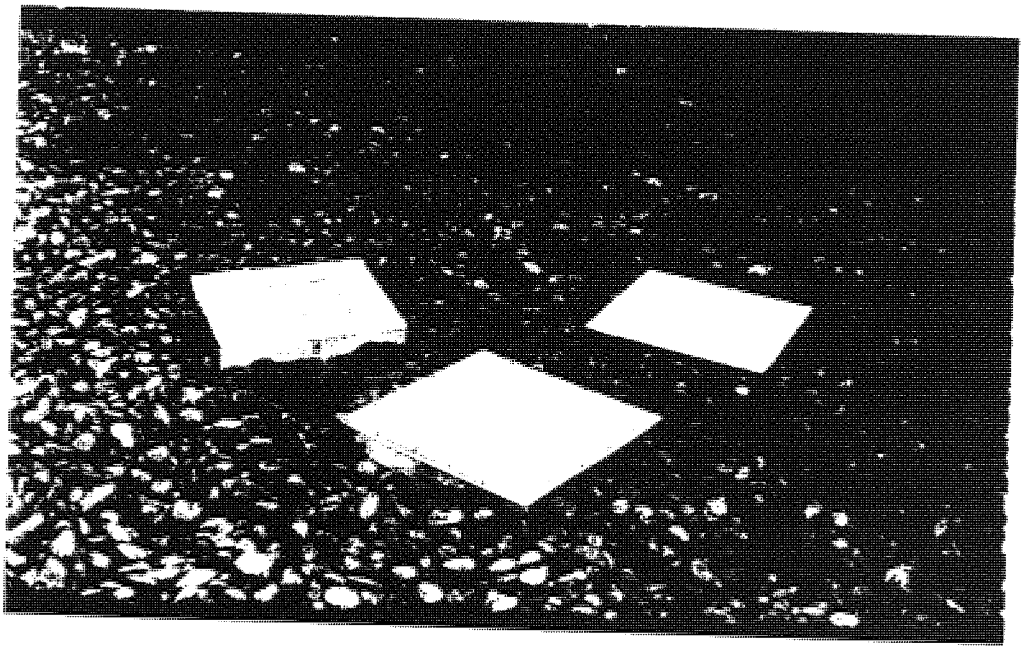

Fig. 2

HAWKES—*Study of the biology and control of* Anisopus fenestralis

Paper No. 3

The ecology of *Anisopus fenestralis* (Scop.) (Diptera) in sewage bacteria beds.

Hawkes, H.A.
Ann. appl. Biol. 39, 181-192, 1952

[FROM THE ANNALS OF APPLIED BIOLOGY, VOL. 39, NO. 2,
pp. 181–192, JUNE 1952]

THE ECOLOGY OF *ANISOPUS FENESTRALIS* SCOP. (DIPTERA) IN SEWAGE BACTERIA BEDS

BY H. A. HAWKES

Birmingham Tame and Rea District Drainage Board, Rookery Park, Erdington, Birmingham

(With 2 Text-figures)

The assessment of populations of *Anisopus fenestralis* (Scopoli, 1763) in sewage bacteria beds by the trapping of adults at the surface has been previously proved to be unsatisfactory. Methods were therefore developed for determining the numbers of egg masses, larvae and pupae as well as the total organic matter in a unit volume of bed. The relative larval populations of three areas under investigation were related to the loading of the beds as measured by the sewage strength and rate of application. In the upper 2 ft. 6 in. the numbers of larvae and pupae per unit volume of bed decreased with depth. There was no evidence of any vertical migration of the larvae before pupation. The horizontal distribution of larvae was found to be affected by the method of distribution. In beds served with fixed spray jets larvae are more abundant nearer the jets than at some distance away. In beds served with travelling distributors the larvae are more abundant in the zones below the jets than in the drier intermediate zones. In both cases relatively higher percentages of pupae in the drier zones might indicate a horizontal migration of larvae before pupating or of the pupae themselves.

The incidence of the larvae throughout 1949 in all three beds showed recurring peaks. In the following year a more intensive investigation on one area showed that this was due to successive generations of the fly; the proximity of the peaks is determined mostly by temperature and their size by the amount of food available in the bed during the larval grazing phase.

In the area not treated with insecticide intraspecific competition during a period when food was limiting, due to depletion by the previous generation, resulted in a natural reduction in the population. In the area treated with insecticide the food was retained and this natural control was thereby delayed.

INTRODUCTION

Grazing organisms such as fly larvae, worms and Collembola in sewage bacteria beds play a major role in the removal of accumulated organic matter and bacterial and fungal film which would otherwise eventually choke the beds. In beds treating domestic sewage there is a mixed fauna of these grazing organisms; trade wastes, however, limit the fauna to one or few species (Reynoldson, 1948). At the Minworth Works of the Birmingham Tame and Rea District Drainage Board the fauna is thus limited; the dominant fly for most of the year being *Anisopus fenestralis* (Scopoli, 1763). Although beneficial in its larval phase the adult fly, because of its shade-seeking habits, has caused nuisances in the neighbouring villages. Methods of chemical control were investigated, and these have been described (Tomlinson, Grindley, Collett & Muirden, 1949; Jenkins, Baines & Hawkes, 1949). Estimation of the *A. fenestralis* populations of bacteria beds by trapping the flies in trays on the surface of the beds was considered unsatisfactory because of the effects of climatic variations on the numbers trapped (Hawkes, 1951). To apply the control measures most effectively a knowledge of the incidence and distribution of the different stages in the bed was considered necessary. An ecological study was therefore carried out and the effects of a single application of insecticide were also investigated. The simplified habitat of bacteria beds, as previously discussed by Reynoldson (1948), provides an ideal field for the study of the relationship between an animal population and its food supply.

DESCRIPTION OF MINWORTH BACTERIA BEDS

Only the final stages of purification are done at Minworth, the removal of suspended matter by sedimentation having been carried out at another works farther up the Tame valley. On arrival at Minworth a portion of the settled sewage is partially purified by activated sludge before being applied to some bacteria beds; the remainder of the sewage, after further sedimentation, is applied to other beds. Two methods of distribution of the sewage are in use. On some beds it is distributed from fixed spray nozzles projecting from pipes laid on the surface of the bed. These beds thus receive a continuous spray of sewage, but for several hours each day depending upon the flow of sewage, the beds are rested. On the surface of these beds there develops each winter a thick fungal growth of species of *Fusarium*, *Oospora* and *Sepedonium*. On other beds the sewage is applied through travelling distributors which provide an intermittent dose on to each part of the bed about every 15 min. On these beds no surface fungal growth develops, but the surface is coloured by a thin film of unicellular Chlorophyceae. For the purpose of the investigation three areas B, D and F were chosen which were operated under these different conditions, Area B was treating the partially purified sewage distributed hrough fixed spray nozzles, whereas area D treated only settled sewage similarly distributed. The third area, F, treated partially purified sewage distributed through travelling distributors. The filtering medium varies in size but for the most part is of 2–3 in. crushed stone in beds B and D and of round gravel of the same size in F bed.

GENERAL METHODS

Assessment of eggs, larvae and pupae. Canisters 6 in. deep and 6 in. diameter, the base and sides being perforated with seven and sixty $\frac{3}{4}$ in. holes respectively, were buried in the bed at the required levels after being filled with medium removed from the corresponding level. The positions and depths of the canisters were marked with metal flags. The canisters were left in the bed for at least 12 weeks, then removed according to a sequence previously determined at random.

The eggs, larvae and pupae were removed from the contents of each canister by washing in a trough on a grid of $\frac{1}{4}$ in. mesh. The flow of water carried the organisms through the grid and along the trough into a sieve with $\frac{1}{16}$ in. perforations which strained out the eggs, pupae and larger larvae of *A. fenestralis*; the young larvae and other grazers such as *Achorutes subviaticus* Begn., and *Psychoda* spp. larvae, however, passed through. The organisms were then counted over a sectored illuminated counting chamber.

Assessment of adults. Adult flies were assessed by inverting metal tray traps, 1 ft. square and 3 in. deep over the bed for 24 hr. and then chloroforming the flies collected. As previously reported (Hawkes, 1951), this method does not give valid results throughout the year because of effects of climatic variations on the trapping method.

Determination of organic matter in bed. Using the same type of canister and method as described above, samples were removed from the bed. From these the film and accumulated organic matter were removed in a revolving drum-washing apparatus.

Determination of population size, distribution and seasonal incidence of Anisopus fenestralis *in three beds working under different conditions* (1949)

From each of the three areas, B, D and F, eighteen samples at ten locations were removed each month. Ten (1*a*–10*a*) were from 0 to 6 in. depth, five (2*b*, 4*b*, 6*b*, 8*b* and 10*b*) from 12 to 18 in. and three (2*c*, 6*c* and 10*c*) were from 24 to 30 in. To investigate the distribution of larvae and pupae at different distances from the spray jets the canisters on areas B and D were set at 1, 2, 3, 5 and 8 ft. from the jets. Two samples were removed monthly from each of these five positions at the surface, one sample from each position at 12 in. deep, and one sample from the 1, 3 and 8 ft. distances at 24 in. The numbers of larvae and pupae of *A. fenestralis* in each sample were determined. The means of the number of adults trapped daily in three trays on each area were calculated as weekly averages.

Comparison of populations and seasonal incidence in the three areas

The means of the numbers of larvae and pupae found in the eighteen samples removed monthly from each area are expressed graphically in Fig. 1, together with the monthly mean of the numbers of adults trapped. The results show throughout the year a succession of three or four peaks in the larval population. The size of the peaks varied from area to area and throughout the season within the same area. In area B there were three large peaks during the first half of the year followed by reduced numbers during the months of July to September, with another smaller peak in the autumn. In area D two very large peaks occurred in the first half of the year, again followed by reduced numbers in the period July to September but with a third large peak late in the year. There was only one large peak in area F; this occurred early in the year and was followed in May by a second peak of reduced size, and in September by a third reduced peak. A fourth, larger, peak occurred towards the end of the year.

A similar periodicity has been recorded in the populations of the sewage flies

Spaniotoma minima Mg. and *Psychoda alternata* Say. (Lloyd, 1941, 1943). The relative size of the peaks throughout the year could be accounted for by the varying amounts of food material available. Although this was not measured during 1949, the fungal film in B and D beds was clearly plentiful during the winter and spring but became scanty by the end of June and did not build up again until October. In bed F the film accumulation was at all times less than in the other beds but followed a similar cycle.

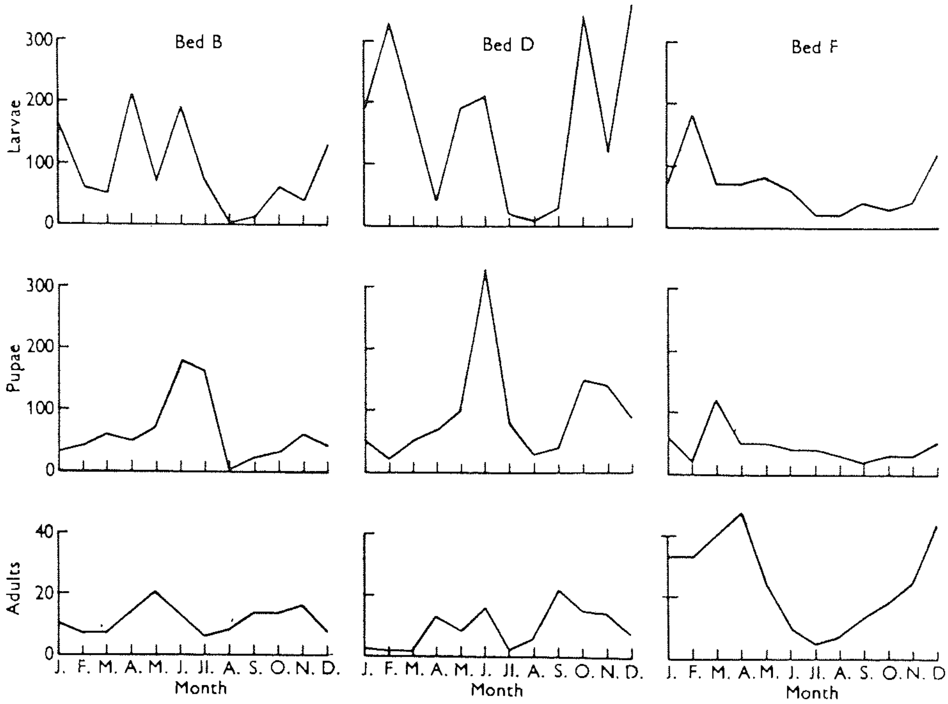

Fig. 1. Seasonal incidence and relative populations of *Anisopus fenestralis* in beds B, D and F.

Table 1 shows that bed D supported the largest larval population, B the next largest and F the least. Although no measurements of the organic matter in the beds were made, the sewage strength and volume treated per unit area of bed may be taken as a measure of the food available, and Table 1 shows that this factor can be correlated with the larval populations.

The pupal population as shown in the graphs does not follow the larval periodicity. This may be due to some peaks not being recorded because of the infrequency of sampling or to a natural high mortality rate of the larvae at some periods. In beds B and D there was a large pupal peak corresponding to the June larval peak and a smaller one in the autumn. In bed F a large pupal peak corresponded to the first generation of larvae. The cleaner conditions in this bed were probably more favourable for pupation; these conditions were not present in the other beds until later in the year.

TABLE 1.* *Relationship between bed loading and abundance of larvae, pupae and adults of* Anisopus fenestralis

Bed	Bed loading (lbs. B.O.D.†/acre/day)	Mean no. of larvae	Mean no. of pupae	Mean no. of adults
B	1848	87	61	10
D	> 2900, estimated max. 4850	169	95	9
F	1811	66	44	24

† The B.O.D. (Biochemical Oxygen Demand) is a measure of the oxidizable organic matter in the sewage.

The incidence of the adults as measured by tray trapping shows a summer reduction; the period of maximum abundance occurring earlier in bed F than in B or D, as would be expected from the incidence of the pupae. The comparative figures of the mean numbers of adults trapped on the three beds would suggest a higher mortality rate of the pupae in the dirtier beds. It may, however, be due to a direct effect of the thick growth on the trapping method.

Vertical distribution within the beds

Using the results obtained from five samples from the surface, five at the 12 in. level and the three at the 24 in. level each month, the vertical distribution in the upper 2 ft. 6 in. of the beds was investigated. For each month the means of the numbers at the three levels in each area were calculated. Because of the month-to-month variations in the totals, these means were expressed as percentages of the total. Table 2 shows the means of these monthly percentages for the whole year for both larvae and pupae.

TABLE 2. *Percentage vertical distribution of larvae and pupae in upper 2½ ft. of bed*

	Depth (in.)	Bed		
		B	D	F
Larvae	0–6	50 ± 5·6	52 ± 3·76	40 ± 3·4
	12–18	31 ± 4·2	29·2 ± 2·1	32 ± 2·9
	24–30	19 ± 3·9	18·8 ± 0·86	27·5 ± 3·1
Pupae	0–6	52 ± 6·5	56 ± 4·7	38 ± 4·3
	12–18	29 ± 4·55	26 ± 2·8	38 ± 4·5
	24–30	19 ± 3·46	18 ± 3·2	24 ± 3·15

Throughout, the numbers of larvae and pupae decrease as depth increases. The differences were most significant in D and least in F. This vertical distribution can be correlated with the greater development of the fungal growth nearer the surface.

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* The full biological data relating to this paper are lodged in the General Library of the British Museum (Natural History), Cromwell Road, London, S.W. 7.

This was especially apparent on beds B and D; on bed F, because of the different method of distributing the sewage, the film was more evenly distributed throughout the depth of the bed. There is no evidence of vertical migration of larvae before pupation, as occurred in the case of *Metriocnemus longitarsus* Goet. (Dyson & Lloyd, 1935), the proportional distribution of the pupae being much the same as that of the larvae.

Horizontal distribution within the beds at three levels

Although the fixed spray jets were designed to give even distribution of the sewage over the bed, varying sewage flows and other factors caused the areas nearer the jets to receive more sewage and consequently a greater accumulation of film than those at a distance. The results of the larval and pupal determinations at five positions at the surface and 12 in. levels, and the three at the 24 in. level were each expressed as percentages, and the means of the twelve monthly figures for each area are given in Table 3. These show that although there is no gradual zonation with distance two population zones can be distinguished. On bed B at all three levels the inner three positions have higher populations than the outer two. In bed D, it is only the inner two positions which have higher populations than the outer three, this not being so, however, for the lowest level where presumably the sewage had become more evenly distributed. Comparison of the proportional distribution of the pupae with that of the larvae indicates that there was some outward horizontal migration to the drier regions, the proportion of pupae at the 8 ft. distance being greater than that of the larvae at that distance.

TABLE 3. *Percentage horizontal distribution of larvae and pupae in relation to distributor jets*

			Distance from jet (ft.)				
Stage	Bed	Depth (in.)	1	2	3	5	8
Larvae	B	6	29 ± 8·1	21 ± 8·9	24·5 ± 4·3	12·5 ± 4·4	13 ± 4·2
		18	27 ± 9·7	26 ± 9·0	24 ± 6·1	8 ± 2·4	14 ± 3·7
		24	36 ± 8·3	—	45 ± 10·0	—	19 ± 4·3
	D	6	22 ± 5·9	28 ± 5·3	15 ± 4·9	19 ± 4·0	16 ± 3·25
		18	29 ± 6·5	31 ± 5·4	14 ± 7·2	12 ± 2·7	14 ± 3·45
		24	49 ± 8·6	—	19 ± 4·5	—	32 ± 8·5
Pupae	B	6	32 ± 6·6	26 ± 8·25	12 ± 3·35	8 ± 1·58	22 ± 7·3
		18	26 ± 7·15	21 ± 6·7	20 ± 6·35	10 ± 4·55	23 ± 3·65
		24	38 ± 7·9	—	40 ± 8·85	—	22 ± 4·75
	D	6	21 ± 5·3	28 ± 6·95	15 ± 4·55	20 ± 4·15	15 ± 3·75
		18	24 ± 5·7	20 ± 3·2	19 ± 4·75	15 ± 2·9	22 ± 5·2
		24	37 ± 8·95	—	27 ± 7·5	—	36 ± 7·6

In bed F, the distribution of the sewage through travelling distributors produces a different type of zonation. Immediately below each travelling jet is a strip which receives every 13 min. a jet of sewage, while between these jets is a zone which is kept moist only by splashing and condensation. This zonation is indicated on the surface by a striped appearance due to the growth in the 'subjet' position of unicellular algae, these being grazed away in the 'interjet' zone by *Achorutes*, which are unable to exist under the jet. Because of the close proximity of the jets this zonation was only evident near the surface. On other beds, however, with similar distribution mechanisms but with wider spaced jets a broader zonation was produced permitting representative sampling. On three occasions during the first half of the year, nineteen samples were taken from each of the two zones at three different levels.

TABLE 4. *Percentage horizontal distribution of larvae and pupae in the subjet and interjet zones of a bacteria bed served with a travelling distributor*

	Larvae		Pupae	
Depth	Subjet zone	Interjet zone	Subjet zone	Interjet zone
Surface	69	31	6	94
18 in.	87	13	20	80
24 in.	76	24	50	50

The relative numbers of larvae and pupae in the two zones at each level were calculated. Table 4 shows that there is a horizontal distribution of the larvae determined by the positions of the jets. Whereas the larvae prefer the 'subjet' position the pupae were most numerous in the drier 'interjet' zone, this being most marked near the surface and less at the 18 in. level; at the 24 in. level the distribution in the two zones was equal. These relative distributions of larvae and pupae indicate a migration to the drier zones either of the larvae prior to pupation or of the pupae themselves which are capable of some movement. Egg masses of *Anisopus fenestralis* and the hydrophilid beetle *Cercyon ustulatus* Preys. were found in the 'interjet' zone. *Lumbricillus* sp., however, was for the most part found in the 'subjet' zone.

Film accumulation and the incidence of eggs, larvae, pupae and adults of Anisopus fenestralis *in bed F* (1950) *and some effects of a single treatment of insecticide*

A bed in block F was divided into two areas; area 1, treated with insecticide 7 weeks after observations started, and area 2, not treated. From each area eight containers, previously sunk below the surface, were removed weekly, five of which were used for fauna determinations and three for film determinations. During two 24 hr. periods each week flies were taken in three tray traps on each of the two areas. The means of the two weekly trappings for each area were calculated, and the mean daily bed temperature. During the seventh week of the experiment benzene hexachloride (BHC) was applied to area 1 as a water dispersible powder at the rate of 1·3 lb. of the active γ-isomer per acre.

Graphs (Fig. 2) were plotted, using the weekly mean figures for each area. To smooth out weekly irregularities in the results caused by the method of sampling, a 3-week moving average was applied to the film accumulation figures.

Fig. 2 shows that in both areas there was a periodicity in egg-laying activity as shown by the recurring peaks throughout the year. Commencing with the egg peak in the sixth week and assuming a thermal constant for the development of *A. fenestralis* of 814 days degrees (Khalsa, 1948) the theoretical recurrences of this peak were calculated and indicated on the graphs by vertical lines *A* to *F*. These calculated times of recurrence coincide with the peaks. Peak size varies considerably throughout the year, being smaller during the summer. Resultant larval, pupal and adult peaks are usually evident, the coincidence of the larval and pupal peaks being explained when it is recalled that only the larger larvae are retained in the wash. The variation in the size of the peaks throughout the year and on the two areas is related to the food supply in the beds. At the beginning of the experiment the film accumulation in the untreated area was the greater, but for a period coinciding

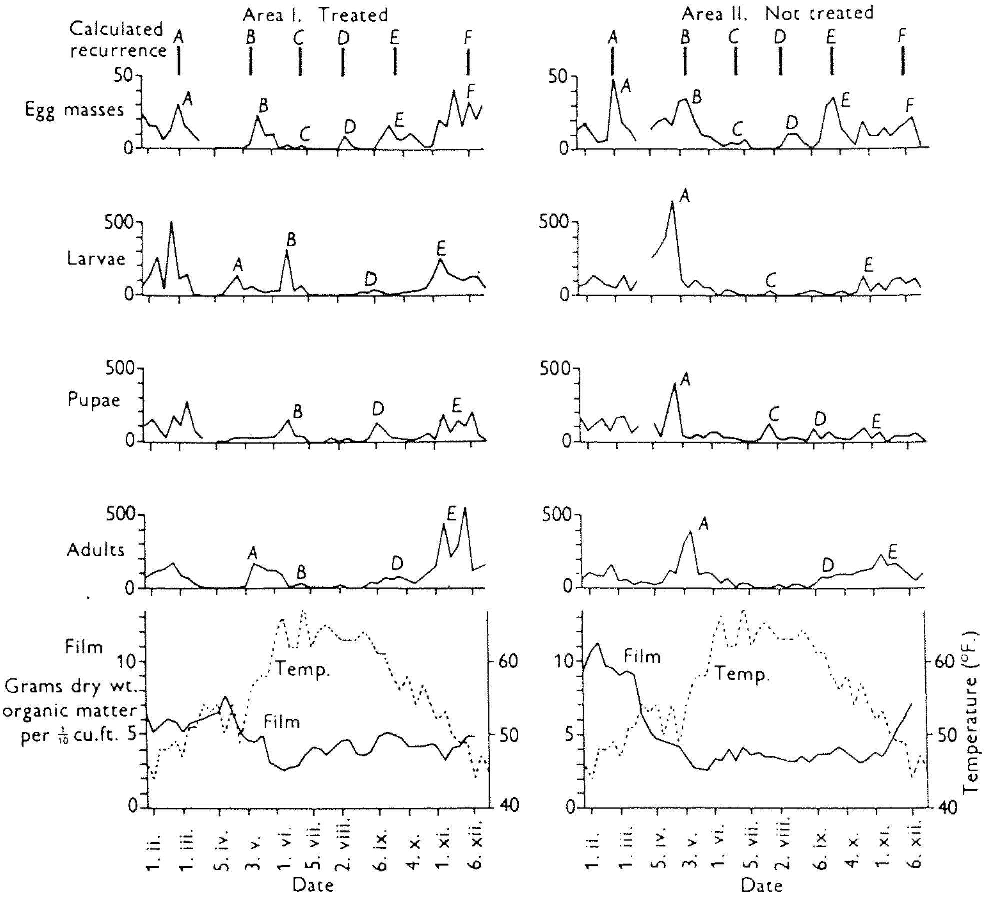

Fig. 2. Incidences of stages of *Anisopus fenestralis* in relation to film accumulation and temperature in bed treated with insecticide (BHC) and in bed not treated.

with the grazing of generation (*A*) of larvae there was a marked unloading of this film. Although a second generation of eggs (*B*) occurred this did not produce detectable peaks of larvae, pupae or adults. The third and fourth generations (*C* and *D*) were also only represented by small peaks. It would appear that although the (*A*) generation had ample food and successfully gave rise to adults which produced eggs, their grazing had so depleted the food supply that intraspecific competition between the second generation (*B*) of larvae resulted in a high mortality. This intraspecific competition when food is limited has been demonstrated in culture work (Hawkes & Jenkins, 1951). The small peaks throughout the summer can also be explained in terms of reduced food supply in the bed.

In area 1 the egg peak (*A*), because of subsequent treatment with insecticide, produced greatly reduced larval and adult peaks (*A*). The suppression of this larval generation by insecticide treatment resulted in decreased grazing, giving only slight reduction in the film at the period of maximum unloading in the untreated area (Fig. 2). However, the second generation of eggs (*B*) gave rise to more larvae and pupae than in area 2, the food supply in area 1 not having been depleted by the first generation. The grazing of this second generation resulted in further unloading of the film which limited the food available for the following generations. The larger size of the (*E*) generation of larvae in the treated area 1 than the corresponding generation in area 2 is related to the greater film accumulation in the former area. With a fall in temperature in the autumn there was a noticeable increase in film, this being subjected to a further unloading in area 1 because of the larger larval population.

Discussion

This investigation of the *A. fenestralis* populations in bacteria beds resolves itself into a study of the relationship between an organism and its food supply. The relative abundance, the seasonal incidence, and the vertical and horizontal distributions of the larvae within the bed are all determined by this factor. The population size, however, in turn affects the subsequent food supply and thus a dynamic state of balance is set up. A similar equilibrium between *Psychoda alternata* and the fungus *Oospora* occurred in the beds at Huddersfield (Reynoldson, 1948). Here there was a differential reaction of the fly and fungus to temperature changes. Because of the lower threshold of development of *Anisopus fenestralis*, 2·1° C. (Khalsa, 1948), it is able to complete its life cycle throughout the winter months. The shortening of the life cycle with increase in temperature suggests an increase in the grazing of the larvae and this, rather than an increased population, would seem to be responsible for the spring depression in the film accumulation, which in turn resulted in a depression of the larval population. The maintaining of the film at a low level throughout the summer months in the absence of a large larval population may have been due to the presence of other grazing organisms such as *Achorutes subviaticus* and *Lumbricillus lineatus* Mull., or to bacterial oxidation of the film at high temperatures (Heukelekian, 1945). With a decrease in temperature in the autumn the film again accumulated and resulted in a recovery in the *Anisopus fenestralis* population. Tomlinson & Stride (1945) showed that the amount of film in beds operating on single filtration increased with increasing filter load. They also correlated this increase with an increase in the *Psychoda* population. In *Anisopus fenestralis*, however, they found no such relationship. The conflicting results may be accounted for by the different methods of assessment used. The previous workers used as their index the numbers of adults trapped on the surface of the bed. Table 1 shows that by using the number of adults trapped a different conclusion can be drawn, but it is considered that this does not give a valid estimate of the fly population of a bed. The previous workers reported that the emergence of flies from the filters into the traps may have been impeded by the clogging of the surface of the bed with film, and they therefore based their conclusions on figures obtained between May and October. It is probable that in beds having a mixed fauna which show interspecific competition no such simple relationship between the *A. fenestralis* population and filter loading exists.

Lloyd (1941, 1943) demonstrated the seasonal rhythm of the sewage flies *Psychoda alternata* and *Spaniotoma minima*, and considered that because of irregularities in temperature changes throughout the year populations of all rapidly breeding insects not having a diapause would in time assume such a periodic rhythm. The present work demonstrates that such a rhythm exists also for *Anisopus fenestralis* in the beds at Minworth. In *Psychoda alternata* and *Spaniotoma minima* there were two or more parallel generations. At summer temperatures, because of the speeding up of the relatively short life cycles, these peaks may run together. On the other hand, a sudden fall in temperature in the autumn may cause a peak to split. In *Anisopus fenestralis* only one succession of generations was traceable, but there was some indication of the splitting of peaks with the fall in temperature in the autumn.

Practical recommendations for the control of the fly can be based on the conclusions of this investigation. The fly population is checked by limiting its food supply, that is by reducing the amount of accumulated organic matter in the bed. At equivalent rates of application this may be achieved by a more efficient removal of the solid matter before applying the sewage to the beds. Methods of restricting the accumulation of film by recirculation and double alternate filtration would also result in a depression of the fly population. With the normal single filtration method, any method of distribution which inhibits the luxurious surface growth of fungus will also limit the fly population. In this respect distribution of the sewage by mechanical distributors would appear to be preferable to distribution through spray jets. A further measure would be the removal or neutralization of toxic components of the sewage to encourage other grazing organisms to compete with the larvae of *A. fenestralis* for the food available. All these methods of control by limiting the food supply do not affect the dynamic balance, this being established at a lower level. In contrast, artificial means of control by insecticides upsets this balance, the grazing population being suppressed whilst the film accumulation remains at a high level. In practice the results of such a state are twofold. Unless other grazing organisms are able to establish themselves this unbalanced state can only be maintained by continuous and expensive treatment. Secondly, the film accumulation in the absence of the larvae may be sufficient to impair the efficiency of the bed.

Under present operating conditions, however, insecticides must be used. For their efficient application, it is necessary to have the information on larval distribution and seasonal incidence, provided by this investigation, and on factors affecting the seasonal egress of the fly from the beds (Hawkes, 1951). The addition of the insecticide in the sewage distributed to the bed would seem to be sound practice as the more vulnerable larval stage is distributed proportionately to the sewage applied. The effects on film accumulation and bed efficiency of complete suppression of the *A. fenestralis* population throughout the year are now being investigated. Until the results of these further investigations are available the grazing action of the fly larvae should be retained; insecticide treatment only being given when necessary to avert nuisance.

This investigation was carried out as part of the fly control programme of The Birmingham Tame and Rea District Drainage Board, and is published by permission of Mr F. C. Vokes, B.Sc., M.I.C.E., Engineer to the Board. I am grateful to Dr S. H. Jenkins for his guidance in the preparatory stages of the work and for his continued interest throughout. I am also indebted to Mr K. Snape for assistance in the routine counting and to the staff at Minworth Works.

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Paper No. 4

Fluctuations in the aerial density of *Anisopus fenstralis* (Scop.) (Diptera) above sewage bacteria beds.

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Fluctuations in the aerial density of *Anisopus fenestralis* Scop. (Diptera) above sewage bacteria beds

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SUMMARY

Using a standard 9 in. diameter disc-dropping suction trap, the aerial density of *Anisopus fenestralis* above bacteria beds was assessed hourly on 410 24-hourly occasions over a period of 19 months, and the prevailing temperatures and wind velocities were recorded. Between 0 and 10 m.p.h. wind velocity there was a gradual rise in catch associated with a rise in temperature to an optimum, beyond which the catch decreased. This optimum fell as wind velocities rose; it occurred between 70° and 75° F. at winds between 2 and 4 m.p.h., at 65–70° F. with winds between 4 and 6 m.p.h. and at 60–65° F. between 6 and 8 m.p.h. At all temperatures between 30 and 80° F. the catch fell as wind velocity increased from 0 to 10 m.p.h. By comparing the dusk catches on successive days a significant positive correlation was found between the deviation in log catch from a 3-day running mean and the corresponding temperature deviation, except when the wind velocity deviation exceeded $+2$. There was also a significant negative correlation between deviation in log catch from the running mean and the corresponding deviation in wind velocity, except when the temperature deviation exceeded -2.

The average regressions showed that for each °F. rise in temperature the log catch was raised by 0·14 and for each 1 m.p.h. rise in wind velocity the log catch was decreased by 0·19. Expressed arithmetically the catch was doubled by a 2·2° F. rise in temperature or by a fall in wind velocity of approximately 1·5 m.p.h.

The aerial density was affected not only by weather but also by fluctuations in the *A. fenestralis* population within the bed arising from direct and indirect climatic effects on its food supply—the microbial growths within the bed. Lower winter temperatures favour an accumulation of food, so the patterns of seasonal incidence of the flies from year to year are affected by the severity of the preceding winter.

INTRODUCTION

Flies breeding in sewage bacteria beds, although contributing in their larval stage to the efficiency of the bed by grazing on the biological film, may cause a nuisance on and around the works when they leave the beds as adults. Beds are therefore often treated with insecticides, but this upsets the ecological balance and may result in an undesirable accumulation of film: consequently insecticide treatment is kept to a minimum compatible with the prevention of nuisance.

The work reported in this paper was carried out to determine the factors influencing the aerial density above the beds of *Anisopus fenestralis* Scop., a fly which has caused much nuisance on and around several sewage works.

METHODS

Assessment of aerial density

The population of *Anisopus fenestralis* above the bacteria beds was assessed by a standardized 9 in. flared suction trap kindly loaned by Rothamsted Experimental Station. The trap (see Taylor, 1951), consists essentially of a gauze cone mounted vertically under a 9 in. Vent-Axia fan which draws in air at about 20,000 cu.ft./hr. The flies pass down the cone and are collected in a detachable tube below. To reduce the effect of wind velocity on the air flow through the trap, a flared inlet is fitted and the gauze cone is shielded by fabric (Taylor, 1955). By means of a solenoid-operated release mechanism housed immediately below the fan, a disc is dropped each hour down an axial rod into the collection tube, thus segregating the catch into hourly samples. The discs carry cloth fringes which, before the trap is set, are impregnated with pyrethrum, thus preventing the trapped flies from passing from one hourly sample to another or escaping up into the cone. At the end of the 24 hr. trapping period the collecting tube is removed and the flies trapped each hour are counted.

Although originally designed for aphids, the trap was found suitable for the trapping of *A. fenestralis*—a weak flier about 7 mm. long. *Psychoda* spp. were also trapped in numbers but the larger and more powerful flier *Spaziphora hydromyzina* was rarely taken. The only difficulty experienced in trapping *A. fenestralis* was that when they were very numerous the collecting tube became full, making the segregation of the hourly catches impossible; however, this could be overcome by increasing the length of the collecting tube and the depth of the spacing collars on the discs. The problem of the deposition of an air pollution film on the axial rod, which hindered the free fall of the discs into the collecting tube was solved by the application of 'antiscuffing paste'.

The trap was mounted over the middle of a bacteria bed the surface of which was some 6 ft. above ground level, with the mouth of the trap 4 ft. 6 in. above the surface of the bed.

Meteorological measurements

For each 24 hr. period when the trap was operated, air temperatures were recorded by a thermograph in a Stevenson screen 4 ft. above the bed and 4 yd. from the trap. Average daily wind velocities were calculated from readings on an indicating cup anemometer mounted at the level of the trap inlet some 10 yd. distant.

Usually readings were also taken over a 2 hr. period about dusk. The hours of sunshine as recorded at Edgbaston observatory, some 7 miles south-west of Minworth, were used. The 24 hr. periods for which the trap was operated commenced at 10.00 hr. G.M.T. (9.00 hr. G.M.T. during Summer Time).

RESULTS

(1) *Hourly catches under different climatic conditions*

The 8340 individual hourly catches will first be considered in relation to the corresponding hourly temperatures and mean daily wind velocities. These hourly occasions were divided into fifty-five arbitrary combinations of temperature and wind velocity, the temperature varying in stages of 5° F. from 30° F. to 85° F. and the wind velocity in stages of 2 m.p.h. from 0 m.p.h. to 10 m.p.h. Table 1 gives the average number of *Anisopus fenestralis* trapped under these varying climatic conditions together with the corresponding number of occasions such conditions prevailed.

Table 1. *Average numbers of* Anisopus fenestralis *taken per hour under different climatic conditions*

Wind velocity (m.p.h.)		Temperature (° F.) 30–35	35–40	40–45	45–50	50–55	55–60	60–65	65–70	70–75	75–80	80–85
0–2	$\bar{x}$	—	—	1·8	1·5	21·2	42·1	96·3	—	—	—	—
	n	0	0	18	10	36	24	6	0	0	0	0
2–4	$\bar{x}$	0·06	0·42	0·95	4·1	20·8	38·0	77·2	113·4	**133·2**	17·9	—
	n	129	211	232	423	551	490	281	132	50	23	0
4–6	$\bar{x}$	0	0·015	0·23	2·6	10·4	21·0	32·0	**44·6**	29·9	5·4	1·0
	n	46	194	497	450	573	673	430	194	101	34	15
6–8	$\bar{x}$	0	0·01	0·15	1·7	5·4	9·9	**13·6**	11·5	0·7	—	—
	n	49	61	189	392	487	337	179	63	4	0	0
8–10	$\bar{x}$	—	0·2	0·04	0·3	2·8	1·6	**3·5**	3·4	—	—	—
	n	0	37	142	156	225	119	68	9	0	0	0

$\bar{x}$ = average number of *Anisopus*; n = number of hourly occasions such conditions occurred. The figures in bold are the maximum counts for a given wind velocity.

At all temperatures there was a marked fall off in the average aerial density with increase in wind velocity above 4 m.p.h.: at any one wind velocity the density rose with the temperature up to an optimum temperature above which fly density decreased. This optimum appeared to be lower at higher wind velocities. These results, based on the large numbers of records over a period of nearly 20 months, imply only the coincidence of fly density and certain climatic conditions. No direct relationship in terms of cause and effect is claimed; it may well be that certain climatic conditions occur at certain times of the day or season when, for other causes, the fly density is high.

For each of the fifty-five climatic conditions defined above, the percentage number of occasions when the hourly catch exceeded 10, 50 and 200 respectively were calculated. The results are expressed graphically in Fig. 1, where the fifty-five climatic conditions are represented by the squares and the areas of the contained circles represent the percentage number of occasions when the catch exceeded the stated values. Thus the unshaded areas represent hourly counts of between 10 and 50, the hatched between 50 and 200, and the black, counts of over 200. It is seen that hourly catches exceeding 10 occurred in thirty of the fifty-five climatic conditions, an arbitrary 10 % occurrence figure being exceeded over a temperature range of 45–80° F. and a wind velocity range of 0–8 m.p.h. The decrease in catches with increase in wind velocity is demonstrated at all temperature ranges by the diminishing sizes of the circles from top to bottom of the columns.

Catches exceeding 50 occurred over a narrower range of climatic conditions, and at the 200-catch level these conditions were further restricted, the arbitrary 10 % occurrence figure being exceeded only between 60 and 75° F. and at wind velocities less than 4 m.p.h. Again the results, although illustrating the coincidence of fly density and certain climatic conditions, cannot be taken as evidence of a direct functional relationship between the two.

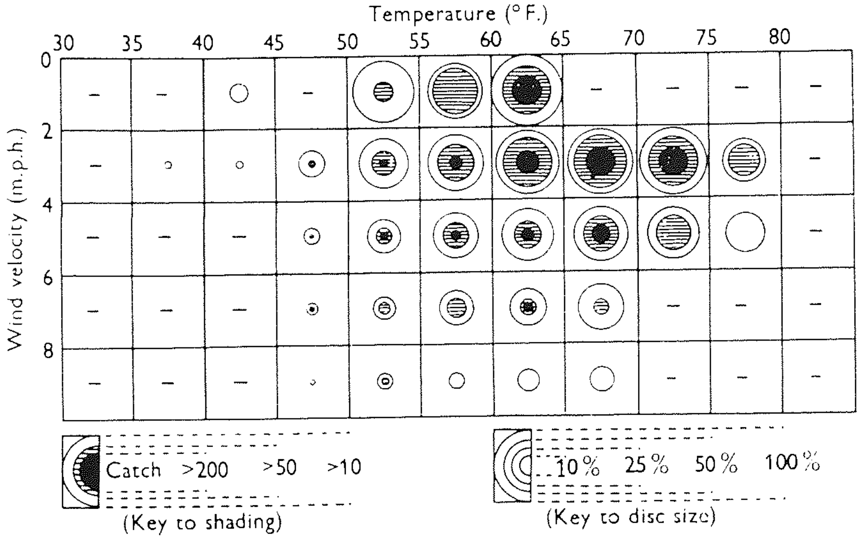

Fig. 1. Percentage number of occasions when catches exceeded 10, 50 and 200 per hour under different climatic conditions.

(2) *Relationship between temperature, wind velocity and aerial density*

To minimize some of the effects of diurnal variation, demonstrated later, the fluctuation of the fly-population within the bed, and climatic changes such as rainfall and humidity, it was decided to compare day-to-day variations in the catch for the 2 hr. period around dusk with the corresponding variations in temperature and wind velocity. The deviations of the log counts from a 3-day running mean and the deviations in temperature and wind velocity from the 3-day running means were calculated. In all, some 130 sets of deviations were obtained. To compare the effects of temperature these were divided into six ranges of wind velocity deviations. The graphs in which the deviations of the log count from a 3-day running mean (dev. log × 3-D.R.M.) were plotted against the deviations in temperature (° F.) from the 3-D.R.M. for the different wind velocity ranges are shown in Fig. 2. Except when the wind velocity deviation exceeded + 2 m.p.h. there was found to be a significant positive relationship between deviations in catch and deviations in temperature. A 1° F. change is associated with 0·14 change in the log catch, or the catch is doubled by a

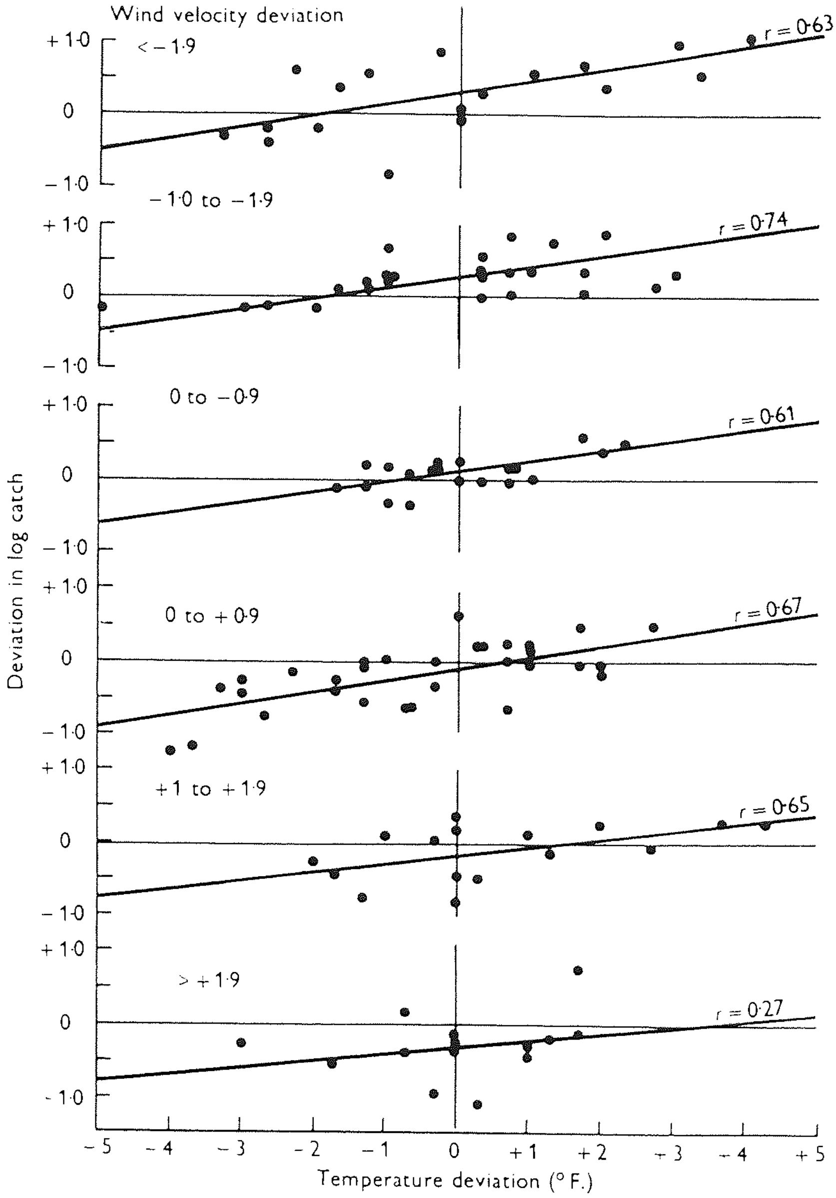

Fig. 2. Regression lines for relation between deviation of log catch and corresponding deviation of temperature for different wind velocity deviation ranges.

2·2° F. rise in temperature. The effect of wind velocity is indicated by the progressive shift in position of the regression line.

To investigate the effect of wind velocity the results were re-arranged into five ranges of temperature deviation, viz. > + 2, + 1 to + 1·9, + 0·0 to − 0·9, − 1·0 to 1·9 and < − 2. Regression of deviations of the log catch from a 3-day running mean (dev. log × 3-D.R.M.) on corresponding deviations in wind velocity from the 3-D.R.M. for the different temperature deviations is shown in Fig. 3. Except when the temperature deviations exceeded −2° F. a significant negative correlation was found between

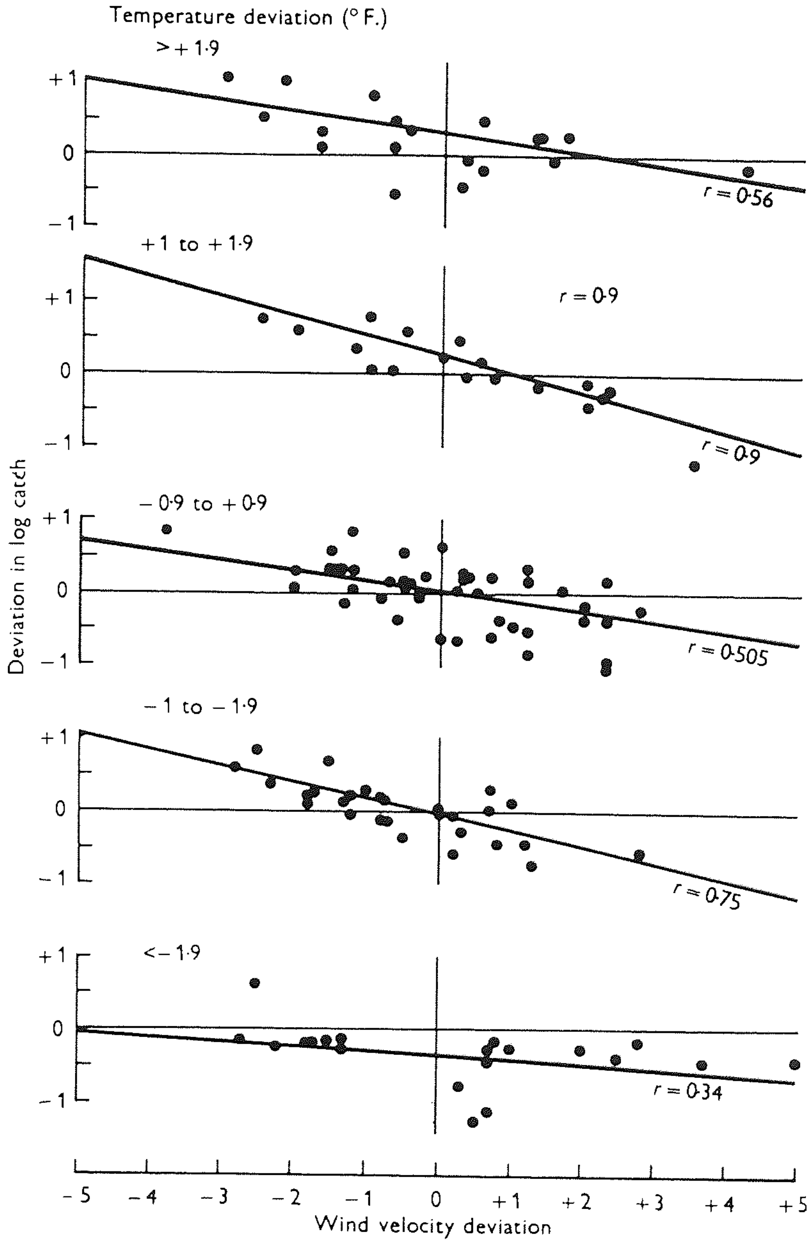

Fig. 3. Regression lines for relation between deviation of log catch and corresponding deviation of wind velocity for different temperature ranges.

the deviation of the log catch from the 3-D.R.M. and the deviation of wind velocity from the 3-D.R.M. A 1 m.p.h. change in wind velocity is associated with a 0·19 change in log catch; or the catch is almost doubled by a fall in wind velocity of 1·5 m.p.h.

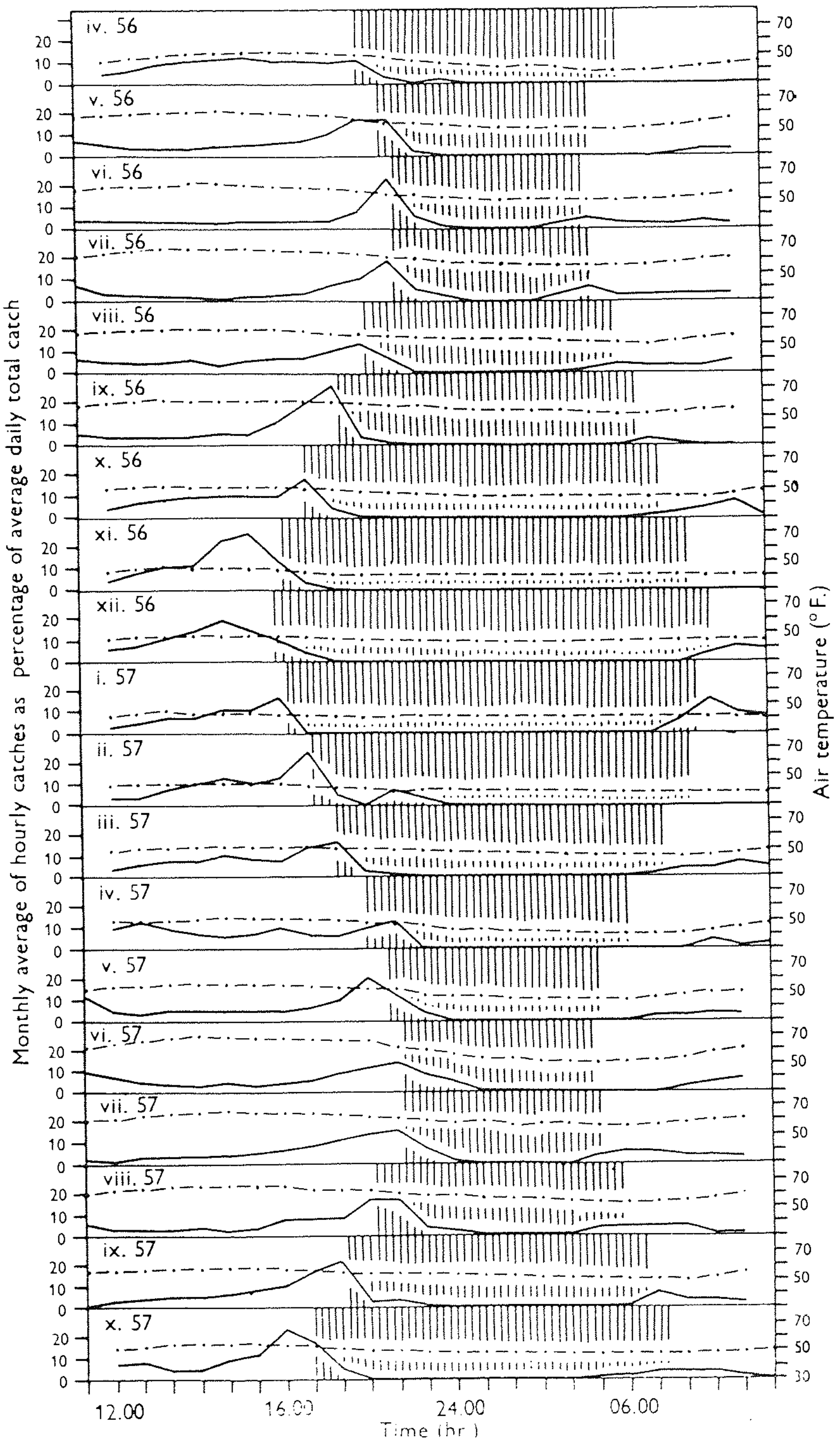

Fig. 4. Diurnal fluctuations in aerial density of *A. fenestralis* in relation to length of day for different months of the year. ——, Catch; —·—, temperature; ||||, hours of darkness.

(3) *Diurnal fluctuations in aerial density*

Diurnal fluctuations in the aerial density of *A. fenestralis* above the beds, previously observed on isolated occasions (Hawkes, 1952*b*), occurred on most occasions, as shown in Fig. 4, where the monthly average catch for each hour of the day expressed as a percentage of the average daily total is shown graphically for each month. In all months, the flies were much less active during darkness and usually there was a marked increase in aerial density about dusk and sometimes also about dawn.

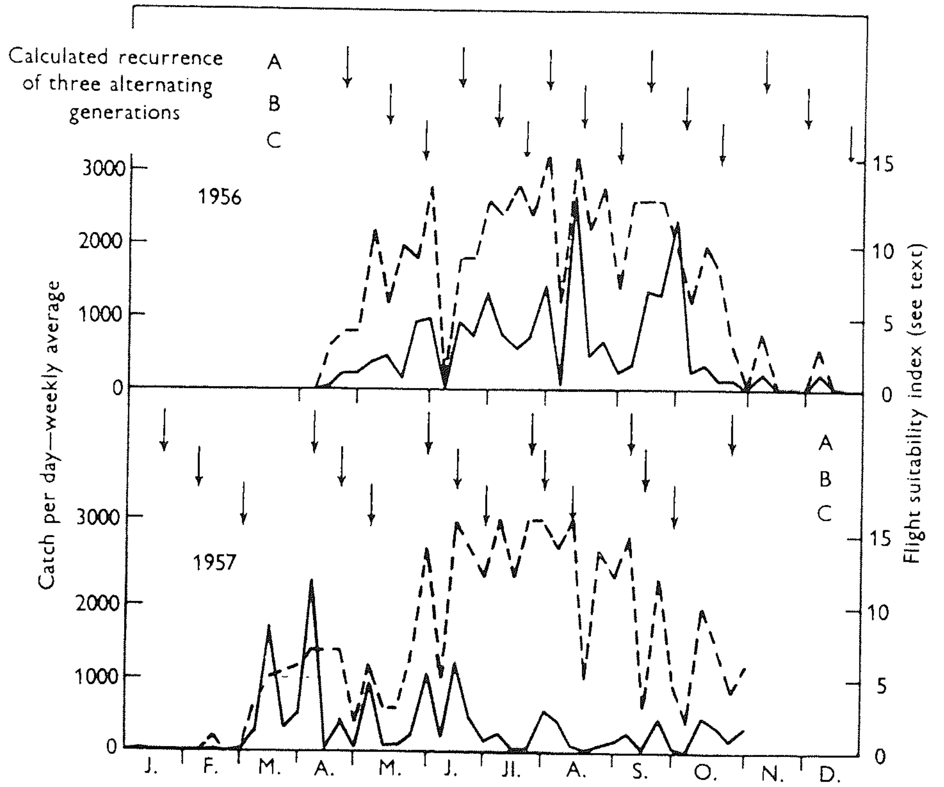

Fig. 5. Weekly and seasonal fluctuations in aerial density above beds and corresponding suitability of climatic conditions for flight. ——, Nos. of *Anisopus*; ---, flight suitability.

Although in the winter, night temperatures could themselves reduce activity, a similar reduction occurred in the summer when temperature was not limiting; the dusk increase in activity also often occurred at times of temperature fall: it is therefore probable that this diurnal pattern was associated with light intensity and not with temperature.

(4) *Seasonal fluctuations in aerial density of* Anisopus fenestralis

Fig. 5 shows the weekly average of the daily catches for the 85 weeks of trapping. During 1956 the flies were frequent on several occasions between May and October, few flies being trapped again until March 1957. During 1957, however, the period of abundance was between March and June with reduced numbers during the remainder of the summer. To find whether these seasonal fluctuations were associated with climatic changes, an assessment of flight suitability was made for each day of trapping. This was calculated from the number of hours favouring flight; i.e. having temperatures between 50 and 75° F. at wind velocities of 0–4 m.p.h., between 55 and 75° F. at wind velocities of 4–6 m.p.h. and between 60 and 70° F. at wind velocities of 6–8 m.p.h. These figures are based on the results expressed in Fig. 2. The weekly average of the daily counts was plotted together with the corresponding flight suitability figure for the whole of the 19 months of observations (Fig. 5). It is seen that marked depressions in the flight suitability graph are usually associated with a corresponding depression of the catch. Also the seasonal incidence of *A. fenestralis* between May and October 1956 and the sparsity during the following winter period could be attributed largely to the degree of suitability of conditions; however, some of the sharp fluctuations quite disproportionate to suitability changes suggest that other factors affect the aerial density. One such factor is probably a rapidly fluctuating population within the bed as has been demonstrated for other sewage-bed flies by Lloyd (1941, 1943) and later for *A. fenestralis* by Hawkes (1952*a*). Assuming a thermal constant of 814 day degrees for the development of *A. fenestralis* (Khalsa, 1948) the theoretical recurrence of peak populations was calculated. Three parallel successions of generations were thus traced throughout the whole period as indicated by the vertical arrows on the graph (Fig. 5). The peaks are

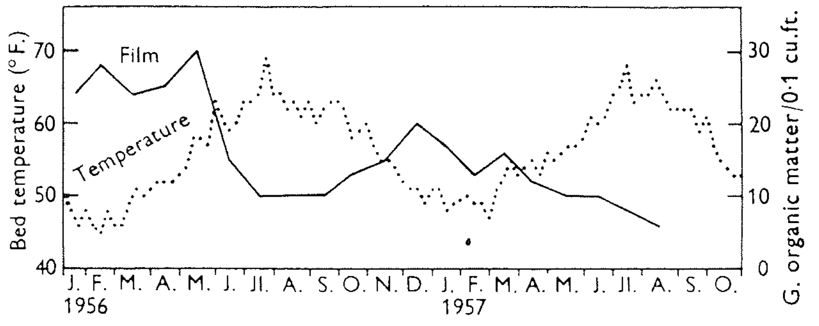

Fig. 6. Comparison of film accumulations in two winters of different severity.

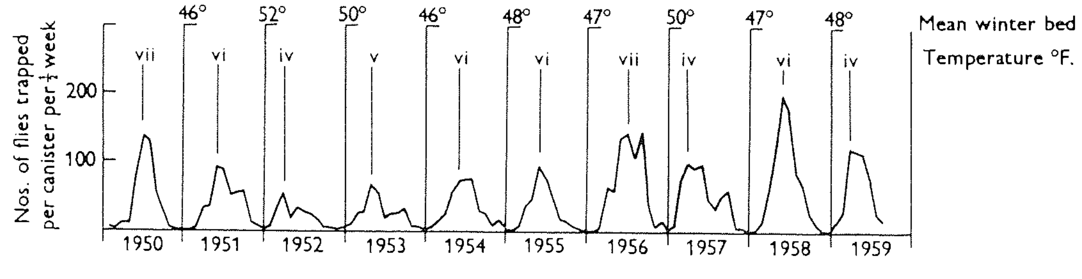

Fig. 7. Seasonal incidence of *A. fenestralis* trapped in canisters above sewage bacteria beds for different years with the corresponding mean bed temperatures during the periods January–March.

sometimes displaced to the right, being delayed by adverse weather; the flies are able to live 20 days at winter bed temperatures and 10 days at summer temperatures. During long spells of adverse weather the emergence peak did not appear at all, the flies being able to complete their full life cycle within the beds.

The following year (1957), however, showed a different incidence of the fly; the population realized its maximum early in the spring and collapsed in June to remain low throughout the summer period when conditions for egress were more favourable. The contrast between the two years is probably due to differences in the incidence of the fly within the bed. Although this was not assessed for the trapping period, previous work (Hawkes, 1952*a*) has shown that it is largely determined by bed temperatures and the availability of food in the film. For other purposes these two factors were assessed on a similar bed and are shown in Fig. 6. The lower winter temperatures of 1955–1956 arrested the development rate of the fly larvae and correspondingly reduced their grazing activity, resulting in a large accumulation of film. Thus early in the spring of 1956 there was a small fly population with sufficient food for it to increase throughout the spring and summer, producing the high incidence shown in Fig. 5. The following winter (1956–57), however, was unusually mild and the more active grazing population restricted the film accumulation (Fig. 6), and thus in the following spring there was not only a larger fly population but a reduced food supply which limited the population later in the year, causing the depression, evident in Fig. 5. Examinations over the past 10 years, as assessed by canister trapping over the beds, show that in 1952, 1953 and 1957 when the mean bed temperatures for January–March were relatively high (see Fig. 7), a maximum population was reached early in the year (April–May) followed by a low summer density. In the other years, when the bed temperature during the first 3 months was lower, the maximum was not reached until later (June–July).

The extent to which fluctuations in the aerial density of *A. fenestralis* are due to population changes or to variations in activity is difficult to assess from the present results. It is hoped that the results of further work will supply the necessary information to account for the fluctuations in aerial density of the fly found in the present work.

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Paper No. 5

Film accumulation and grazing activity in the sewage filters at Birmingham.

Hawkes, H.A.
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Midland Branch

Film Accumulation and Grazing Activity in the Sewage Filters at Birmingham

By H. A. Hawkes, M.Sc. (Associate Member)

In this country it is generally held that the grazing fauna in sewage filters play an important role in controlling the amount of film growing on the filter medium (Lloyd[1]). The seasonal variation in the amount of film has been explained by the differential effect of temperature on the fauna and film balance; low temperatures having a greater retarding effect on the grazers result in the accumulation of film whilst at higher temperatures both the numbers and activity of the grazers are so increased that they outstrip the increased film growth rate and bring about the spring unloading or "vernal slough" and the continued conditions of low film accumulation throughout the summer (Tomlinson[2]). In the Minworth filters of the Birmingham Tame and Rea District Drainage Board, although several species are to be found, by far the commonest grazers are the larvae of the flies *Anisopus fenestralis* and *Psychoda alternata*, the springtail *Achorutes subviaticus* and the small worm *Lumbricillus lineatus* (*Pachydrilus lineatus*). The emergence and dispersal of the adults of *Anisopus fenestralis* causes considerable nuisance in the nearby villages and necessitates the treatment of the filters with insecticide.

Another feature of the Minworth filters is the considerable build up of fungal film during the winter months, the dominant fungi being ***Fusarium***, *Oospora* (*Geotrichum*), and *Sepedonium*; under extreme conditions these form dense extensive mats, several inches thick, on the surface of the filters. Under such conditions it appeared probable that the elimination of fly larvae by insecticide treatment would have an adverse effect on the activity of the filters. To investigate the relationship between film accumulation and grazing fauna and other factors and the effect of the film accumulation on the efficiency of filters a series of ecological studies was made on several filters operating under different conditions both at Minworth and at other works of the Board. Some of the observations have already been reported in detail elsewhere and the present paper is intended as a summary of the more practical aspects of the findings over the past seven years.

PLANT AND METHODS

Plant

The Minworth filters treat an industrial sewage some of which has received pre-treatment in bioflocculation plants which achieve between some 10 to 15% reduction in O.A. Most of the filters are "rectangular"; some are served by travelling distributors and others by fixed spray jets. Four 120-ft. diameter circular filters were operated experimentally by the Water Pollution Research Board until 1954 and later by the Drainage Board. These and one of the six blocks of "rectangular" filters, Block A, which was converted during the period of observations, operated on the alternating double filtration principle; the other filters on which observations were made were operated as single filters and some were heavily loaded due to general overloading and reconstruction work. Other filters on which observations were made were at the Board's Barston Works, where the sewage is predominantly domestic in nature, and on the newly constructed filters at Langley Mill Works, which treat a purely domestic sewage.

Methods

Previous workers on sewage filter ecology have devised their own methods as determined by their particular requirements and facilities. Some of these methods were examined with reference to their use in the Minworth investigations.

The Tray Trap

The assessment of fly populations in filters using the "tray trap" was used by several workers (Tomlinson and Stride[3]). This consisted of a square tray 1 ft. sq. and 2½ ins. deep, which after being inverted over the filter for a period of time, was removed, a lid fitted and the trapped flies counted after chloroforming. Investigations (Hawkes[4]), showed that on the Minworth filters such traps gave no true measure of the fly population of the filter or even of the numbers of flies leaving the filters; they were, however, of use in comparing fly populations in similar filters at any one time and can therefore be used in assessing the effect of fly control measures.

The Lloyd jar trap, as used by Dr. Lloyd,[5] could not be used at Minworth because of the low distributor arms on some areas. It was considered that the aerial density of *Anisopus* was best measured by a canister trap comprising a cylindrical tin with lid, the bottom being replaced by a cone at the apex of which was a 1-in. diameter hole through which the flies entered the trap. The traps, the inside of each of which was coated with insecticide, were supported with the apertures facing downwards 4 ft. above the filter surface on posts. It was found that *Anisopus* entered such traps in large numbers, although few of other species such as *Psychoda* did so.

Baited Traps

During 1951 an attempt was made to assess the fauna population by means of baited bags as previously used by other workers (Reynoldson[6]). Results of weekly samples throughout 1951 showed that when the average numbers of *Anisopus* larvae found in the baited bags at different degrees of film concentration were compared with the corresponding numbers actually found in unit volumes of filter media, it was found that, as suspected by previous workers (Reynoldson[6]), the number entering the baited bags was affected by the availability of food in the filter (Hawkes[7]). Table 1 shows the numbers of larvae found in the baited bags expressed as a percentage of the corresponding numbers present in unit volume of filter at different film concentrations. Since the film varies considerably, both seasonally and from filter to filter, it was considered that such a method was not suitable for assessing larval populations of sewage filters.

TABLE 1

PERCENTAGE ENTRY OF *Anisopus* LARVAE INTO BAITED BAGS AT DIFFERENT DEGREES OF FILM ACCUMULATION

	Film (g. per 0·1 cu. ft.)	Average No. found in baited bags per 100 present in 0·1 cu. ft.
Filter F with slight film accumulation	2—4	1025
	4—6	413
	6—8	355
	8—10	196
	10—12	71
Filter B in which thick fungal growths developed in winter	0—5	99·5
	5—10	76·4
	10—15	51·2
	15—20	15·6
	20—25	43·3
	25—35	21·2

Assessment of fauna and film by Perforated Canisters

Canisters 6-in. deep and 6-in. diameter, the base and sides of which were perforated with seven and sixty ¾-in. holes respectively, were buried in the filter at the required position after being filled with medium removed from the corresponding position. The position and depths of the canisters were marked by metal flags the number of holes in which indicated the sequence of removal. The canisters were left in the filters for at least 12 weeks, after which time the medium was sampled by excavating a given number of canisters as required. Usually a pair of such canisters were buried side by side, one of which was used for the fauna determination and the other for film. In most cases canisters were buried in the surface 6 ins. and between 6 ins. and 12 ins., but in some cases some were buried at greater depths. Below 2½ ft., however, excavations became very difficult and to investigate greater depths it is necessary to have perforated shafts in the filters (Hawkes and Jenkins[8]). At least six pairs of canisters were removed from each filter, in some cases weekly, but in the more extensive work, monthly.

The fauna was removed by washing in a trough on a grid of ¼-in. mesh ; the flow of water carried the organisms through the grid and along the trough into a sieve of fine mesh which retained all the macro-organisms. These were counted over a sectored illuminated counting chamber.

The film and accumulated organic matter was removed from the medium in a revolving drum washing apparatus and the volatile matter determined, this figure being taken as the amount of accumulated film.

Seasonal temperature changes were recorded either by daily readings of a max.-min. thermometer inserted in a pipe sunk in the filter, or by a recording thermometer. In order to assess the efficiency of the filter under observation the 4-hrs. O.A., 5-day B.O.D. (20°C.), ammon-N, and oxidised nitrogen were determined on samples taken either daily or twice weekly. The discharge of humus from the filters was followed by determining weekly the suspended solid content of bulked daily samples.

RESULTS AND DISCUSSION

The results are expressed graphically in figures 1 to 11. Each point on the film and fauna graphs represents the mean of at least 6 samples and in some cases as many as 24. In figures 3, 4, 5c, 6, 7, 8, 10 and 11, in which comparisons are made between pairs of similar filters, a three-point moving average has been applied.

In Fig. 1 are shown the relative amounts of film and its seasonal fluctuation in several filters operated under different conditions. The amount of accumulated film varied considerably between the different filters and was not proportional to the relative filter loadings. Fig. 1a shows the relatively small accumulation of film in Block F at Minworth on which the sewage is applied by travelling distributors at a periodicity of 7 to 14 mins. The excessive accumulation of fungal film in Block B on which similar sewage is applied at only slightly

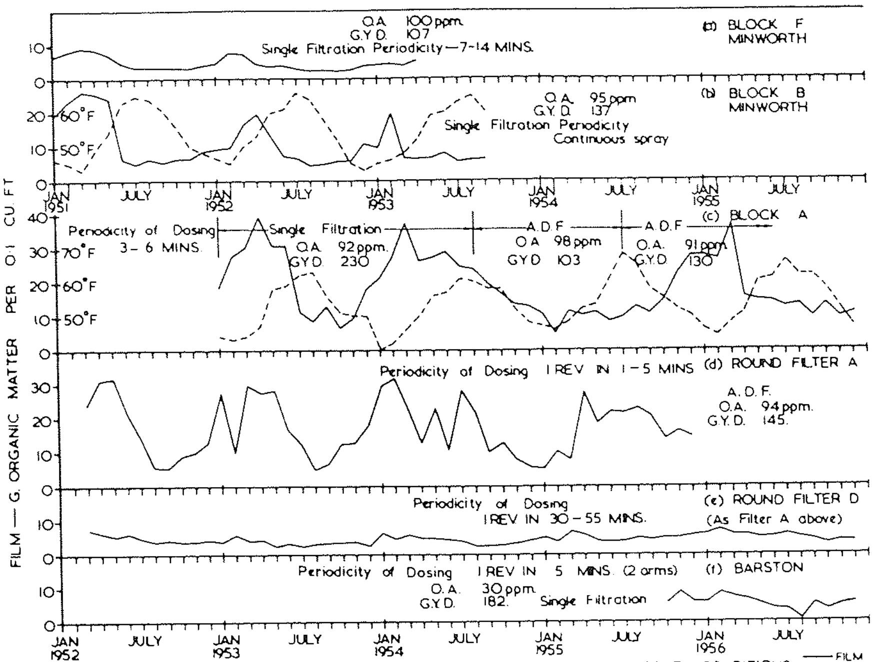

FIG. 1 SEASONAL FLUCTUATIONS OF FILM IN FILTERS OPERATING UNDER DIFFERENT CONDITIONS

higher rates, but as a continuous spray through fixed jets, is shown in Fig. 1b. Fig. 1c shows the variations in film accumulation in part of Block A Minworth since it was converted 4 years ago from single filtration using fixed spray jets to alternating double filtration with travelling distributors, giving a periodicity of dosing of 3 to 6 minutes. The area chosen was that first converted and for the first 18 months operated on single filtration at high rates, during which period excessive accumulations of fungal film occurred each winter. During the winter of 1954-55 when operating on alternating double filtration, but at much lower dosage, no corresponding winter accumulation took place. The following summer the dosage rate was increased to approximately 130 gal/cu. yd/day and this was followed by a recurrence of the winter fungal film accumulation. Besides the increased dosage the beds concerned were not operated for a prolonged period during the autumn due to repair work and, as will be mentioned later, the grazing fauna population in some beds was depleted as a result. At the time of writing the oncome of winter was awaited with interest to see whether the 1955-56 winter accumulation would recur. It would appear however that even at flows less than 150 gal/cu. yd/day alternating double filtration does not in itself suppress the winter accumulation of fungal film in the Minworth filters. This confirms the results obtained from the experimental circular filters with the four-armed distributors revolving at between 1 to 5 minutes per rev. and treating similar sewage by alternating double filtration at approximately 150 gal/cu. yd/day (Fig. 1d). On other filters treating similar sewage by alternating double filtration at comparable rates but with distributors revolving at 30, 42 and 55 minutes per rev. at successive periods of the observations, no excessive accumulation occurred (Fig. 1e). At Barston, however, where the sewage is mostly domestic in origin, the filters remain in a very clean condition throughout the year (Fig. 1f), and the slightly dirtier condition in the winter is due to bacterial rather than fungal growths. The blue-green alga *Phormidium* also occurs on the surface of some of the filters but does not develop to the extent reported elsewhere (Reynoldson[9]). On the surface of other filters containing crushed gravel the alga *Monostroma* develops each spring and summer and although this can hardly be considered as film, on decaying in the autumn it sometimes produced incipient ponding near the surface. Although much less heavily loaded, the filters at the Langley works have so far suffered from excessive accumulations of bacterial slime and flocculated sewage solids during the winter period (Fig. 2b). Comparing the relative film accumulations, loading, and sewage strength at Barston and Langley confirms Tomlinson's finding that "the rate of growth of film depends upon the strength of sewage, quite apart from the rate of application" (Tomlinson[2]).

Except when suppressed by controlled periodicity of dosing, there was, in the filters studied, a definite seasonal fluctuation in the amount of accumulated film. In the case of the Minworth filters the winter accumulation was predominantly fungal in nature ; in the other cases it was due to an increase in the bacterial slime, with surface growths of *Phormidium* at Barston and flocculated solids at Langley. This seasonal fluctuation has been explained in terms of the differential effect of temperature on the film-fauna balance. In Fig. 2 are shown the seasonal fluctuations in film accumulation and corresponding grazing fauna populations for several different filters. The figure for grazers was the sum of the fly larvae and pupae plus the *lumbricillid* worms ; *Achorutes*, which were not counted on all occasions, were not included but a note of their frequency was made. No information is available on the relative grazing activities of the different species but it is known that the rate of grazing of insect larvae is affected by temperature. For example, in laboratory culture work it was found that at 30°C., although *Anisopus* larvae remained alive, very little grazing occurred. At higher temperatures the grazing activity varied considerably throughout the larval stage but the average rate per day was 42% higher at 20°C. than at 10°C., but at 22°C. the rate was less than at 20°C., suggesting that this temperature was above the optimum for *Anisopus*.

In the case of the Barston and Langley filters (Figs. 2a and b) in which the film is predominantly bacterial, the seasonal fluctuation in film accumulation can be attributed to the seasonal fluctuation in the grazing populations. At Barston, large numbers of *lumbricillid* worms are present throughout the year and these dominate the film. In the Langley filters, however, although during the summer of 1955 large numbers of fly larvae became established in the new filters and kept them in clean condition, during the winter no grazers were evident in the upper foot and dirty conditions prevailed. In April when counts were commenced some *Psychoda* larvae had appeared and during the next month these increased rapidly in numbers and the film accumulation was reduced. Personal observations left no doubt that the unloading was due to the activity of the *Psychoda* larvae, which worked in pockets of ever increasing size until all the filter was cleaned.

In the case of the Minworth filters however, where the film was dominated by fungal growths, no such simple relationship exists. Figs. 2c and d represent the film-fauna relationship in two beds of Block A which, as mentioned previously, had been reconstructed to operate on alternating double filtration, although during the first 18 months both beds were operated as single filters at high rates. It was originally intended to compare the effect of fitting splash plates (bed 8) as opposed to direct jets (bed 7) but it proved impossible to operate the two beds in an otherwise identical manner so no valid conclusions could be drawn from the investigation. However, a study of the film-fauna relationship in each filter is possible. In studying this relationship, not only must the effect of the grazing fauna on the film be considered, but also the influence of the amount of film on the fauna population. When the amount of film is small the fauna population is limited because of competition for the restricted food. When excessive accumulations of film result in anaerobic conditions the fauna is again suppressed. The progress of this film-fauna competition is influenced by several external factors such as filter loading, temperature, and periodicity of dosing and it is often difficult and sometimes misleading to attribute cause and effect when changes take place in the film-fauna balance. For example, an excessive accumulation of film in a filter may be the result of a low grazing population or, if such growths have resulted in anaerobic conditions, it may be the cause of the low population. To assist in interpreting the results shown in Fig. 2, anaerobic conditions within the filters have been indicated by the thick horizontal lines.

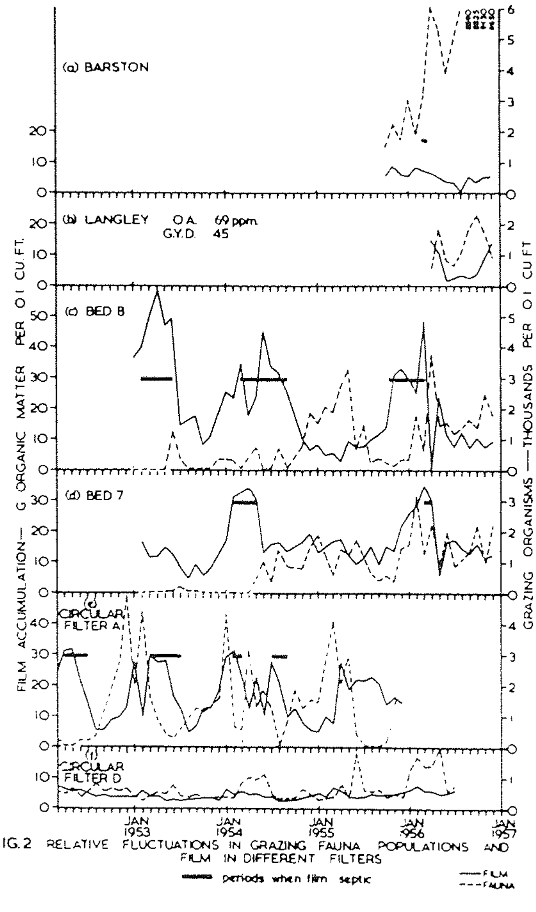

FIG. 2 RELATIVE FLUCTUATIONS IN GRAZING FAUNA POPULATIONS AND FILM IN DIFFERENT FILTERS

▬ periods when film septic — FILM - - - FAUNA

Bed 8, the first to be completed, was initially very heavily loaded as a result of which, in the absence of a grazing population, a heavy accumulation of film took place during the first winter (Fig. 2c). The unloading took place between April and July ; towards the end of which period a grazing population of *Lumbricillus* and collembola had become established. Throughout the summer and autumn the grazing population was much reduced but the film only increased appreciably during the following winter, producing septic conditions which persisted throughout the spring and summer and suppressed the development of the *Anisopus* population after it had become established in the spring. The introduction of alternating double filtration, but at lower rates of application, was followed by a reduction in the film content of the filter and an increase in the grazing population which must have contributed to the suppression of the usual winter accumulation of film.

During the summer the rate of application was increased and unfortunately it was later necessary to discontinue operation of the filter as mentioned previously. As a result, the *Anisopus* population, which would normally have built up during the autumn, failed and the winter accumulation of film again took place and resulted in septic conditions. A rapid unloading in the spring coincided with a peak in the *Anisopus* population and throughout the summer and autumn a well established grazing fauna and conditions of low film accumulation were maintained.

Bed 7 (Fig. 2d), the distributors of which were not fitted with splash plates as were those of bed 8, was started in the early spring. Throughout the first summer and autumn although only a few *lumbricillid* worms and collembola had become established no accumulation of film took place. During the winter however, in the absence of grazers, a rapid increase in film accumulation occurred and anaerobic conditions prevailed. In the spring an unloading took place followed by a recovery of the grazing population under more aerobic conditions. With the change over to alternating double filtration the film was maintained at a uniform level throughout the next 12 months, no winter accumulation occurring. The amount of film however was greater than that in bed 8, and the grazing population lower. The suppression of the grazing fauna in the autumn, due to the stoppage, was not as serious as in bed 8 and the winter accumulation of film not as great. After the spring unloading conditions returned to those of the previous summer.

Although the beneficial activity of the grazing organisms is obvious in controlling film accumulation and on some occasions must have assisted in the spring unloading, the seasonal variation in film in the two Minworth filters (beds 7 and 8) cannot be solely attributed to the differential effect of temperature on the growth rate of film and the grazing rate of the fauna. Even in the absence of an effective grazing population no excessive accumulation of film took place in the summer months but did so in the winter, in some cases in spite of a marked increase in the grazing population. These findings are confirmed by the results from the circular experimental filter A (Fig. 2e). The grazing fauna was dominated by *Anisopus* which was abundant during the winter and spring, at which times the film accumulation was the greatest. As with other flies (Lloyd[10, 11]), there was a succession of peaks in the *Anisopus* population throughout the year representing successive generations, as previously demonstrated (Hawkes[12]). When observations first began in the spring of 1952, filter A contained heavy fungal growths which resulted in ponding and suppressed the grazing fauna. The fungal film then broke down under anaerobic conditions to produce a watery sludge which passed from the filter.

Towards the end of the summer when aerobic conditions again existed the grazing fauna rapidly increased. The winter increase in film was checked until after the second population peak occurred. The film then increased sufficiently to produce ponding and anaerobic conditions which suppressed the next generation of *Anisopus*. The film again broke down under anaerobic conditions as during the previous year. The following winter the fauna was later in recovering and the film rapidly accumulated to produce ponding which resulted in some unloading to permit the following generation of *Anisopus* to develop ; these further suppressed the film (April, 1954). Thus successive *Anisopus* larvae generations alternated with peaks in the film accumulation, but the final unloading in the summer again took place under anaerobic conditions in the absence of a grazing fauna (August, 1954). During the next autumn and winter the grazing population was maintained at a high level and the winter accumulation of film was suppressed until the spring when the fungus increased considerably between the peaks in the grazing fauna populations ; no serious ponding occurred however and the filter remained aerobic. As a result there was no general unloading, and the film accumulation remained higher than during the previous summers.

It would appear from these results that in filters in which the winter accumulation of film was due to luxuriant fungal growths the seasonal fluctuation in film was not due to the differential effect of temperature on the growth rate of the film and the grazing activity but rather to the natural winter incidence of the fungus, the possible causes of which will be discussed later. The dominance of *Anisopus* in the grazing fauna at Minworth with its succession of recurring peaks during the winter and spring modulates the peaks in the film curve (Fig. 2e).

The suppression of film accumulation in circular filter D, in which the periodicity of dosing was controlled by driving the distributor arms round at slow rates of revolution, is shown in Fig. 2f. The fauna which was mostly *lumbricillid* worms was also limited by the reduced food available and the flushing action of the sewage.

THE EFFECT OF INSECTICIDE TREATMENTS ON GRAZING FAUNA POPULATIONS AND FILM ACCUMULATION

To determine the effect of insecticide treatment of filters carried out to prevent fly nuisance, experimental applications of benzene hexachloride were made to selected filters. Observations were made on these filters and on identical filters not treated. Fig. 3 shows that in filters where the film was bacterial in nature and no excessive fungal growths developed (Block F) and *Anisopus* was the dominant grazer, the spring unloading was delayed by a single application of benzene hexachloride. The unloading of both treated and control filters coincided with peaks in the fauna population. It would appear that the unloading in such filters is due to the increased grazing activity. Suppression of the *Anisopus* population over longer periods by a succession of insecticide treatments resulted in the treated filter being later to unload and having a greater amount of film during the following winter (Fig. 4a). After the insecticide treatments ceased the film content was the same as in the control filter.

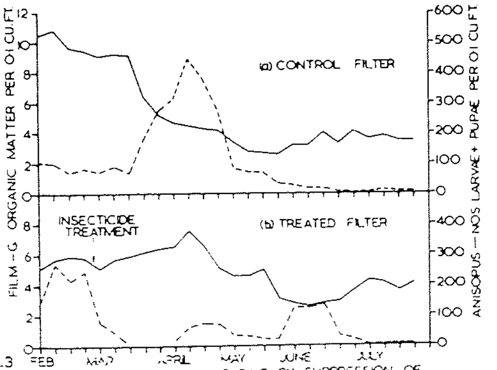

FIG.3 THE DELAY OF FILTER UNLOADING BY SUPPRESSION OF ANISOPUS POPULATION (b) CONTROL FILTER (a)

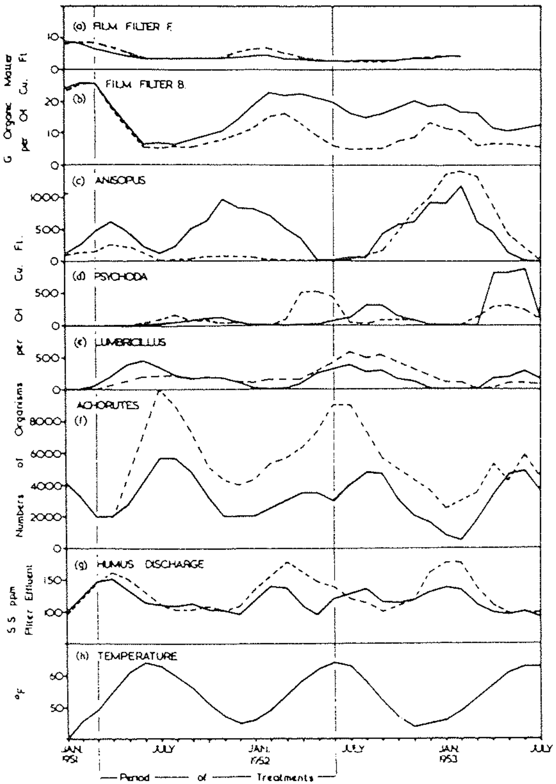

FIG.4

Effects of Insecticide Treatments on :—
(a) Film accumulation – – – Filter F
(b) " " – – – Filter B
(c) – (f) Grazing Fauna Populations "
(g) Discharge of Humus "

———— Control Filter
– – – – Treated Filter

Similar applications of insecticide to filter B, which each winter supported heavy fungal film growths, had surprising results (Fig. 4b). At first, due to the accumulation of film, insecticide treatments were not effective in eliminating the *Anisopus*, although the numbers were reduced compared with the control filter. A rapid unloading took place in both filters and thereafter during the period of treatment the *Anisopus* population in the treated filter was successfully suppressed (Fig. 4c). In spite of this, less film accumulated in the treated filter than in the control ! The effect on the other grazing populations is shown in Fig. 4 (d-f) ; the *Psychoda* population was at times higher in spite of the treatment ; the *lumbricillid* worms were slightly more frequent in the treated filter, *Achorutes* however were far more frequent in the treated filter during the period of treatment and it must be concluded that they were responsible for the cleaner conditions. Their beneficial activity in filters was reported by Bell.[13] The increased grazing in the filter without *Anisopus* is confirmed by the increased amounts of humus discharged in the effluent (Fig. 4g). It would seem that the elimination of the dominant grazer—*Anisopus*—resulted in the establishment of a fauna better able to control the film growth. It is difficult to establish the relative grazing efficiencies of different species but it may well be that the fluctuations in the *Anisopus* larval population due to the rhythmic occurrence of successive generations permits the build up of film between successive peaks (Fig. 2e). A grazing fauna dominated by organisms such as worms and collembola, which graze throughout their life, should be more effective in controlling film growths. Other flies such as *Spaniotoma minima* and *Psychoda alternata* also have a rhythmic occurrence (Lloyd[10] and [11]), but because of their shorter life cycle the population peaks are closer so in all probability the film has less chance of accumulating between successive peaks.

It was hoped that having established a new grazing fauna by insecticide treatment it would persist after treatments ceased and suppress the *Anisopus* population. That this did not occur is evident from the graph (Fig. 4c). It was also hoped that by suppressing the grazing fauna by insecticide treatment, their effect on the seasonal accumulation of fungal film would be evaluated. The establishment of a more efficient grazing fauna however foiled this attempt. It was considered not practicable to eliminate all the grazing fauna without affecting the film by the same means. It was noticed, however, that a similar film growth occurred on the paddle wheels of the "bio-flocculation unit" where pretreatment of part of the sewage was effected. Examinations revealed that no grazers were present in the film, and although the environment was somewhat different to the filters the composition of the film was similar, *Fusarium*, *Oospora*, *Sepedonium* and bacterial growths being found. It was therefore decided to investigate the seasonal fluctuations in the growth and accumulation of the film on the paddles in the absence of grazers. At the end of each month the film was carefully scraped from a pre-selected lath of a paddle and by determining the weight of volatile solids, the amounts of film accumulated during each month were assessed; these were expressed as histograms in Fig. 5 (a). At the same time the film was removed from another lath chosen at random (except the ones previously used) to assess the amount of film present at different times of the year. These results are expressed graphically in Fig. 5 (c).

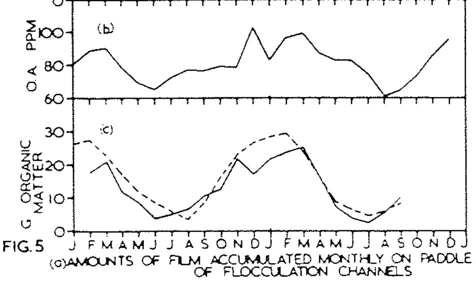

FIG. 5 (a) AMOUNTS OF FILM ACCUMULATED MONTHLY ON PADDLE WHEELS OF FLOCCULATION CHANNELS
(b) STRENGTH OF SEWAGE (O.A) IN FLOCCULATION CHANNELS
(c) COMPARISON BETWEEN FILM ACCUMULATED ON PADDLE WHEELS IN ABSENCE OF GRAZERS —— AND FILM ACCUMULATED ON UPPER 6" OF FILTER (BED 4 MINWORTH) - - - - -

It will be seen (Fig. 5a) that the amount accumulated per month during the winter and spring was much greater than during the summer and autumn. The low accumulations during April and December, 1955, are invalid due to the closing down of the plant for repair work. The results confirm the conclusions drawn from the observations on the filters, viz.—that the winter accumulation of film at Minworth is mostly due to the natural incidence of fungal growths during the colder weather, independent of grazing activity. It has been found that the growth rate of film in the absence of grazers is greater in the summer months than in the winter (Tomlinson[2]). This finding was based on the increase in weight of film over comparatively short periods and should therefore only be applied to the early growth phase of the film. Laboratory work on pure cultures of the component organisms of the film confirms that over 15-day periods the growth rate is higher at summer temperatures. In the filters, however, over longer periods and in the presence of inter-specific competition, decay by autolysis and bacterial activity takes place and in considering the rate of accumulation both the rate of growth and rate of decay must be considered. It is possible, therefore, that the winter incidence of fungus is due to the differential effect of temperature on the growth rate and rate of decay of the fungi.

Examinations of the film revealed that during the summer months of low film accumulation the film was mostly bacterial in nature, whilst the thick growths of the winter were fungal. Similar observations were made on the filters where a succession of species occurred throughout the year. The bacterial summer film gave place, during the autumn, to a growth of *Fusarium* giving the surface of the filter a pink colouration, this was later overgrown by the brown *Oospora* and later in the winter by the thick growths of *Sepedonium*. It was observed that the growth early in the winter was removed from the stones only with difficulty, but towards the end of the winter the thick growths were readily sloughed off, the under layer of the film previously attached to the stone having decayed.

Comparison between the seasonal fluctuations of film on the paddle wheels in the absence of grazers and in the upper 6 ins. of a filter (Bed 4, Minworth) (Fig. 5c), confirm the conclusion that grazing activity by the macrofauna is not the cause of this seasonal fluctuation in fungal film in the filters. American workers have explained it in terms of bacterial oxidation of the film at higher temperatures (Heukelekian[14]), and on the differential effect of temperature on the bacterial-fungal competition (Holtje[15]). Both are possible explanations of the results of the observations on fungal film accumulation at Minworth. A further possible explanation is that some seasonal changes in the nature of the sewage, involving either nutrient or inhibitory substances, takes place, *e.g.*, the increase in gas liquor content during the winter months. Painter[16] investigated the nutrient requirements of several filter fungi but as yet there is no evidence that these could cause the seasonal fluctuations, and the exact cause of the winter growth of fungi in the Minworth filters has yet to be determined.

It is of interest to note that in the slightly more natural habitat of the polluted River Cole where in the winter similar luxuriant fungal growths occur, a spring unloading takes place, although due to toxic conditions no macrofauna is present. This unloading results in the water becoming thick with suspended fungal matter and when this settles, as in a mill dam, it decomposes causing considerable nuisance.

THE EFFECT OF FILM ACCUMULATION ON THE EFFICIENCY OF FILTERS

Single Filtration

As is common experience, the efficiency of a filter as measured by the percentage removal of O.A. and B.O.D. and the increase in oxidised nitrogen of the effluent was found to be higher during the summer and lower during the winter. To what extent this winter decline in efficiency is due to lower temperatures or to the increase in film accumulation is open to question. Stanbridge[17] concluded that low air temperatures during the winter do not greatly affect the performance of filters if the upper layers of the medium can be maintained in a clean condition. Fig. 6 shows the seasonal fluctuations in filter efficiency, measured as (a) % B.O.D. removal, (b) % O.A. removal, and (c) nitrification, in relation to filter temperature and film accumulation. To assist comparison the film accumulation graph has been inverted. In the case of the B.O.D. and O.A. removal, the efficiency curve correlates with both film and temperature curves, but in the case of the nitrification curve it follows more closely the film accumulation.

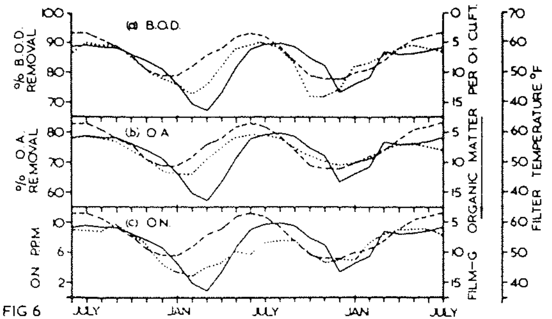

FIG 6 SEASONAL FLUCTUATIONS IN FILTER TEMPERATURE ---- FILM ACCUMULATION —— AND FILTER EFFICIENCY ....
(a) % B.O.D. REMOVAL (b) % O.A. REMOVAL
(c) O.N. IN FILTER EFFLUENT

Comparison of two filters operating under similar conditions except for the degree of film accumulation (Fig. 7) shows that on the whole the cleaner filter was the more efficient; especially in the case of nitrification.

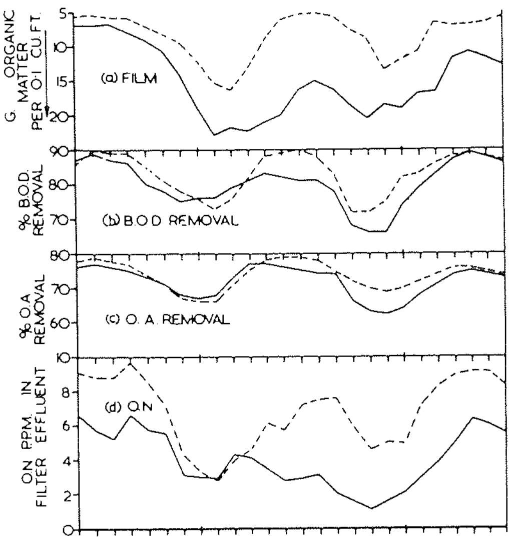

FIG. 7. COMPARISON OF EFFICIENCIES OF TWO SIMILAR FILTERS IN WHICH AMOUNT OF FILM DIFFERED
(a) FILM ACCUMULATED
(b) % REMOVAL BOD
(c) % REMOVAL O.A.
(d) ON IN FILTER EFFLUENT
———— BED 10 MINWORTH
- - - - - - BED 11 MINWORTH

Alternating Double Filtration (A.D.F.)

It has been claimed that one advantage of alternating double filtration is that by alternately applying sewage and returned filter effluent to a filter, the film accumulation is controlled (Tomlinson[18]). As previously mentioned, however, the operation of Block A at Minworth on alternating double filtration failed during the winter of 1955-56 to prevent excessive fungal film accumulation, and the effect of this on the efficiency of the system has been studied. As shown in Fig. 8, the efficiency of the primary stage of filtration was lower at times of high accumulation of film and low temperature just as in the case of single

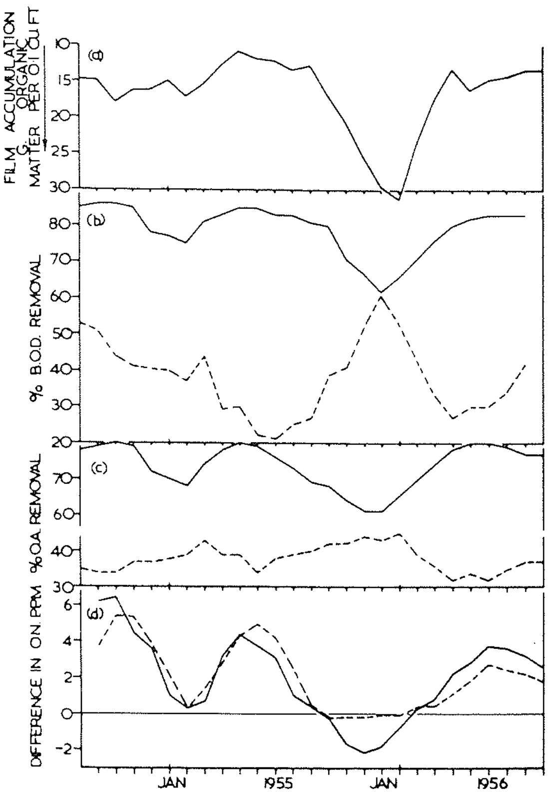

FIG. 8 SEASONAL FLUCTUATIONS IN FILM ACCUMULATION AND EFFICIENCIES OF PRIMARY AND SECONDARY STAGES OF A.D.F. (BLOCK A MINWORTH)

(a) FILM ACCUMULATION
(b) % B.O.D. REMOVAL
(c) % O.A. REMOVAL
(d) O.N. FILTER EFFLUENT

—— PRIMARY STAGE
- - - SECONDARY STAGE

filtration. It should be pointed out that the relatively high efficiency and low film accumulation during the winter of 1954-55 compared with the large film accumulation and low efficiency of the 1955-56 winter are probably the result of increased dosage during the later period ; the two periods are not therefore strictly comparable. The efficiency of the secondary stage of filtration, based on the per cent removal of O.A. and B.O.D. of the secondary feed, was however higher during the winter period when the efficiency of the primary stage was lower (Fig. 8b and c). This was probably due to there being more readily oxidisable matter in the feed liquor because of the lower efficiency of the primary stage, and occurred in spite of lower temperatures and increased film accumulation and not because of them. Whatever the cause, the secondary stage of alternating double filtration would appear to act as a buffer taking up the slack in the system when the primary effluent falls off in quality. The secondary stage then acts as a continuation of the primary stage and although it does more work in oxidising organic matter it ceases to perform the task of controlling the film. Nevertheless, the overall result of the increased efficiency of the secondary stage at times when the efficiency of the primary stage is lower, tends to prevent serious deterioration in the final effluent during the winter. Fig. 9 shows the comparative results from Block A and from the experimental alternating double filters in which the film was controlled by controlling the rate of revolution of the distributors. For most of the period the rate of application to Block A was lower than that to the experimental filters. During the second winter when excessive amounts of film accumulated in Block A the primary effluent deteriorated considerably but the deterioration in the secondary effluent, especially as measured as B.O.D., was proportionately less (Fig. 9b and c). The nitrification however, which was at all times lower in Block A, was greatly affected by excessive film accumulation, there apparently being no compensatory action of the secondary stage. This confirms the results from filter 7, Block A, in which the nitrification in both the primary and secondary stages of alternating double filtration was adversely affected by film accumulation (Fig. 8d). The fact that the degree of nitrification in both primary and secondary stages is similar suggests that although excessive organic film in the filter suppresses nitrification the amount of

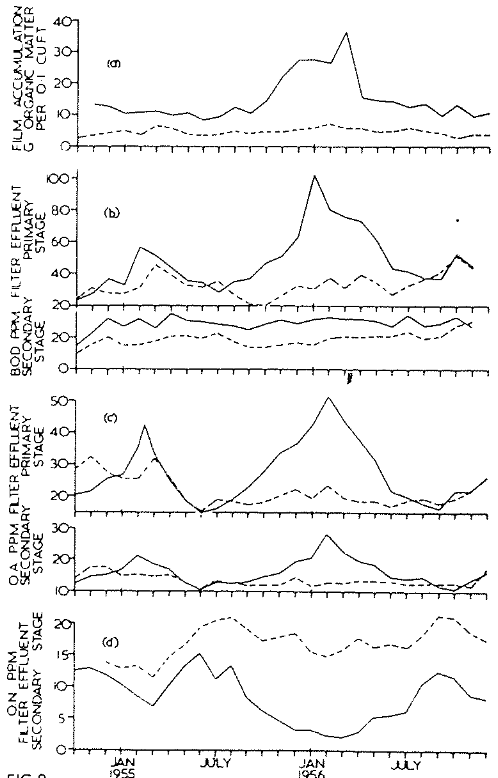

FIG. 9 COMPARATIVE EFFLUENTS FROM A.D.F. UNIT (BLOCK A) —— AND EXPERIMENTAL A.D.F. FILTERS (C & D) - - - IN RELATION TO

(a) RELATIVE FILM ACCUMULATIONS
(b) B.O.D. PRIMARY & SECONDARY FILTER EFFLUENTS
(c) O.A. PRIMARY & SECONDARY FILTER EFFLUENTS
(d) O.N. SECONDARY FILTER EFFLUENT

DOSAGE - BLOCK A —— OCT-JUNE 1955 = 110 G.Y.D. & JULY 1955 - DEC. 1956 (= 131 G.Y.D.
C & D FILTERS - - - - 145 G.Y.D.

organic matter in the sewage has little effect. On this basis two-stage filtration with the secondary filter acting as a nitrifying filter would produce a more highly nitrified effluent than alternating double filtration or recirculation.

EFFECT OF SUPPRESSING SEASONAL FLUCTUATION IN FILM ACCUMULATION ON FLUCTUATIONS IN FILTER EFFICIENCY

In the experimental filters C and D operating as alternating double filters and having the distributor arms driven to revolve 1 rev. in 30 mins. there was little seasonal fluctuation in the film (Fig. 1e). Fig. 10 shows the corresponding efficiency of one filter (D) throughout the year as measured by the % B.O.D. and O.A. removal and nitrification in the primary stage of filtration. It will be seen that the efficiency of the filter showed no seasonal fluctuations as in Fig. 6 in which there was a marked seasonal fluctuation in film as well as temperature. No filter temperatures are available for filter D, but the temperature fluctuations of the filter effluent (Fig. 10a) may be taken as reflecting those of the filter. The results confirm that film accumulation is an important factor in causing the deterioration in filter efficiency during the winter but the direct effect of temperature as a contributory factor cannot be ruled out.

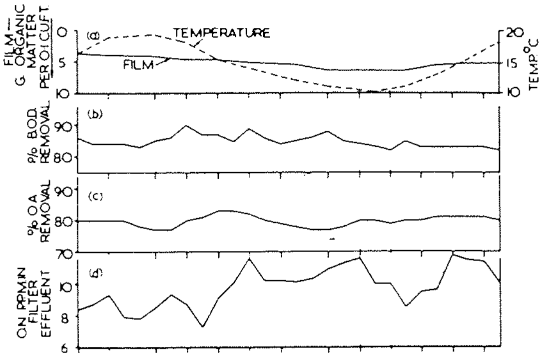

FIG. 10 EFFECT OF SUPPRESSING SEASONAL FLUCTUATION OF FILM (a) ON SEASONAL FLUCTUATIONS OF FILTER EFFICIENCY—
(b) % B.O.D. REMOVAL
(c) % O.A. REMOVAL
(d) O.N. IN FILTER EFFLUENT

The manner in which film accumulation affects filter efficiency can at present only be assumed. In considering the relationship not only must the amount of film be considered but also its nature and condition. The nature of the film is largely determined by the nature of the sewage, but its condition is also affected by the degree of accumulation as previously described, the decaying fungal mats or the resultant septic sludge being less efficient than an actively growing film. Apart from this direct effect on the condition of the film itself, film accumulation probably affects the efficiency of the filter in two other ways. Firstly, by restricting the aeration of the filter; in this connection it is of interest to note that nitrification is greatly affected by film accumulation, confirming the view that the suppression of nitrification by organic matter is due to the resultant deficient aeration and not directly to the presence of organic matter. On this hypothesis the restriction of nitrification to the lower portions of a filter should be accounted for by the lower film content in these regions and not because of the changed nature of the sewage. Secondly, the amount of accumulated film must affect to some extent the period of contact within the filter. Up to a certain amount, increase in film could be expected to increase the period of contact but further accumulation probably restricts the void capacity of the filter and surface area and thus reduces the period of contact. Excessive accumulations which result in ponding also reduce the mean time of contact by causing uneven distribution of the load.

The effect of the grazing fauna on the efficiency of a filter is also not fully known. Apart from the beneficial effect of controlling film accumulation it is possible that they contribute in a more direct manner in the purification by converting the organic film into soluble oxidisable products.

METHODS OF CONTROLLING FILM ACCUMULATION

Theoretically the efficient running of sewage filters involves the maintaining of a film-fauna balance. In operating heavily loaded filters, such as those at Minworth, conditions tilt the balance in favour of the film, and although at times excessive fauna populations may lead to fly nuisance, the problem of filter operation resolves itself into one of fungus control rather than fly control.

Biological Control

In this paper it has been shown that the seasonal fluctuations in the fungal film are due to other factors than the differential grazing activity, but the beneficial activity of the grazing organisms cannot be overstressed. The maintaining and encouraging of a large grazing population is essential. When new filters are started up, film rapidly appears and develops, but the grazing fauna develops much more slowly especially when the filters are started in the winter; the filters should therefore be nursed to maturity—*i.e.*, to when a film-fauna balance has been established. Similarly a filter which has been out of service for any reason may, especially during the colder weather, have a depleted fauna population and require a period of "light duties" until recovered. Short periods of rest when possible during the spring can, however, assist in the unloading. Toxic trade wastes in sewages may, besides directly affecting the oxidation processes, suppress the grazing fauna although permitting excessive fungal growths to occur. This probably accounts for the condition of the filters at the Yardley works, where no effective grazing population is ever established. In general, by treating filters as living organisms rather than as hydraulic systems, they will in the long run give better service !

Alternating Double Filtration (A.D.F.)

The control of film by alternating double filtration may be considered biological in as much as it depends upon a starvation effect during the secondary stage together with a bacterial attack on the fungal hyphae (Tomlinson[2]) rather than upon a mechanical washing out. During the later experimental work on alternating double filtration at Minworth between 1940 and 1944 the experimental filters treated the settled sewage at rates of up to 240 gal/cu. yd/day and produced good effluents (Mills[19]). The process depends upon a good quality primary effluent being produced. The operation of Block A on alternating double filtration with daily changes in the order of the filters has failed in itself to suppress the winter film accumulation, even at rates of 130 gal/cu. yd/day. At such times the primary effluent was of poor quality, although as previously mentioned the secondary effluent deteriorated to a less degree (Fig. 9). This failure of alternating double filtration on Block A to prevent the serious accumulation of film and the failure to reach the efficiency obtained in the experimental work may be due to a change in the nature of the Minworth sewage since 1945. The B.O.D. of the sewage, for example, which averaged 180 p.p.m. during the years 1942-47 had increased to an average of 240 p.p.m. during the years 1951-55. Even using the same two filters (C and D) as used in the experimental work and operating them under optimum conditions of periodicity and at rates of 150 gal/cu. yd/day, although film accumulation is prevented the quality of the final effluent during the winter cannot always be classified as good.

Physical Control

In applying physical or mechanical methods of controlling film, care must be exercised that the method used does not result in reduced efficiency of the filter.

Sizes of Filter Medium

The size of medium used in the construction of the filter will affect the degree of accumulation of film. In comparing four different grades of media it was found (Hawkes and Jenkins[8]), that although the section with the smallest grade medium contained the most film per unit volume of filter and ponded more extensively than the others, it produced on the whole the best effluent when operating as a single filter.

TABLE 2

COMPARATIVE FILM ACCUMULATION AND PURIFICATION OF FOUR TYPES OF FILTER MEDIA

Medium Size (Nominal)	1¼" Cracked Granite	1½" Crushed Gravel	1½" Round Gravel	2½" Round Gravel
Volatile Matter, g. per 0·1 cu. ft.	12·4	9·8	8·4	6·6
4 hrs. O.A. p.p.m. ..	20·4	21·9	23·6	25·3
5-day B.O.D. p.p.m. ..	30·9	30·9	34·8	37·5
Oxidised N. p.p.m. ..	7·4	5·1	4·1	2·9
Amm. N. p.p.m. ..	25·5	28·4	29·7	30·3

Periodicity of Dosing

Probably the most effective method of controlling excessive film growth is by controlling the frequency at which the sewage is applied to any small unit area of the filter. Lumb and Barnes[20] found that by slowing down the rate of revolution of the distributors on circular filters their efficiency was increased and they remained in a cleaner condition. Tomlinson and Hall[21] showed that the Minworth experimental alternating double filtration filters produced better results and were maintained in better condition when the rate of revolution was slowed down to 15 to 30 minutes per rev. It was also found that under such conditions there was little seasonal variation in the film (Hawkes[22]). Similar results have been obtained at other works, *e.g.*, Coventry (Tomlinson and Hall[21]), Ewell (Stanbridge[17]). It is probable that the increased efficiency obtained by controlling the periodicity of dosing is due to the suppression of film accumulation. It has been suggested however (Stanbridge[17]) that other benefits may be derived from the slowing down of distributors. The increased nitrification, a common outcome of slowing down the distributors, it was suggested, is due to the longer periods between doses, assuming nitrification mostly occurs in the period between doses. It will be recalled, however, that enhanced nitrification is the most marked feature of filters having low film accumulation even with continuous application by spray jets (Fig. 7d). Thus the increase in nitrification in low frequency dosed filters may well be due solely to the cleaner conditions.

Although dosing the sewage infrequently may result in part of the dose retained as interstitial liquid being subjected to a long retention, the average retention period may well be decreased by lengthening the period between doses because of the increase in the instantaneous rate of application. To compare the time of contact in a clean filter dosed at low frequencies with that of a filter dosed at higher frequencies and constantly having a larger accumulation of film, does not reveal the direct effect of frequency of dosing on the time of contact.

Continuation of the experiments on alternating double filters has shown that although the ones with distributors revolving at 1 rev. in 30 minutes had little accumulation of film compared with those with distributors revolving at 1 rev. in 2 to 5 minutes (Fig. 11a), the efficiency of the low frequency dosed filters was not always greater than that of the filters having the more rapidly revolving distributors.

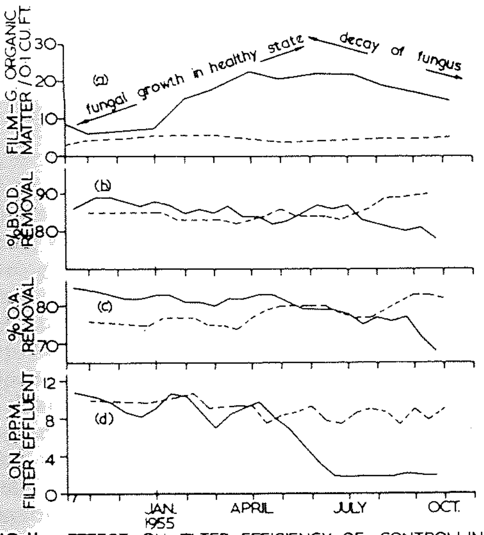

FIG. 11. EFFECT ON FILTER EFFICIENCY OF CONTROLLING FILM ACCUMULATION BY CONTROLLED PERIODICITY OF DOSING

(a) FILM ACCUMULATION
(b) % B.O.D. REMOVAL —— FILTER A 1 REV. IN 2–5 MINS.
(c) % O.A. REMOVAL - - - FILTER D 1 REV. IN 30 MINS.
(d) O.N. PPM. FILTER EFFLUENT

Comparing the efficiencies of filter A, having high frequency dosing, with that of D, having low frequency dosing (Fig. 11), it is seen that although the film in filter D was at all times less than in A, the efficiency of filter A as measured by the percentage removal of O.A. and B.O.D. during the primary stage was for a considerable period greater than that of D. During this period (October-June) although the film accumulated within filter A, it was composed of light foam-like masses of fungal hyphae which remained in a healthy aerobic condition as shown by the large larval population (Fig. 2c). Later some ponding occurred and with the decay of the fungus (July-October) the efficiency of the filter fell off. Again it will be noticed that nitrification was for the most part higher in the cleaner filter D. These observations reveal no further benefit of low frequency dosing other than controlling film accumulation and in fact suggest that, apart from this effect, the practice may well decrease efficiency because of the high instantaneous dosing. Stoddart[23] claimed as a result of experimental work that "So far as from assisting the action of the filter, the intermittent discharge, with its inevitable inequality of flow, reduces the efficiency very appreciably. . . ." Thus until such times that benefits, other than the control of film, have been proved for low frequency dosing, there is no justification for the slowing down of distributors on filters in which there is no serious accumulation of film ; the optimum period of dosing for any filter being the shortest period which suppresses the accumulation of film.

The experimental slowing down of a two-armed distributor at Barston, where a large grazing fauna maintains the filters in a clean condition throughout the year (Fig. 2a), from 1 rev. in approximately 5 minutes to 1 rev. in 15 to 20 minutes has further reduced the film but has so far resulted in a marked deterioration of the effluent.

If by slowing down the distributors the time of contact is reduced, as seems possible, then although during the winter months the advantages gained by keeping the filter in a clean condition may outweigh the loss of efficiency due to the decreased time of contact, during the summer period, when the film is naturally limited, the decreased time of contact would result in a net loss of efficiency. The results, so far published, on the filters at Ewell Sewage Works (Stanbridge[17]) (Fig. 2), support this view. The answer would appear to be a variable speed drive operated to meet the seasonal changes in filter conditions. Such drives have now been fitted to the experimental 120-ft. diameter filters A and B at Minworth.

Experimental work on frequency of dosing has mostly been carried out on circular filters and the application of the results to rectangular filters is not so simple as first appears. The periodicity of dosing on a circular filter is usually taken as time of 1 rev. divided by number of arms. This may well be so when considering the filter at depth and assuming lateral spreading of the sewage within the filter. But when considering small areas on the surface on which the surface film develops and when the jets on the four

TABLE 3

COMPARISON OF FILM ACCUMULATION IN SEVERAL MINWORTH FILTERS HAVING DIFFERENT PERIODICITIES OF DOSING BOTH ON THE SURFACE AND AT DEPTH

FILTER	I Experimental Filter A	II Experimental Filter D		III BLOCK A		IV BLOCK F		V Hypothetical Filter 1		VI Hypothetical Filter 2	
Description	Circular with 4 armed distributor with jets staggered.	Circular with 4 armed distributor with jets staggered.		'Rectangular,' low flow and high flow arms, with jets staggered but when operating both dosing in both directions.		'Rectangular.' At low flows inner and outer halves of bed dosed in opposite directions but at high flows in both directions.		Distributor arm of 4 pipes, each with staggered jets. Each pipe dosing in one direction only and in sequence.		Distributor arm of 2 pipes, each with staggered jets. Each pipe dosing in opposite directions.	
Dosage	145 g.y.d. by A.D.F.	145 g.y.d. by A.D.F.		110—130 g.y.d. by A.D.F.		107 g.y.d. Single Filtration		—		—	
Time of Rotation/Travel Mins.	2—5	15	30	6		14		7		15	
				At Mid-point of travel.	At Ends of travel.	Low Flows.	High Flows.	At Mid-point of travel.	At End of travel.	At Mid-point of travel.	At End of travel.
Periodicity at Depth Mins.	½—1¼	3¾	7½	3 —	— 6	14	7—14	3½ —	— 7	7½ —	— 15
Periodicity at Surface Mins.	2—5	15	30	3 —	— 6	14	7—14	14		15	
Film Accumulation Yearly Average, g. organic matter per 0·1 cu. ft.	17·2	4·5		14·4		4·65		?		?	

arms are staggered, the periodicity is then—"time of 1 rev". In the case of travelling distributors on rectangular filters dosing in both directions, as on Block A Minworth, the periodicity of dosing differs between "time of travel for complete journey" at the ends of the travel to half this time for the midpoint of travel. This periodicity applies both to the surface and to the filter at depth. Thus to achieve a similar periodicity of dosing on the surface of a rectangular filter, to prevent surface growths, the periodicity within the filter would be four times as long as in a circular filter. Such a periodicity would result in a high instantaneous rate of application which would probably reduce the period of contact and impair the efficiency of the filter. Comparison between the degree of film accumulation in several Minworth filters supports this hypothesis. It will be seen from Table 3 that although Block A had a similar "periodicity at depth" to the clean experimental filter D, the larger accumulation of film was similar to that in the experimental filter A, as was the "periodicity at the surface". It would appear that circular filters have an advantage in that it is possible to create conditions of low frequency surface dosing to prevent film accumulation and retain a fairly high frequency at depth (Expt. filter D). To approach such conditions on rectangular filters would require distributors each arm of which would consist of four pipes, the jets in each of which would be staggered and each dosing in one direction of travel in succession ! (Column V). A more practicable machine having two piped arms with staggered jets dosing in opposite direction with a longer time of travel—15 minutes—would approach this condition but the periodicity at depth is lengthened and the instantaneous rate of application is increased.

The distributors on Block A however also differed from those of the circular filters in the spacing of the jets. Each of Block A distributors has a low and high flow arm ; the jets on each of which are just over 2 ft. apart, but staggered so at high flows the distance between jets is just over 1 ft. This results in a very high instantaneous dose and although this prevents excessive fungal growth along the jet line, on either side of this line in the winter, ridges of fungus develop which gradually spread to meet the fungal growths from the neighbouring jet. One area (Bed 8) had similar distributors fitted with splash-plates which ensured even distribution over the whole surface. To do this, however, the force of the jet was broken, thus permitting luxuriant growths of fungus over the whole surface. As previously mentioned, an attempt was made to compare the film accumulation, fauna, and relative efficiencies of distributors with and without splash-plates. Unfortunately, due to mechanical breakdowns, no definite conclusions could be reached. Generally, however, during the summer months when the filters are free from excessive surface growths the filter fitted with splash-plates was in better condition and produced a better effluent than the filter not fitted with splash-plates; this was also the case during the winter of 1954-55 when no excessive surface growths developed. During the other winters, however, when the surface growths on the filter fitted with splash-plates were greater than on the other filters, the filter without splash-plates produced the better effluent. It was concluded that neither type of jet was entirely satisfactory and investigations on different types of jet and jet spacing are at present being carried out at Minworth.

Although many types of distributors are available it may be said that their design has been governed by mechanical and hydraulic requirements; important as these factors are, may a biologist put in a plea that some consideration be given in the design and operation of distributors to ensure that the sewage is fed to the bugs in such a manner as to encourage them to carry on the work of purification at their maximum efficiency?

SUMMARY

(i) The nature of the film in the filters studied differed considerably. Filters treating domestic sewage supported a predominantly bacterial film with alga on the surface of the filter. Sewages containing trade wastes encouraged the development of fungal growths in the winter months.

(ii) The amount of film in filters treating domestic sewage appeared to be determined by the strength of the sewage (O.A.), rather than by filter loading (strength × gal/cu. yd/day).

(iii) Seasonal fluctuation in bacterial film was accounted for by the differential effect of temperature on the growth rate of the film and the grazing activity of the macrofauna.

(iv) Seasonal fluctuations in filters having fungal film are not accounted for by the differential grazing activity. They are due to some factor, as yet not known, which causes the winter growth and accumulation of the fungal film.

(v) Although not responsible for the seasonal fluctuation in fungal film, grazing fauna are of importance in checking this winter accumulation and may assist in the spring unloading.

(vi) The elimination of an insect larval population (*Anisopus fenestralis*) by insecticide treatment, may in some cases result in the establishment of a more efficient grazing population (*e.g.*, one dominated by *Achorutes subviaticus*).

(vii) The seasonal fluctuations of filter efficiency coincided with fluctuations of film accumulation and temperature, being lowest at times of low temperature and high film accumulation. It was established that film accumulation itself adversely affects the efficiency of a filter.

(viii) Methods for controlling film accumulation such as medium size, alternating double filtration, and periodicity of dosing are considered and their effect on the efficiency of the filters are discussed.

ACKNOWLEDGMENTS

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The foregoing Paper was presented at a meeting of the Midland Branch held in Birmingham on 22nd January, 1957.

Introducing the author, the Chairman (MR. C. H. HEWITT) said that the physical effort needed to cope with biological investigations of the kind described in the paper was considerable and when in addition Mr. Hawkes had to plan and organise those investigations and then to assess the value of the results obtained his capabilities were to be greatly admired.

Alternating double filtration was first applied by O'Shaughnessy to filters at Aschurch in Gloucestershire which were treating discharges from a factory processing fruit and vegetables. The filters had failed previously to produce satisfactory results because of surface deposits which caused ponding but the new method resulted in a clearing of the beds. Similar results were achieved at Ellesmere in Shropshire, where Dr. Jenkins (working for the W.P.R. Board) applied the method to the treatment of milk wastes. Mr. Whitehead was eager to test the method and offered facilities at Minworth so that the W.P.R. Board could submit it to large-scale experiment. The first stage in the application of the results of that work had been the conversion of approximately eight acres of bacteria beds to alternating double filtration.

Although the present paper was not specifically a report on the results obtained from those beds, it contained what might be regarded as a biologist's views on the application of alternating double filtration and provided a fascinating account of the problems associated with film growth. Only by an appreciation of the needs and limitations of the organisms which inhabited bacteria beds could sewage be purified successfully.

It should be stressed that this was not a paper by a biologist written exclusively for biologists, but rather a paper by a biologist who was concerned that engineers, designers, and managers should make use of the information which biologists had produced.

Introducing the paper, MR. HAWKES thought it was true to say that in most applied sciences development took place in stages, with advances in theory and practice alternately. Reading the history of sewage purification, however, one felt that theory had often lagged behind practice, *e.g.*, it was known *how* to purify sewage by land irrigation before it was realised that micro-organisms were involved. Percolating filters were run quite efficiently before the beneficial activity of the higher forms of life was recognised towards the end of the last century. To-day, although in practice it was known how to control film accumulation in filters by controlling the periodicity of dosing, the principles involved were still not fully understood.

The more practical type of person might well take the view that if the process worked, why bother about the theoretical considerations. The answer of course was that as long as the process continued to function satisfactorily, then apart from the academic interest a theoretical understanding was not needed. When, however, the process broke down a knowledge of the theory of the process was essential for diagnosis of the cause. Again, improvements in the process were best based on sound theory ; the publication in 1890 of the results of the Massachusetts experiments, carried out to determine the fundamental principles of filtration, resulted in a rapid development in this country of methods of filtration. Mr. Hawkes said that, although it was not suggested that any new developments would result from the paper, it was hoped that it would add to some extent to the present understanding of the biology of biological filtration.

The work reported was not the result of a carefully planned and rigid programme ; one investigation had led to another. Initially, the problem was that of fly control but this had been largely answered by the advent of synthetic insecticides. To a biologist, however, that was not the ideal form of control, and investigations into the factors influencing the insect populations in filters had therefore been commenced. At the same time, the relative importance of fly larvae in the filters and the effect of insecticide treatments on the balance of populations was not fully known. The studies had therefore been extended to cover those points and the results had been reported in the paper.

Mr. Hawkes said that the studies had been of organisms in their natural environment rather than being of a truly experimental nature in which the factors could be controlled. The results were more difficult to interpret than experimental work but could be more readily applied to practice. They were not all in agreement with the findings of other workers, and were not in fact even in accord with the generally held views in this country although they were in agreement to a certain extent with those of American workers.

DISCUSSION

MR. T. G. TOMLINSON (Water Pollution Research Laboratory), proposing a vote of thanks, said that Mr. Hawkes had written a number of papers on the biology of percolating filters and his considerable experience was now being brought to bear on the problem of explaining differences in efficiency between filters operating under widely different conditions.

So many factors influenced filter efficiency that it was difficult to generalise. It might, however, be useful to start with a general principle and then to study the effects of deviating from that principle. It might be stated that the maximum efficiency would result from spreading the load uniformly over the maximum active surface and from keeping the liquid in contact with the active surface under aerobic conditions for the maximum time. One could visualise the ideal system as an intermittent rain of sewage over the surface of the filter. That would give uniform surface coverage, and the intermittent discharge would tend to give a uniform distribution of load with depth. As the total active surface varied inversely as the size of the medium this should be as small as practicable. The texture of the medium would also be important.

Recent experiments carried out on the treatment of sewage in an inclined rotating tube had shown that the maximum efficiency of removal of organic carbon was reached when a film of only 0·25 mm. average thickness was formed. Under those conditions 75 to 80% of the organic matter was removed from the sewage. Fig. 1e of the paper showed that Filter D contained film equivalent to about 50 g. organic matter per cu. ft. If it were assumed that dry film contained 70% organic matter and wet film contained 3·5% dry matter and that 1 cu. ft. of medium had a total surface of 20 sq. ft cu. ft., then the average thickness of fresh film would be about 1 mm. Previous work (Tomlinson and Hall, 1955 ; Hawkes, 1955) had shown that this filter gave better purification than Filter A, which contained on average about 4 times as much film. Mr. Hawkes had shown in the present paper that the greater amount of film in Filter A might be advantageous provided the film was in a healthy aerobic condition.

The main purpose of controlling the frequency of dosing was to keep the film aerobic by preventing an excessive accumulation. Decreasing the frequency tended to cause a decrease in contact time ; consequently there were different optimum dosing periods for different filters. The optimum period of 15 to 30 minutes per revolution (4 to 8 minutes per arm) for Filter D at Minworth was too long for filters at Barston, where increasing the period from 2½ to 7½ and 10 minutes per arm had caused a marked deterioration in the quality of the effluent.

The clogging of filtering medium was usually a surface phenomenon and Mr. Hawkes had pointed out in Table 4 differences between dosing periodicity at the surface and at depth in circular and rectangular filters. In this connection it might be mentioned that experiments with a filter having its base divided into compartments had shown that in a comparatively clean filter the lateral spread of sewage passing through 6 ft. of 1 in. stone medium was quite small. This would seem to indicate the necessity for jets fairly close together or for the use of splash plates. The use of simple jets and their wide spacing might be an insurance against ponding, but freedom from ponding was better achieved by controlled dosing.

There were a number of processes by which film was broken down and Mr. Hawkes had emphasised the importance of anaerobic decomposition. Some years ago determinations had been made of the dissolved oxygen in sewage collected in a tray placed on the surface of a filter in the path of a distributor jet and it was found that the concentration during winter was appreciably higher than during the warmer months. Increased temperature and reduced oxygen concentration in the sewage would cause the underlying part of fungus film to become anaerobic during spring. Presumably under such conditions the fungus would die and become liable to bacterial attack. The absence of metazoa at the surface did not, however, prove that metazoa were inactive. Lloyd (*J. Inst. Sewage Purif.*, 1944, 71), for example, had explained the dispersal of ponded areas on a high-rate filter as being due to attack by *Lumbricillus* from below.

Mr. Tomlinson thought it unlikely that the fluctuations in the two curves in Fig. 5c were due to the same cause. It was probably significant that the highest monthly and total accumulations of growth on the paddles coincided with the highest O.A. Film which grew on glass slides placed on the surface of one of a pair of alternating double filters responded rapidly to changes in composition of the filter influent (Tomlinson, *J. Inst. Sewage Purif.*, 1941, 39). Reynoldson's (*J. Inst. Sewage Purif.*, 1942, 116) experiment with growth on a wooden block in a filter led to different conclusions to those given in the paper.

Dr. S. Baines (Birmingham University) spoke of the complexity of the biological system constituting the filter bed. It could be regarded almost as a living organism, feeding and excreting, and reacting to various stimulii such as temperature variation, the type of food it received, chemical poisons and so on. Much to the engineers' regret, the analogy could not be carried further since the filter bed was incapable of increase in size, and of reproduction.

With a complex biological system of that type it was obvious that the many component organisms existed in balanced populations which varied from time to time and that the balance might in some cases be extremely delicate and affected by a large number of external environmental conditions. The effects of such upsets could be observed, also the causes, and the problem was to fit the two together as Mr. Hawkes had done in the paper. The problem of film accumulation, which was most striking at Minworth, revolved round the balance of fungal and bacterial populations ; in general, a bacterial film being preferable for good working conditions of the filter.

The type of film was most probably related to the type of sewage, with fungal film dominant in the more industrial sewages. That might well be due to the pH factor. Fungi as a group grew more readily in an acid environment whereas bacteria preferred a slightly alkaline environment. However, the range of pH which bacteria could withstand was, in general, narrower than that of fungi and therefore the latter might well be able to withstand extremes of both acidity and alkalinity. Fungi, again in general terms, were able to utilise a greater variety of chemical compounds and that might account for their dominance in a sewage containing a wider range of chemicals, such as trade wastes, some of which would be toxic to many bacterial species. Bacteria, on the other hand, made up for their limitations in these respects by their rapid rate of growth and distribution in a fluid environment once they had become established, under suitable conditions rapidly outgrowing fungal competitors.

Concerning the grazing organisms of the filter beds, one point seemed to be outstanding, namely, the overall dominance of *Anisopus* at Minworth. It did appear that the dominance of *Anisopus* and the dominance of fungal film might be associated. Two possible explanations of such a theory suggested themselves : (1) it was possible that fungal growth supported the growth of *Anisopus* larvae better than that of other grazers—in this respect it would be interesting to know if *Anisopus* developed on other works as the dominant grazer and also if at such works fungal film predominated over bacterial film. The reduction of the *Anisopus* population more than other grazers by insecticide treatment often resulted in increased fungal growths ; (2) *Anisopus* might be a more active grazer than its competitors and therefore might reduce the bacterial film to the extent where fungi became dominant. The dominance of *Anisopus* was then explained by competition. However, if the dominance of *Anisopus* were due to its greater efficiency as a grazer on bacterial film, it could be expected that it would be dominant at most works and in this respect further information on its dominance at other works was required.

Dr. Baines said he put forward those two explanations largely to point out the difficulties in determining cause and effect. In explanation (1) the dominance of fungus was probably the cause of the dominance of *Anisopus*, whereas in explanation (2) the dominance of fungus was an effect of the dominance of *Anisopus*. This was an over-simplified explanation, ignoring to a large extent factors affecting both grazers and film growth. He felt it would be interesting to clarify some of these points by carrying out small-scale laboratory experiments to determine, for instance, the suitability of fungal and bacterial film for supporting the growth of the different grazers, first in the culture stage and secondly, perhaps, in small-scale experimental filters. It was possible in such experiments to eliminate complicating factors by controlling them to a large extent. It was also possible to avoid the errors which occurred in experiments on a full works' scale due to plant breakdown and other factors beyond the biologist's control.

Mr. Hawkes had presented his work clearly and without bias, he had set out results and pointed the way, and had admirably demonstrated the importance of living organisms in sewage purification—from bacteria and fungi, through insects and worms, to the biologist himself.

Mr. V. M. Brown (Derby) asked if it were really advisable (although no doubt expedient) to treat biological filters with insecticides and whether this was a practice to be generally encouraged. The filter bed, an artificially created habitat, maintained with some degree of constancy under varying climatic conditions, was allowed to become naturally populated and the population which developed was an association of organisms having the capacity to best exploit the potentials (food, material, microhabitats) of that particular environment. To proceed, therefore, at some particular time to eliminate a dominant grazing organism (an integral member of the system) or, for that matter, any element of this natural association, by catastrophic treatment seemed to be a fundamentally wrong approach to an ecological problem. Such treatment might give rise to many side problems, and at the best, would seem to lead to the development of associations of organisms proving difficult and costly to maintain. In addition, many insecticides (such as the one mentioned in the paper) could affect filter-bed organisms other than insects and might also, in the absence of careful control, pass out with the effluent to do damage in rivers.

Since the filter bed environment was an artificial one, its biota would seem most satisfactorily and permanently capable of control by a variation of some of the components of that environment rather than by the partial destruction of the fauna and consequent general upset of the biotic equilibrium. The rate and method of application of settled sewage to the filter bed could be varied but, ideally, if protection from gross climatic changes could also be given, so that there could be some control of temperature, humidity and illumination, then it would seem possible to avoid the development of unwanted organisms and to encourage others, so producing a less variable degree of filter efficiency throughout the year.

Mr. H. Dixon (Redditch) said that when he took over his present works the filters were badly choked and the surface of each was completely sealed during the winter due to a heavy accumulation of fungus. Conditions were such that the fungus did not completely disappear even in summer. At that time the sewage had a high O.A. value, contained flushes of acid trade waste, also chromium salts and a higher proportion of gas liquor than usual. However, as a result of discussions with the manufacturers and with the West Midlands Gas Board, the trade effluents were considerably modified in character, peaks in the O.A. of the sewage were "ironed out," and the strength of the sewage became more constant. At the same time the sewage flow, and therefore the rate of application to the filters, increased but the accumulation of fungus on the filter surfaces steadily decreased so that now it was possible to control winter ponding by forking those surfaces. This appeared to confirm statements made by the author in his paper. Mr. Dixon asked what type of medium the author considered to be the best from the biologist's point of view.

Dr. S. H. Jenkins (Birmingham) said that the work which Mr. Hawkes had carried out on biological observations on filter beds had been of assistance in helping the staff of the Birmingham Tame and Rea District Drainage Board to interpret the results of different operating conditions and also in the design of works extensions. Filter beds were regarded from different points of view by the engineer, the biologist, and by the river board. The engineer's concern was to design a plant that would take the maximum volume possible ; whatever benefits might result from designing the plant so that conditions were ideal when low or moderate flows were received, it was the maximum flow which was often the governing factor. The biologist was concerned with the establishment of a varied or balanced population, capable of dealing at all times with the maximum load of impurity—always in an aerobic condition and loaded to suit the capabilities and rate of growth of the film. The river board aimed at producing a good effluent at all times, especially in warm dry weather when rivers were low and the rate of oxidation of organic matter at its maximum. It would be pertinent to ask Mr. Hawkes to specify the design of filter (and ancillary plant) which would best satisfy those three objectives, having in mind the fact that the designer would be concerned with either a weak sewage or a strong sewage, or a sewage which showed little response to biological oxidation on account of the presence of trade wastes.

As regards the effect of the film formed on the efficiency of a filter, it seemed to Dr. Jenkins that the fauna could be credited with a direct contribution towards the purification process. although organic impurity in sewage was measured in terms of B.O.D., much of the impurity was in suspension and purification by filtration or by activated sludge treatment represented, to a large extent, a change in the state of the suspended matter from a form in which its B.O.D. was high to one in which it had a lower B.O.D. Oxidation was then a term meant to include this change in state of suspended matter without much oxidation having necessarily occurred. The suspended matter in the sewage undergoing filtration became flocculated. By changing the flocculated solid into faecal matter which compacted the suspended matter still more, the grazing fauna prevented the possible reversion of flocculated solid to colloidally suspended matter. That was quite apart from any effect the fauna might have in converting solid matter into more easily oxidisable soluble matter.

In dealing with the results of film accumulation, there did not appear to be any discussion concerning the effect of the efficiency of sedimentation on this accumulation. Sedimentation tanks operated with very varying efficiencies. Prolonged settlement was capable of giving an effluent free from settleable solid matter and perhaps with some of the solid matter originally present in a non-settleable form having become flocculated and deposited during settlement ; short period settlement would leave all the non-settleable and part of the settleable matter still present in the tank effluent. It was conceivable that these differences would have profound effects on the nature and amount of the film accumulated.

Mr. Hawkes' observations suggested that bacterial and fungal breakdown of the film might be of importance, as well as the scouring action of the scavenging fauna. If this were so, it pointed to the importance of encouraging the decomposition of organic matter outside the filter, either by septic action or possibly by the employment of two-stage filtration which allowed a heavy accumulation of film in a primary filter and which depended upon anaerobic action to free it from that excessive film accumulation.

Dr. Jenkins mentioned that the Royal Commission on Sewage Disposal had drawn attention to the beneficial effects of treating dilute sewage in preference to strong sewage having the same pollution load. Since then much had been written on the advantages of dilution and recirculation but he was of the opinion that there was an urgent need to carry out large-scale tests on the effects on the final effluent and on the conditions within a filter of applying sewage diluted with different proportions of effluent. It was of importance to know how quickly a filter could be improved in condition by recirculation of effluent, whether there was anything to be gained by recirculating effluent to dilute a weak sewage, and whether advantages would result from operating a filter at a steady high rate by means of recirculation.

Mr. T. A. Austin (Leamington) said that when he first went to Leamington he had had a problem similar to that mentioned by Mr. Dixon, namely, the severe ponding of filters, especially in winter. It was assumed that septic conditions encouraged the growth of fungi. Because there was insufficient fall between the tanks and the filters he was unable to treat more than a limited volume, any additional sewage being stored in a stormwater tank and treated later when the flow had fallen, usually at night ; this in turn created septic conditions. The weirs on the tanks were raised to give extra head, thereby enabling the flow to be treated as it arrived, so preventing septicity. Since that time, four years ago, no ponding had occurred. He asked the author if he had noticed any differences between fungal growths in hard and soft water areas.

Mr. H. H. Stanbridge (Epsom and Ewell), in a written contribution, said that from the investigations described in the paper, which was of outstanding value, Mr. Hawkes had concluded that the seasonal fluctuation in the amount of fungal film in a filter could not be accounted for by the differential effect of temperature on the growth rate of the film and the grazing activity of the macrofauna. At the Ewell works the period during which the amount of film on the surface of the filters was usually at a maximum each year did not correspond with the period of minimum temperature. The greatest tendency to ponding usually occurred during November and December, and as this was before the period of minimum temperature the ponding could not be attributed to a delayed effect of low temperature. Mr. Stanbridge thought there might be some relationship between the growth of film at this time of the year and the presence of dissolved oxygen in the sewage being treated due to stormwater entering the sewers. It was well known that during wet weather, particularly in the soft-water areas of the north, there was a tendency for growths to develop on the sides of the sewers, and these might become so thick that sloughing off occurred so that large masses reached the sewage works.

The author had suggested that with low frequency dosing the average period of contact might be less than when a filter was dosed at more frequent intervals, and it was agreed that this might be the case. There was the possibility, however, that any reduction in efficiency due to the reduced period of contact might be more than compensated for by the fact that with the high instantaneous rate of application a greater proportion of the available internal filter surface would be exposed to the sewage and covered with active film, and that with the longer period between doses the interstitial liquid would be more highly nitrified. Tomlinson and Hall (*J. Inst. Sewage Purif.*, 1955, (1), 46) had shown that after a dose of sewage had been applied to the surface of a filter the first flush of displaced interstitial liquid was highly nitrified, which suggested that a considerable amount of nitrification was taking place during the period between doses. However, Fig. 7d supported the author's contention that the increased nitrification with low frequency dosing was solely due to the cleaner condition of the filter, although it would be interesting to know why Bed 11 was much cleaner than Bed 10.

Mr. Hawkes considered that during the summer, when filters would be maintained in a clean condition by the activity of the scouring organisms, the reduced period of contact with low frequency dosing might lead to a reduction in the efficiency of a filter. Throughout the past summer the efficiencies of the three experimental filters at the Ewell works, based on the 4 hrs. O.A. and the degree of nitrification of the effluents, had been almost the same. If anything, the effluent from the low-frequency dosed filter had had a slightly higher 4 hrs. O.A. but, except for a period of five weeks during September-October, it had been slightly more nitrified than the other effluents. Any decrease in efficiency had not been sufficient to warrant increasing the distributor speed during the summer.

In Fig. 2, in each case, breakdown of the film to a watery sludge had been given as occurring when the amount of film in the filter reached 30 g. organic matter per 0·1 cu. ft. of medium. Mr. Stanbridge wished to know if the void space and surface area per unit volume of medium had any effect on the film concentration at which anaerobic conditions would occur within a filter. In Fig. 8d the primary filter effluent had been shown at one point as containing —2 p.p.m. of oxidised nitrogen. He enquired if it was correct to assume that the settled sewage had contained 2 p.p.m. while the effluent had been devoid of oxidised nitrogen.

Mr. Stanbridge said he wished strongly to support Mr. Hawkes in his plea that filters should be treated as living organisms rather than as hydraulic systems. In this connection, the use of the term "biological filter" rather than "percolating filter" did serve to emphasise the fact that the process was biological rather than physical in character.

Reply to the Discussion

Replying to the discussion, Mr. Hawkes said that he was in full agreement with Mr. Tomlinson's outline of the general principles of sewage filtration. He was pleased Mr. Tomlinson had mentioned the small degree of lateral spread of the sewage as it passed through a relatively clean filter, for although this may be somewhat greater in a filter having considerable film growth, the author considered that in many filters much of the medium was not being used effectively. He fully agreed that surface growth and ponding were better controlled by other methods than by widely spaced simple jets. It was not the author's intention to belittle the usefulness of the grazing fauna ; their activity in the winter months was essential for the control of fungal film in the Minworth filters. All that had been claimed was they were not in themselves responsible for the seasonal fluctuation in fungal film as had previously been suggested. At this stage of the investigation he could not say definitely what caused the seasonal fluctuation in fungal film although, as discussed in the paper, many factors might be suggested. Mr. Tomlinson had mentioned the higher O.A. but there was also an inverse relationship with temperature (Fig. 5a). Whatever the cause, he thought it reasonable to suppose that this could result in similar fluctuations of fungal accumulation on the paddle wheels and on the filters (Fig. 5c).

In reply to Dr. Baines, the author welcomed his academic contribution on the factors influencing the fungus/bacteria balance and considered the many aspects raised were worth following up if and when time permitted. Although *Anisopus* could be cultured on several different foods it might well be that fungal film encouraged *Anisopus* more than other grazers. To complete the picture of the relationship between film and grazers, laboratory work as suggested by Dr. Baines would be necessary. At Barston, where a bacterial film was present within the filters, although *Anisopus* had increased during the past few years the Lumbricillid worms were the dominant grazers.

The advisability of using insecticides on biological filters was a vexed question to a biologist ! As Mr. Brown had stated, the best result that could be expected of such treatment was the establishment of a different association of organisms, which would be costly to maintain. He agreed that a more satisfactory method of control was by controlling the physical environment ; indeed in a previous paper (Hawkes, H. A., *J. Inst. Sewage Purif.*, 1955, (1), 48) it had been shown that the fly population was replaced by a Lumbricillid worm population by controlled frequency of dosing. Such physical control, however, usually entailed structural alterations costly to carry out if not incorporated in the original design. In operating a sewage works, the operator not only had to purify sewage but also had to do so without causing undue nuisance to the neighbourhood. Unfortunately, the ideal conditions for filter operation and for prevention of nuisance were not always compatible. At Minworth, there were over 40 acres of filters in which *Anisopus* bred successfully. Until such times as they could be controlled by changing the physical environment, chemical control would be necessary to prevent fly nuisance in the neighbouring villages.

Mr. Dixon's remarks confirmed the view that the amount of fungal film was determined by the nature of the sewage. From a biologist's point of view, the best type of filter medium would be that which whilst providing the largest surface area per unit volume also provided sufficient void space to allow for the accumulation of film without restricting the necessary aeration of the filter. Thus, the ideal medium for different works and sewages would necessarily differ and it might also be necessary to change the medium seasonally ! Clinker, with its pitted surface, not only provided large surface areas for the growth of film but also provided an ideal surface on which the grazing fauna could withstand the flow of sewage. Thus, from a biological point of view of the medium commonly available, clinker was probably the best type of medium. In practice, however, the differences in the quality of effluents produced from filters of different media were not sufficient to outweigh the many other factors involved, such as durability and availability.

Dr. Jenkins had invited a design for a filter to satisfy the three different objectives—the engineer's maximum flows, the biologist's concern for his bugs, and the river board's desire for a good effluent at all times especially in warm dry weather. Mr. Hawkes considered that of the three objectives mentioned, if the biologist's concern for his bugs were taken care of, the river board's desire for a constantly good effluent would also be satisfied ! The engineer's practical concern to take maximum possible volumes at peak flows could best be aligned with the other objectives by providing maximum balancing capacity, thus providing a uniform and steady load to the filters, under which stable conditions they would operate most efficiently. Time did not permit a discussion on detailed design, but perhaps the enumeration of the fundamentals on which such a design would be based would suffice. Firstly, the biological filter should only be called upon to perform that stage of the purification for which it was best fitted, *i.e.*, biological flocculation and oxidation of organic matter in solution and colloidal suspension. This called for efficient settlement of the sewage prior to application to the filter. Much attention was given to the settlement and removal of humus from filter effluent before discharge to the river, probably because of river board requirements. Self-imposed standards of suspended solids in the feed to the filter would also result in an improved final effluent because the filter would then be free to carry on its true function unhindered by the accumulation of suspended solids. The design of the filter and the choice of the system of filtration would of course be influenced by the nature of the sewage. So far as the sewages mentioned were concerned, straight filtration was probably sufficient for the weak domestic sewage followed by humus tanks and, wherever possible, by land treatment. With a stronger domestic sewage, as during the colder months the grazers were driven into the depths of the filter, beds treating this type of sewage suffered from accumulation of film in the upper layers and recirculation was advocated. In this connection the choice of a site for the filters might prove important, a position sheltered from the cold N.E. winds being preferred.

The problem of sewages containing trade wastes and which promoted luxuriant growths within the filter was more serious. Mr. Hawkes considered that to attempt to design filters to treat "sewage which showed little response to biological oxidation on account of the presence of trade wastes" was tackling the problem at the wrong end of the sewer! At Minworth, however, the sewage although containing trade wastes was amenable to biological treatment, the limiting factor being the accumulation of fungal film during the winter months. For such a sewage and in order to overcome this limitation, a system of recirculation or alternating double filtration together with controlled variable periodicity of dosing would be called for. Biologically, two-stage filtration was to be preferred and Mr. Hawkes agreed also with Dr. Jenkins that pre-treatment by septic or other treatment was desirable. He appreciated the beneficial activities of the grazers referred to by Dr. Jenkins and considered that work on that aspect would probably reveal further benefits resulting from grazing activity.

Mr. Austin's experience at Leamington, where septic sewage encouraged fungal growths, was not in accord with the experience at Minworth where the trouble with fungal growth had only occurred after septic tank treatment had been abandoned. In accord with this observation it was found that little fungal film accumulated in the summer months at Minworth when the sewage was septic. By "septic" the author meant sewage which was black, smelling of sulphide, and devoid of dissolved oxygen. He was not suggesting that septicity alone or in part accounted for the lack of fungus in the summer months. It would be interesting to know what the fungus was to which Mr. Austin had referred. He regretted he had no information on the differences between fungal growths in hard and soft water areas as his observations were limited to the Birmingham area where any such differences were masked by other factors such as trade wastes.

The experience of seasonal film accumulation at Ewell as recorded in Mr. Stanbridge's contribution was welcome. The presence of dissolved oxygen in the sewage was probably a contributory factory in promoting fungal growths. Mr. Hawkes agreed that with long periods between doses the interstitial liquid would be more highly nitrified but the reduced average period of contact would result in a less oxidised effluent (*i.e.*, one having a higher O.A.), other things being equal. It was also agreed that a high instantaneous rate of application would result in a greater proportion of the bed being used, but this could be better achieved by a more efficient distribution of the sewage over the surface of the filter. The report on the continuation of the experiments at Ewell on periodicity of dosing confirmed the author's view that the chief advantage of periodicity of dosing was in controlling winter film accumulation. Although at Ewell Mr. Stanbridge considered that the decreased efficiency of the slowed-down distributors in the summer months had not warranted increasing the distribution speed, the author still felt that on other works this might be desirable and therefore advocated variable speed drives for distributors.

Mr. Hawkes considered that the percentage of void space in filters was an important factor in determining the concentration of film at which anaerobic conditions became established. In reply to the other questions put by Mr. Stanbridge, the author explained that Bed 11 was cleaner than Bed 10 by virtue of the more efficient grazing fauna present as a result of insecticide treatment. In Fig. 8d the figures given were the differences in oxidised nitrogen between feed and effluent and it was correct to assume that the settled sewage contained oxidised nitrogen and that this was reduced in the bed, presumably under anaerobic conditions.

NORTH EASTERN BRANCH DISCUSSION

The foregoing Paper was also presented at a meeting of the North Eastern Branch held in Leeds on 15th February, 1957.

Dr. Nixon (Yorkshire Ouse River Board), proposing a vote of thanks to Mr. Hawkes, said it gave him very great pleasure, firstly because the author was a visitor from another Branch and secondly because of the excellence of the paper itself and the manner in which it had been introduced. Although much of the early pioneer work on the ecological studies of bacteria beds had been carried out in Yorkshire by Dr. Lloyd and his students, the centre of activity, since his retirement, had shifted to the Midlands. Much as Yorkshire members must regret this, Dr. Nixon felt sure that after reading Mr. Hawkes' paper they would agree that the work was being carried on in accordance with the highest traditions by the only member of Dr. Lloyd's team still actively engaged in the sewage profession.

The question of film accumulation and possible ponding must have interested all sewage works operatives at some time or other, and work which attempted to find the reason for its growth and decay was of fundamental importance. Mr. Hawkes had pointed out that the film might vary from a thin bacterial film in a filter treating mainly domestic sewage, to a mat of fungal film several inches thick in the filters treating trade wastes at Minworth. The competition between the rate of growth of the fungal film and the ability of the scouring organisms to dislodge it from the stones and cause it to be washed down into the underdrains seemed to be influenced by other factors which caused heavy growths in winter, in spite of active scourers, and light growths in summer in the absence of scourers. No doubt, in the near future, Mr. Hawkes would find an explanation for this anomaly.

The results given in the paper had clearly indicated that a clean filter gave better results, especially so far as nitrification was concerned. Mr. Hawkes' observations on the influence of periodicity of dosing had confirmed the findings of earlier workers and had brought into sharp focus the special difficulties encountered with rectangular filters. In addition to the influence of the scouring organisms, the effect of the instantaneous rate of dosing per unit area seemed to be of vital importance in keeping a filter open and aerobic.

Mr. J. R. Brown (Bingley), seconding the vote of thanks, said that the paper would be particularly interesting to those members who specialised on the engineering side of sewage purification. Whilst it was true that modern distributors gave little or no trouble, he would suggest that makers should provide more convenient means of speed control, with means for the adjustment of jet angles and of the height of the arms above medium level.

The quantity and quality of the information given in the paper made it into a text-book, and it would provide an excellent guide to all who might carry out similar research in the future.

Mr. F. Oliver (Harrogate) said he was particularly interested in the conclusion arrived at by Mr. Hawkes that periodicity of dosing had not in fact produced any improvement in the quality of effluent. It was the first time, so far as he was aware, that such a statement had been made since the presentation of the original paper by Mr. Lumb, and he was in entire agreement with it. Shortly after Mr. Lumb's paper was presented he tried slowing down the distributors on the high-rate filters at Harrogate and no improvement in the effluent quality occurred after a twelve-month trial period. He was now experimenting with two "straight" filters, these being fed from one dosing siphon and with each filter treating the same volume. After two months' operation there was no difference in the quality of the two effluents. The rates of rotation of the two distributors were one revolution in 1¼ minutes and one revolution in 3 minutes respectively. A small snail, identified by Dr. Lloyd as *Limnaea pereger* had replaced *Achorutes* in the high-rate filters and now appeared to be the dominant grazer. As these small snails had increased the *Psychoda* and *Anisopus* had almost disappeared. *Limnaea pereger* snails were present in the underdrains of the conventional filters at Harrogate, but never on the surface. He wondered if Mr. Hawkes would agree that they performed a useful service as grazers and if dissolved oxygen was necessary for them to live and thrive. Mr. Oliver also wondered if they had come originally from the primary filter in the effluent forming part of the feed.

Mr. C. Lumb (Halifax) said he was particularly interested in Mr. Hawkes' findings on the growth and accumulation of fungal film, which were in accordance with his own experiences at Halifax where considerable growth of this film occurred in filter beds in winter although scouring organisms were still present. At Halifax the sewage at times of greatest fungal growth generally tended to be more dilute than usual and he would be glad of Mr. Hawkes' comments on this aspect, also on the growth of fungus in tank effluent feed channels, particularly near the water line, which also occurred at such times.

He agreed with Mr. Hawkes that the optimum periodicity of dosing was the shortest one which would suppress film accumulation—in effect a periodicity should be aimed at which would apply the tank effluent in flushes sufficient to disperse surface growths and yet small enough to afford a large measure of spread-over in passage downwards through the bed. He also agreed with Mr. Hawkes that it logically followed that in those cases where no difficulty was being experienced in keeping the bed open, increase in periodicity would not be warranted ; this was also in conformity with the conclusions of Stoddart from his classical work on the oxidation of pure solutions of ammonium salts, where only nitrification was involved.

Mr. J. A. Christian (Barnsley) thought Mr. Hawkes' paper was something to be treasured for several reasons : clarity of expression, the quality of the original work, and the beautiful way in which the threads formed by the work of many other distinguished investigators had been drawn together. The whole paper formed something which should prove invaluable to those who had filters in their charge and should be equally useful to those who were contemplating the laying down of new plants and required a rationale for the choice of media size, distribution equipment, and distributor speed.

At Leicester ponding in the winter at modest flows and in the presence of trade wastes was caused by *Fusarium*. At Barnsley, with high flows, an absence of trade wastes and with smaller media, trouble arose initially from bacterial growth in which sewage solids became enmeshed. This led to anaerobic conditions, loss of retention time through streaming and a serious fall in efficiency, especially so far as nitrification was concerned. The application of massive doses of bleaching powder opened up the filter again, restored the retention time, and brought back efficiency to normal—and this in the winter. At Leicester *Psychoda* were a nuisance until *Achorutes* had been established by cultivation, first in the laboratory and then in the filters themselves. It was found, however, that the efficiency of the filters fell by 5% as a result. At Barnsley the clearing of the filter surfaces in the late spring was like the growth of "fairy rings." On several occasions when the winter had been very wet and mild, with sewages correspondingly weak, serious ponding had not occurred although it was thought that the loading was much as usual.

Mr. R. V. Collman (Bradford) said that an interesting example of the growth of fungus had occurred at Bradford's Esholt works, where the tank effluent was conducted to the filters through a covered conduit about half a mile in length. It had been found that *Fusarium aqueductum* and other fungi had established themselves so persistently on the walls and floor that it had become necessary to empty the conduit every two or three weeks for the purpose of removing them. Fine screens had had to be provided to prevent the blockage of filter nozzles by detached fragments of fungus. The growth appeared to be encouraged by the acid used in the precipitation process, and diminished when the pH value of the effluent had been raised. It had also been noticed that the growth was more abundant in winter.

In discussing the factors affecting fungus growth the author had not referred to the effects of light. It might be significant that the winter months were the darkest, and that in the case of the conduit referred to the vigorous growth occurred in conditions of darkness.

Mr. G. Taylor (Bradford) said he was surprised to learn that the efficiency of a filter became less as the quantity of film increased, as he had always felt that a filter would be most efficient when almost ponding. There would then be the optimum amount of film present, which would give the best results—provided of course that the film was wholly active.

At Bradford, during one winter a certain bed had developed a considerable growth of the alga *Phormidium*. This completely blanketed the surface in places, but with the development of ponding the alga was replaced by a heavy fungal growth, both growths dispersing during the spring.

The question of the culture of fungi under conditions similar to those existing in filters had been raised and he suggested that the rotating drum filter, such as had been referred to in American publications, might be of value for this purpose.

Dr. H. H. Goldthorpe (Huddersfield) said the Chairman had already suggested that the shorter period of daylight in winter might affect the growth of fungi at a time when the sewage was cold, dilute, and perhaps contained a trace of dissolved oxygen. In the summer, with stronger sunlight it might be that the algae were merely an overgrowth at the surface. It would be interesting to know more about the rates of growth of the two classes of biological film and to find out which class was preferred by each insect or grazer. The rate of decay of fungi under favourable conditions must be rapid. There was also the question of fungi storing specific elements in the same way as *Beggiatoa* stored sulphur, and Dr. Goldthorpe wondered whether some species of fungi were able to store metals. He had had experience of zinc being found in a fungus, and thought the presence of zinc in the sewage had stimulated the growth of the fungus.

He did not agree with Mr. Lumb that the jets from a slowly rotating distributor removed the living growth, although they might modify it. Growth occurred on the paddles of an aeration unit although the difference in the relative velocities of the water and the solid surface must be much greater.

Mr. Scouller had often spoken of an experiment in which sewage was allowed to trickle down a length of sloping roof gutter. Where the sewage fell on to the gutter a massive gelatinous growth of organisms developed, but the growth decreased in amount and its character changed as the purifying sewage flowed slowly down the gutter. If such a gutter could be fitted with transparent or solid removable covers so that the sewage trickling down it was exposed either to light or to total darkness this would provide an opportunity of studying the progress of purification through a filter. It would not be a costly experiment to set up and could be carried out by almost any manager.

Reply to Discussion

Replying to Dr. Nixon, Mr. Hawkes said he considered it an honour to have been asked to present a biological paper on filters to the N.E. Branch, and to have it considered as a continuation of the work of Dr. Lloyd and his team of workers was the highest award such a paper could receive.

In claiming that the seasonal fluctuation in fungus film at Minworth could not be accounted for solely by differential grazing activity, the author did not wish in any way to minimise the beneficial activity of the grazing fauna in filters ; they played an important role in the operation of the filter and their activity should be encouraged. Mr. Hawkes was pleased that the difficulties of applying controlled periodicity of dosing to rectangular filters was appreciated.

He agreed with Mr. Brown that research on other stages of purification, such as sedimentation, which resulted in less solids being applied to the filter must result in the filters being better able to deal with that stage of the purification process for which they were best fitted, *i.e.*, removal of matter in fine suspension and solution and in the biological oxidation of such matter. He also agreed that distributors should be supplied in such a form that they could be readily modified, not only to meet the many different conditions at different works but also the varying conditions both seasonally and over longer periods at the same works.

In connection with the effect of periodicity of dosing on filter efficiency, raised by Mr. Oliver, it was only fair to point out that at times when low frequency dosing had resulted in an inferior effluent, the filter had been in a good aerobic condition. There was little doubt that controlled periodicity of dosing did prevent excessive accumulation of film and in filters where this accumulation resulted in decreased efficiency then controlled periodicity could bring about improved conditions and a better effluent. To slow down distributors on filters which were not subject to film accumulation was not only unwarranted, as Mr. Lumb had said, but could probably result in an inferior effluent.

Mr. Hawkes recalled being shown the snails *Limnaea pereger* by Mr. Oliver when he visited the Harrogate filters some years ago. Their occurrence in the filters at Harrogate was of considerable biological interest. They occurred in Birmingham streams which were organically polluted and were used as an "indicator organism" in assessing river pollution. It would appear that Harrogate sewage was of a similar nature to Birmingham streams ! There was little doubt that it was doing a useful job as a grazer and because of its clinging habit it was admirably suited to withstand the flushing action of high-rate filtration which would limit other grazers such as fly larvae and *Achorutes*. Mr. Hawkes doubted, however, whether the snails would develop in many filters treating stronger sewages. *Limnaea* was a member of the pulmonate molluscs which breathed atmospheric oxygen and was therefore independent of the dissolved oxygen in the water of sewage, although in waters containing dissolved oxygen it had been found that snails had to surface for air less frequently than in deoxygenated water, suggesting that use could also be made of dissolved oxygen when available. It was agreed that the snails had probably been carried on to the filters with the primary filter effluent, although birds could also have been the agency of introduction.

He was interested in Mr. Lumb's remarks about the incidence of fungus at times when the sewage was weaker than usual. This was the opposite of the case at Minworth where, due to extra gas liquor, the sewage was stronger in the winter. It would be interesting to know what the fungus was.

Different fungi had different nutritional requirements, the growth of some being encouraged by the presence of complex organic matter at low concentrations. Examination of a fungus which produced luxuriant growths in the feed channels to the Walsall filters following a period of heavy rain had shown that it was *Leptomitus lacteus*. A further factor which would encourage fungal growth at times when the sewage was weaker could be the possibly greater amount of dissolved oxygen.

On the question of the manner in which controlled periodicity of dosing suppressed film accumulation, raised by Mr. Lumb and Dr. Goldthorpe, Mr. Hawkes considered that although the increased flushing action might assist in preventing thick growths from accumulating on the surface, this action could only be operative near the surface. With controlled periodicity the growth of fungus within the filter was also controlled and this needed an explanation other than scouring action. Mr. Hawkes felt that the starvation effect of long periods between "meals" resulting from low frequency dosing was an important factor in controlling film growth. Micro-organisms such as fungi and bacteria needed to be constantly bathed in their nutrient for optimum growth. Thus film accumulation might be said to promote conditions for its further development by impeding the sewage flow. The case mentioned by Mr. Taylor, where the surface growth of *Phormidium* had resulted in ponding which then brought about the fungal growths, confirmed this view.

Mr. Christian's observations at Leicester and Barnsley were in accord with those submitted in the paper. The observation concerning the better condition of the filters during wet winters supported the view that it was the strength of the sewage rather than the loading that was important in film accumulation and this probably explained the benefits of recirculation.

Replying to Mr. Collman, he confirmed that *Fusarium aqueductum* was encouraged by acid conditions. On the question of the effect of seasonal light variation, also mentioned by Dr. Goldthorpe, he had no information. This factor, however, would only be operative on the surface and could not explain the seasonal variations in film which take place within filters and which Mr. Collman had stated occurred in the covered conduit.

Mr. Taylor's view that a filter was most efficient when almost ponding, with the "optimum" amount of film present, needed qualification. Mr. Taylor had himself made one important proviso, *i.e.*, "that the film was wholly active." He considered that in practice the maintenance of a thick film in an active condition over prolonged periods was, to say the least, very difficult. A further point was that the accumulated film had to be discharged and under the conditions Mr. Taylor considered ideal it was probable that much of the breakdown was by autolysis, the breakdown products adding to the load of the filter. Such conditions existed in the circular experimental filters and Fig. 11 showed that although during the period when the fungal growths were actively growing the efficiency of the filter had been higher than the clean filter, thus supporting Mr. Taylor's view, when the fungus decayed the effluent had rapidly deteriorated. Mr. Hawkes considered that only a very thin slime on the stones was necessary for efficient purification to take place, and to permit the accumulation of excessive growths within the filter was like carrying a lot of "dead wood" in the system.

Dr. Goldthorpe had suggested some very useful lines of investigation and had pointed the way in which they could be carried out at little expense ; it was hoped that some managers would find it possible to set up such an experiment. He was particularly interested in the finding of zinc in fungus as it must be some such trade waste that was responsible for the fungal film in filters treating industrial sewages. Regarding the decay of fungus, laboratory work on pure cultures of *Sepedonium* had shown that temperature had a marked effect ; the percentage loss in weights of mats of fungus after 16 days in filter effluent at 34°, 48°, 68°, 72°, and 80°F. had been 9·8, 8·2, 51·2, 75·3 and 75·3% respectively.

The Ecology of Sewage Biological Filters

Paper No. 6

An ecological approach to some bacteria bed problems.

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PAPER :

An Ecological Approach to Some Bacteria Bed Problems

By H. A. HAWKES, M.Sc., M.I.Biol.

Biologist, Birmingham Tame and Rea District Drainage Board

To be presented on Thursday, June 23rd at 2.30 p.m.

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2

An Ecological Approach to Some Bacteria Bed Problems

By H. A. Hawkes, M.Sc., M.I.Biol. (Associate Member)

(*Biologist, Birmingham Tame and Rea District Drainage Board*)

INTRODUCTION

The oxidizability of sewage and other organic wastes can be assessed by manometric methods (Jenkins[1]) and the results of such tests may be used in the design of treatment plants (Eckenfelder and McCabe[2]). Theoretically the rate at which a waste can be oxidized in bacteria beds is limited by the reaction constant (K), which is a measure of the oxidizability of the waste. According to Velz[3] "the rate of extraction of organic matter per interval of depth of a biological bed is proportional to the remaining concentration of organic matter, measured in terms of its removability". This is to be expressed in the equation

$$\frac{L_D}{L} = 10^{-KD}$$

where L represents the total removable B.O.D. in the feed, L_D the remaining removable B.O.D. at depth D, K is then the reaction constant.

In practice, however, other limiting factors may affect the rate at which bacteria beds can treat organic wastes. Early in the development of bacteria beds difficulty was experienced with the clogging of beds by excessive growths especially in the winter. With increased flows and trade effluents the problem increased and it was realised that an important factor limiting the rate at which sewage could be treated in bacteria beds was the winter accumulation of film. Another problem associated with bacteria bed operation was the nuisance caused by flies dispersing from the beds in which they bred. This problem also grew with the increased loadings applied to the beds. It would appear that such problems as clogging and insect control were tackled by two lines of attack. Modified methods of operating bacteria beds in an attempt to treat at higher rates by preventing excessive accumulations of film resulted in the development of recirculation, double filtration, alternating double filtration, and low-frequency dosing of beds. Other investigations involved the study of the plant and animal communities within the beds—and notable among such investigations were those of Johnson[4], Lloyd and his succession of students[5], and Tomlinson[6]. In the present paper these two practical difficulties—film control and fly control—are considered as one ecological problem and an attempt is made to correlate the results of the two lines of investigation in the light of recent theories.

ECOLOGY OF BACTERIA BEDS

In common with other methods of biological oxidation, the purification of organic matter in bacteria beds is basically the use of the organic matter as food by certain micro-organisms. Part of the organic matter is utilized as fuel in the respiratory process of the micro-organisms whereby the energy for life processes is liberated, with the production of CO_2 and H_2O as the usual end products. Another part is used as basic material for the synthesis of new protoplasm thus increasing the microbial mass, the energy for such synthesis being provided by that released in respiration.

Organisms which use organic compounds as primary sources of energy are termed *heterotrophic*

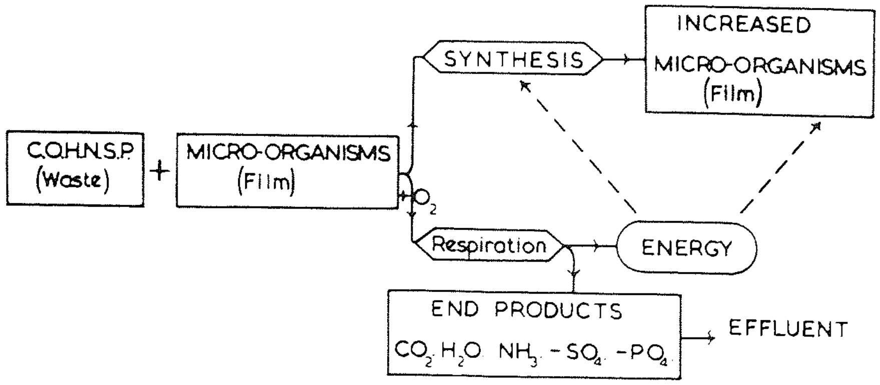

Fig. 1. Synthesis and energy production in the biological oxidation of organic matter

in contrast to the *autotrophic* forms which obtain their energy initially from light (photosynthetic plants) or by inorganic chemical reactions (chemosynthetic bacteria) such as nitrifying bacteria. Some heterotrophic organisms obtain their food by utilizing dead or decaying matter; these are termed *saprobic*. Others obtain their organic food by preying on other living organisms and are termed *holozoic*. Obviously only the saprobic forms are the primary organisms in the initial breakdown of organic wastes, although the autotrophic nitrifying bacteria are also involved later in the final oxidation of nitrogenous matter. In the bacteria bed, bacteria, fungi and certain protozoa—mostly flagellates—are the primary organisms of purification. Nevertheless other organisms play an important secondary role in the process. In bacteria beds and activated sludge holozoic micro-organisms such as ciliate protozoa, rotifers and nematode worms feed on the saprobic organisms. In bacteria beds the system is further elaborated by the presence of the larger

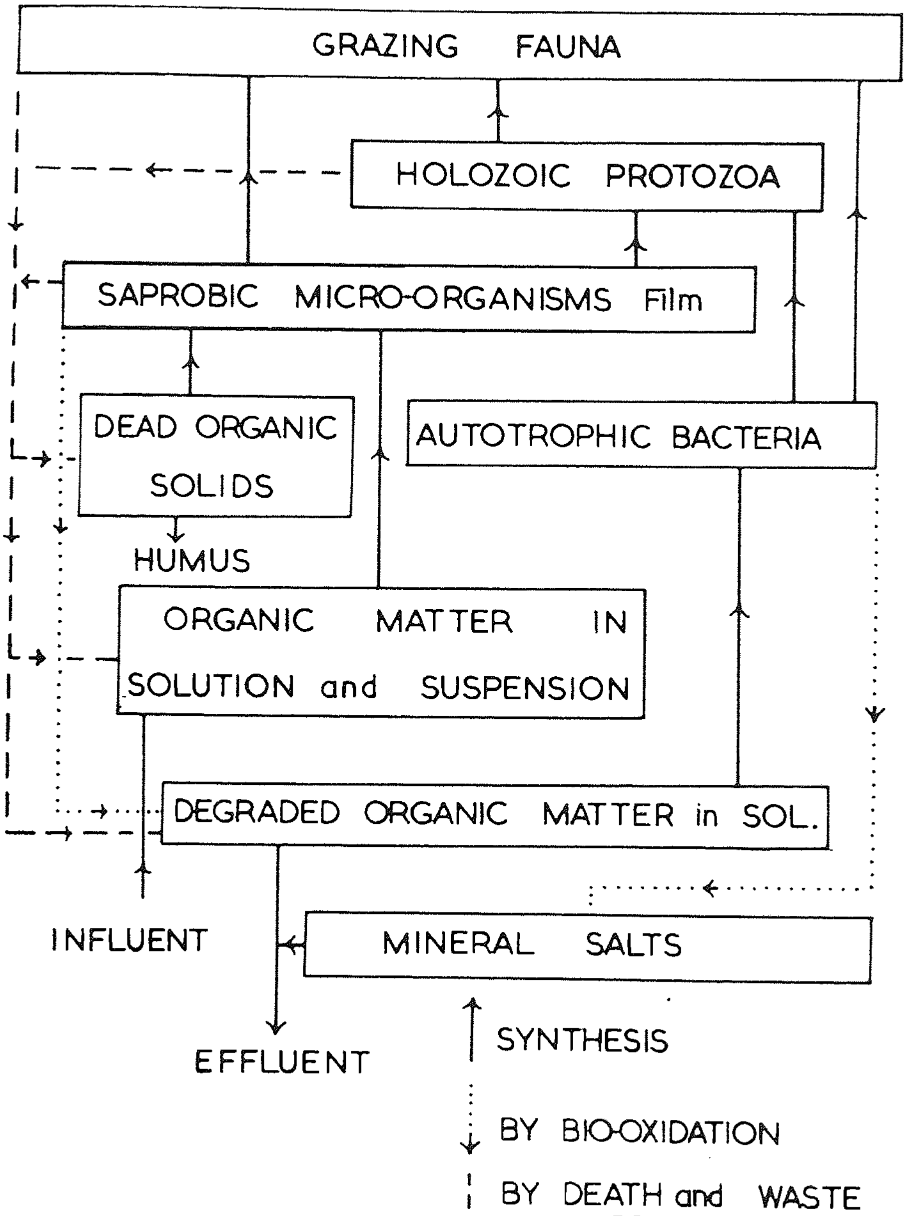

Fig. 2. Diagrammatic representation of the main paths of material transference in the purification of organic wastes in bacteria beds

holozoic animals such as worms and insects. Thus the bacteria bed community consists of a wide range of organisms existing on different trophic or nutritional levels according to their food requirements. Complex inter-relationships exist between the populations of the different species. On the same trophic level competition may exist for a common food source and this usually results in one species becoming dominant at any one time. On different trophic levels relationships exist between predator and prey populations. Superimposed on these relationships are the chemical and physical environmental factors imposed by the nature of the waste, the rate and method of application, the nature of the bed medium, and climatic factors especially temperature.

An understanding of the bacteria bed process of purification must then include a knowledge of these inter-relationships of the organisms involved. Ecology is the branch of biological study dealing with such inter-relationships within a community, and a modern ramification of the subject—the study of the transference of materials and energy between populations—which has, in other fields, been applied to productivity studies, could well be applied to a study of the processes involved in purification. The present paper confines the study to relationships between those elements of the bacteria bed community which have given rise to difficulties in operation; the relationship between the primary food (the organic waste), the saprobic micro-organisms (the film), and the holozoic predators (the grazing fauna) will be considered.

Fig. 2 illustrates the relationship between the organic waste, the microbial film and the grazing fauna in a conventional bacteria bed. The microbial film is dependent upon the organic waste as food and in turn the grazing fauna is dependent upon the film. Thus an increase in concentration of the waste results in increased amounts of film which is then capable of supporting a larger grazing fauna population. Conversely, a decreased amount of film results in a diminished grazing population. At the same time an increase in grazing fauna tends to decrease the film. This interdependence of waste concentration, film and fauna results in a balance being established. The maintenance of this balance at a level at which efficient purification without nuisance can be achieved is the essence of good bacteria bed operation. To achieve this we must first consider at what level it is desirable to maintain the film-fauna balance, the factors which affect this balance, and finally some practical operational methods by which the desired level of populations can be maintained.

FILM ACCUMULATION, GRAZING FAUNA POPULATION IN RELATION TO BACTERIA BED EFFICIENCY AND FLY NUISANCE

Whilst most workers agree on the desirability of preventing excessive accumulations of film there would appear to be some difference of opinion as to the optimum amount required. Lloyd[5] considered that were it not for the increased metabolic activity of the micro-organisms at higher temperatures in the summer their reduced numbers, due to the dominant grazing fauna, could result in decreased purification. Taylor[7] had stated that he considered a filter to be most efficient when almost ponding. Experience with the beds at the different Birmingham works led the author to believe that a very thin film indeed is all that is required for efficient purification. This view is supported by experimental evidence reported by the W.P.R.L.[8]; it was found that using inclined rotating tubes, the maximum efficiency of removal of organic carbon was reached when a film of only 0·25 mm. average thickness was formed.

Although there is usually a seasonal decline in efficiency during the winter, the extent to which this is due to the lower temperatures or to increased film is difficult to assess. Fig. 3 shows the seasonal fluctuations in film accumulation, temperature and efficiency of two beds, one in which the usual accumulation of film occurred in the winter and the other in which it was suppressed by controlled frequency of dosing. It will be seen that the efficiency of the bed in which there was no winter accumulation of film showed little seasonal fluctuation compared with the efficiency of the bed in which winter film accumulation occurred. Although not eliminating temperature as a factor, these results do confirm that film accumulation itself is an important factor.

More important than the amount of film however is its condition. Previous work (Hawkes[9]) had shown that during the period when a fungal film was actively growing and in a healthy condition the efficiency of the bed, as measured by O.A. and B.O.D. removal, was greater than in a corresponding bed in which the film was limited by controlled frequency of dosing. After reaching a certain degree of accumulation, however, the growth rate fell off and the fungus decomposed; associated with this was a reduction in efficiency so that the bed became less efficient than the bed with controlled frequency dosing.

In the growth of micro-organisms, a culture passes through several well defined phases. The classical growth curve as described by Monad[10] is shown in Fig. 4 together with the resultant growth

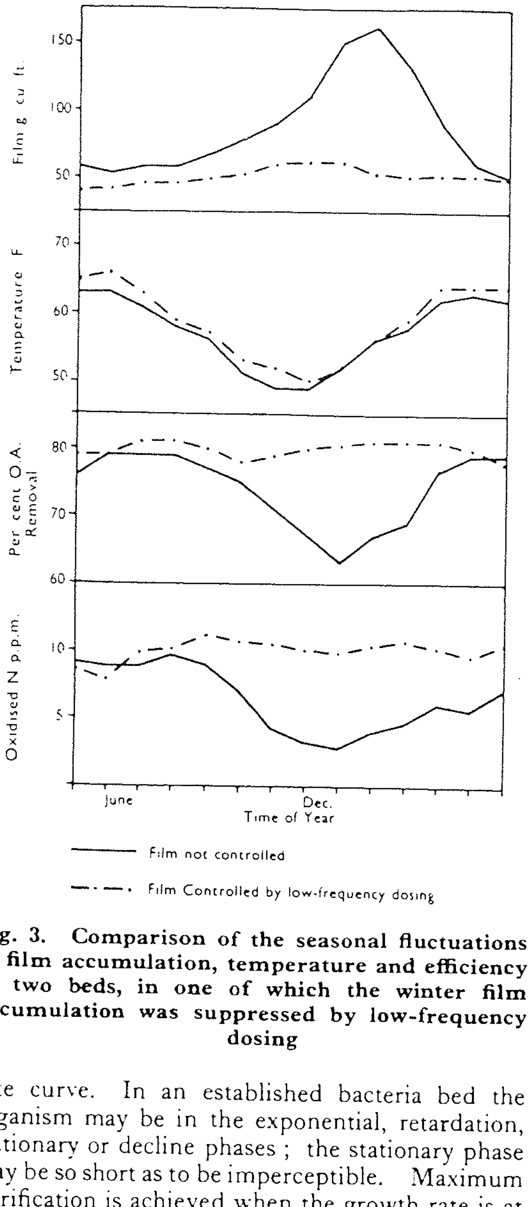

Fig. 3. Comparison of the seasonal fluctuations in film accumulation, temperature and efficiency of two beds, in one of which the winter film accumulation was suppressed by low-frequency dosing

rate curve. In an established bacteria bed the organism may be in the exponential, retardation, stationary or decline phases ; the stationary phase may be so short as to be imperceptible. Maximum purification is achieved when the growth rate is at a maximum, i.e. in the exponential phase. In this phase the only limiting factor, assuming the oxygen supply to be adequate, is the intrinsic rate of division of the organism. Conditions which terminate this phase and bring about first the retardation phase and then the decline phase are important. One cause is the exhaustion of the nutrients which first become limiting, successively reducing the growth rate to zero, when the cells begin to utilize materials of their own cell contents as a respiratory substrate, thus bringing about a decrease in the living mass. This decline phase is now usually known as the endogenous phase. Another cause of the termination of the exponential phase is the creation of adverse conditions by microbiological activity such as the accumulation of toxic metabolic products. In bacteria beds the thickness of film reducing the availability of oxygen is probably such a factor. Theoretically then, the film in a bacteria bed should be maintained in the active exponential phase of growth by preventing the degree of accumulation being reached at which this phase is terminated. Consideration must also be given to the distribution of film throughout the bed. Because of the reduction in concentration of the waste during purification as it passes through a conventional bed, most growth occurs at or near the surface. Although at times when such surface growths are sufficient to reduce the efficiency of the uppermost portion of the bed the film within the bed is still in the active log phase, the surface growths themselves may cause ponding which interferes with the distribution of the waste and with the aeration of the bed thus affecting the efficiency of the whole bed. Furthermore, because of the reduction in efficiency of the upper layer the film below receives a higher concentration of the waste, thereby increasing the growth rate of the organisms ; thus a downward growth of the film takes place, the efficient portion of the bed being successively reduced and the nitrification zone lowered or eliminated. During the unloading of the film the reverse probably occurs, the lower accumulation of film being discharged first. On most works not only must bacteria beds be operated

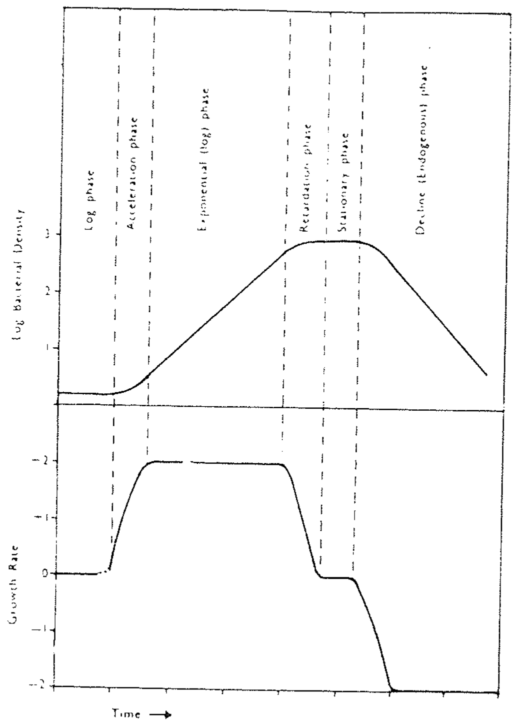

Fig. 4. Characteristic growth curves of cultures of micro-organisms (After Monad[10])

efficiently but also without causing nuisance. Nuisance from flies, such as *Psychoda spp* and *Anisopus fenestralis*, has caused serious trouble. Synthetic insecticides are being used successfully in controlling these flies but such a practice is considered ecologically unsound for the following reason. The occasional application of insecticide resulting in a reduction in the insect population causes an upset in the ecological balance and may result in a rapid increase in film which is then available to support an increased fly population. Continuous application of insecticide may bring about a change in the type of grazing fauna to one which causes no nuisance. Such conditions are however expensive to maintain and when insecticide applications cease the original fauna is rapidly re-established (Hawkes[11]). The greatest factor limiting the fauna population in most bacteria beds is the amount of food, i.e. the film accumulation. The ideal way of controlling the fauna population and preventing nuisance is then by limiting the film accumulation. Thus for efficient purification and for prevention of nuisance, control of film accumulation is desirable.

FACTORS AFFECTING THE DEGREE OF FILM ACCUMULATION

The rate at which film accumulates is the difference between the rate of growth and the rate of removal :

Rate of accumulation = Rate of growth—Rate of removal.

Simple though the equation is, it is essential to appreciate the two components determining the rate of accumulation and in considering the various operational factors, their effect on both must be taken into account.

Rate of Growth

With the development of continuous culture methods in industry the need to maintain a constant bacterial population within the culture tubes has stimulated work on factors controlling the growth rate of micro-organisms (Novick[12]). The findings of such work are of interest when applied to micro-organism populations in bacteria beds. Although, as shown in Fig. 4, the growth rate of organisms in the exponential range is constant and at a maximum, if organisms in such a physiological state are subjected to conditions of restricted food supply (and even a single nutrient factor may be limiting) then the growth rate is reduced. This indeed is one of the causes terminating the exponential phase of growth, but the organisms remain for some time capable of exponential growth when food no longer limits growth. The relationship between growth rate and food concentration may then be represented by the latter portion of the curve in Fig. 4 reproduced in Fig. 5, assuming the stationary phase to be insignificant.

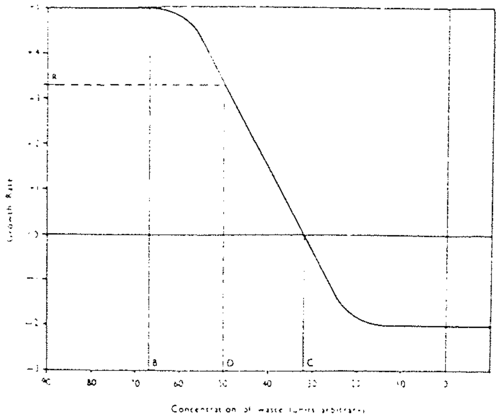

Fig. 5. Relationship between growth rate of micro-organisms and nutrient concentration

A similar graph was conceived by Sawyer[13] relating the rate of synthesis to food supply during biological treatment. At high food concentrations food is not limiting and the growth rate is determined by the minimum generation time of the organism. Below a certain concentration *B* however at which food becomes limiting, there is a successive decline in the growth rate with decreasing food concentration until the rate is 0 at concentration *C*—which is above 0 food concentration. Below this concentration auto-oxidation of the cells takes place producing a negative growth rate.

In continuous culture work a constant bacterial population is maintained by limiting an essential nutrient such as an essential amino acid, or sources of C.N or P at such a concentration *D* that the resultant growth rate *R* is equal to the washout rate which is determined by the flow-through rate of the system. The system is self regulating, for if the bacterial population within the tube tends to rise the concentration of limiting nutrient is reduced, resulting in a fall in the population and vice versa.

Attractive as this method of controlling a bacterial population is, it cannot unfortunately be applied to bacteria beds where the micro-organisms form a zoogleal film and are not lost at a steady rate.

Nevertheless, the fundamental theory on which such control is based is of importance in considering the growth rate of film in relation to the concentration of the waste. Reference will be made to this relationship later in the paper in discussing practical methods of film control. For the present it is sufficient to conclude from the above that the growth rate of the film is likely to be affected by the concentration of the waste. Even "strong" sewages are not concentrated nutrients compared with some media and it is considered that in most bacteria beds the growth rate of organisms is controlled by limiting nutrients. This is supported by Tomlinson's[14] conclusion that "the rate of growth of film depends upon the strength of the sewage quite apart from the rate of application"—a fact confirmed by the author's own findings[15]. The concentration at which a nutrient becomes limiting and the concentration at which the micro-organisms enter the endogenous phase differ with different micro-organisms. It is possible that fungi require higher concentrations than bacteria and therefore with decreasing nutrient the fungi pass into the declining growth phase and into the endogenous phase before bacteria. The nature of the waste largely determines the nature of the film and different types of film have different growth rates; for example, in breaking down the same amount of glucose, several common bacteria bed fungi increased more than did zoogleal bacteria (Water Pollution Research[16]).

The rate of growth of micro-organisms is also affected by temperature—the rate increasing with rising temperature up to an optimum which with the possible exception of some fungi is rarely reached in bacteria beds in this country. Increase in temperature also increases the metabolic rates of the organisms and if food is limiting then it could be expected that at higher temperatures the same food concentration would support a smaller population and thus the resultant film accumulation would be less. Lamanna and Mallette[17] state "Temperature is a most important variable in determining total growth, and the greatest crops are obtained below the temperatures giving the most rapid growth". This effect is quite apart from the effect of temperature on the removal rate by the predatory activity, discussed later, and is probably a contributory factor in determining the seasonal fluctuation of film in bacteria beds.

Rate of Removal

Besides the decrease in film resulting from auto-oxidation in the endogenous phase, considered here as negative growth, other agencies contribute to the removal of film. British workers consider that the grazing activity of the macrofauna is the primary agency of removal (Harrison[18], Johnson[4], Bell[19], Lloyd[5], Reynoldson[20] and Tomlinson[14]). Tomlinson[21] however has also reported the bacterial attack on hyphae of starving fungi. American workers, on the other hand, have tended to lay greater stress on the scouring by the liquid and on the activity of the micro-organisms in the film, the activity of the macrofauna being considered incidental or at most having a minor role. (Lackey,[22] Holtje[23], Heukelekian[24], Cooke and Hirsch[25]). Usinger and Kellen[26], however, considered that the larvae of *Psychoda* were important in film removal, thereby improving the efficiency of the bed.

These different views may to some extent be explained by the higher rate of filtration practised in America in which the grazing fauna probably play a less important role. It is also probable that the relative importance of the different contributory factors varies with films of different natures such as bacterial, fungal or surface algal growths. Some of the causes suggested by American workers could only be operative if the film is dominated by fungus (Holtje[23]), and anaerobic decomposition of the film is more likely to be important when considerable film accumulation has taken place. A further possible source of misunderstanding is the assumption that the factor causing the seasonal unloading is necessarily the same as that which is responsible for the continuous removal of film throughout the year. Observations at Birmingham have confirmed that grazing organisms play an important role in removing film, although there is evidence of other agencies also being operative especially when the film is dominated by fungus. The rate of removal of organic film by grazing fauna will depend upon the number of grazing organisms and their activity, which increase with temperature. As previously stated, in assessing the effect of the various factors on the rate of film accumulation the differential effect on the growth rate and removal rate must be considered. Such effects of the more important practical factors will now be discussed.

Some Operational Factors Affecting the Film—Grazing Fauna Balance

Nature of Waste

Strong wastes not only encourage the rapid growth of film but restrict the species of grazing fauna; the overall effect is to favour film accumulation. Because of the differential toxicity to film and fauna, some wastes whilst suppressing the grazing fauna permit film growth, and thus again favour film accumulation.

Size of Medium

The size of the medium in a bed has probably more effect on the grazing fauna than on the film. With large medium excessive film accumulation can be better accommodated, with the result that

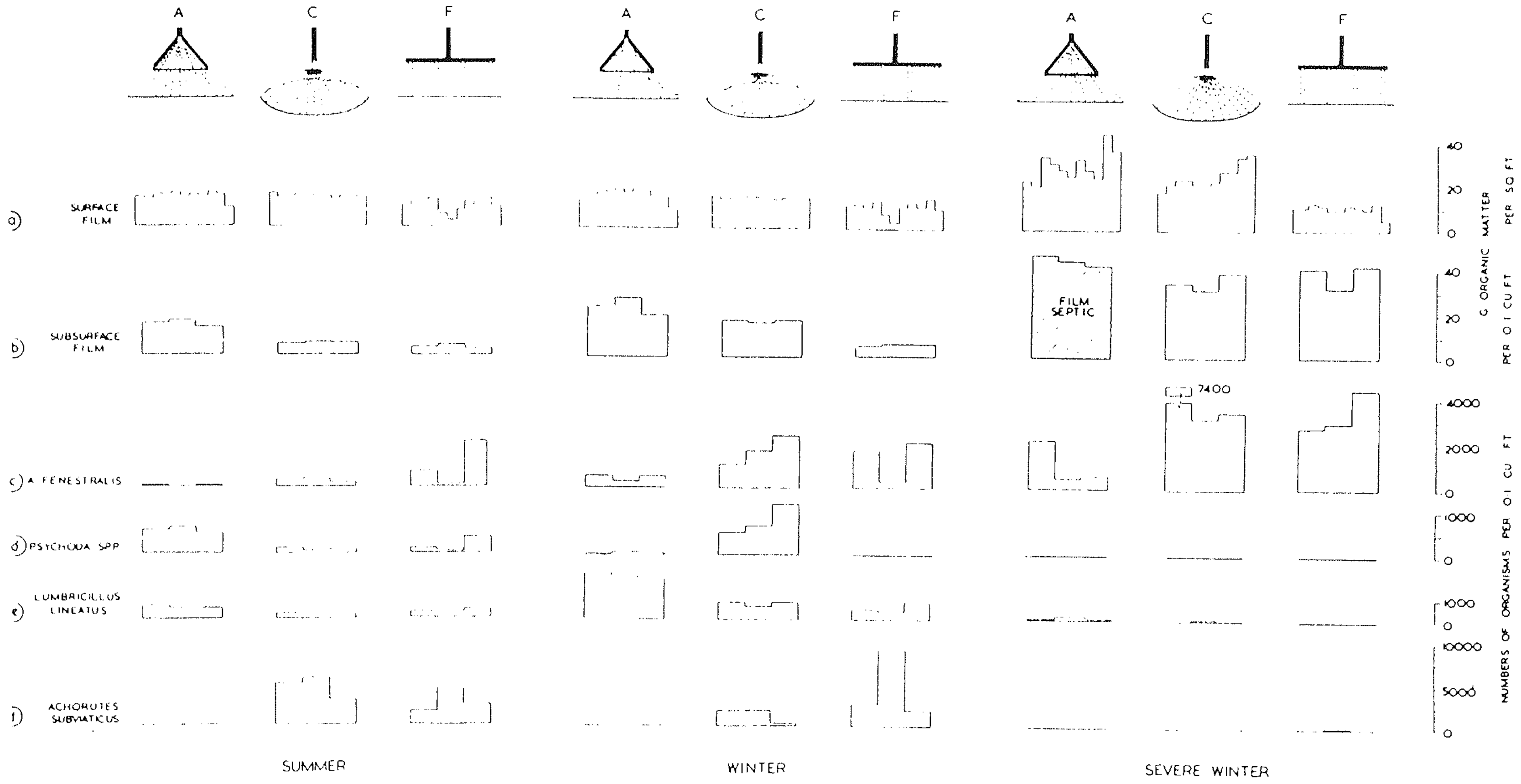

Fig. 6. Comparison of film and fauna in a bacteria bed under three types of nozzle arranged on one distributor, each discharging equivalent volumes of sewage.

(A) Fish tail, in which the jet from the $\frac{7}{8}$ in. diam. nozzle is discharged over a triangular tray slightly inclined from the vertical to produce a sheet of liquid approximately 24 in. wide at the surface of the bed. (C) Splash-plate—a circular disc $2\frac{1}{2}$ in. diam. on to which the jet was first allowed to impinge, producing a circular sheet of approx. 24 in. diam. (F) 'Quad'-jet—whereby the jet was divided into four by means of a horizontal pipe having four $\frac{1}{2}$ in. holes through which the sewage discharged downwards on to the bed as four jets 6 in. apart. The average conditions are shown for (a) summer, (b) mild winter, and (c) severe winter and increased loading the efficiency is less affected (Hawkes and Jenkins[27]), and in the case of a chemical works waste which discourages grazing fauna (Wilson[28]), enables purification at high dosage rates to take place. Under clean conditions with sewage, however, it was found that the smaller medium was superior. Beds should however be designed to prevent excessive film accumulation and not to accommodate it and if these ideals can be achieved, the smaller medium is to be preferred. The surface nature of the medium also probably affects the fauna more than the film. Smooth surfaces as on gravel are able to support an efficient slime growth although the initial log phase, when maturing the bed, may be somewhat longer than with medium having a rough surface. However, the latter medium, especially if pitted, provides a more hospitable environment for the grazing fauna.

The Force With Which the Waste is Applied to the Bed

It is claimed that film accumulation can be prevented by flushing the waste on to the bed. The success of several filtration processes has been attributed to this physical scouring provided by the high instantaneous dosage rate. The downward rate of flow through the bed affects both film and fauna and it is considered that the effect on the film is restricted to the surface of the bed and that below the surface the fauna is affected to a greater extent than the film; heavy downward rates of flow however are probably more effective in removing humus solids previously detached by other means such as grazing activity. Thus by increasing the instantaneous rate of application the film accumulation within the bed could be increased because of the suppression of the grazing fauna. The results of tests carried out to compare six different types of nozzle on the same arm of a distributor support this view (Hawkes[29]). Comparing the surface growth and the film accumulation and fauna below the surface under three of the different types of nozzle through which the sewage was applied to the bed at different velocities, it will be seen (Fig. 6) that the film accumulation below the surface was greatest under the fish-tail nozzle (A) which applied the sewage at the greatest force. Except for the *Lumbricillid* worms, the grazing fauna was less frequent under this nozzle. Of the other two, the splash plate C, although permitting the establishment of grazing fauna, created uniform conditions which resulted in the different species occupying the one niche and therefore being in direct competition; as a result, the *Achorutes* only became abundant when the *Anisopus fenestralis* population was reduced in the summer. The two niches provided by the 6 in. spaced jets of F enabled the two species to co-exist. Since the continuous grazing activity of the two populations is considered desirable, jets spaced at 6 in. were preferable to even distribution.

Temperature

Seasonal fluctuations in bed temperature, although less than the fluctuations in air tempera-

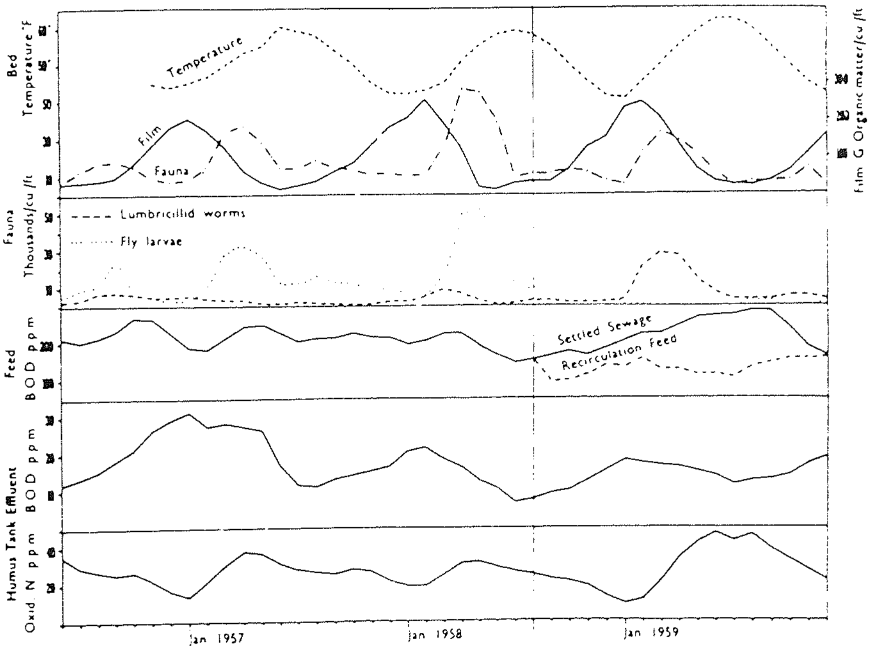

Fig. 7. **Seasonal fluctuations in temperature, film, fauna and resultant efficiency of beds treating domestic sewage**

ture, also have a complex differential effect on the film—fauna balance. The rate of increase and activity of both film and fauna is generally greater at higher temperatures within the range usually experienced in beds. Moreover, it is likely that coagulation or deposition of organic matter is unaffected by normal summer and winter variations in temperature. Low temperatures suppress the grazing activity to a greater extent than they reduce the growth rate of the film and this differential effect is considered to account for the winter accumulation of film. Fig. 7 shows the relationship between temperature, film, fauna and resultant efficiency in beds treating domestic sewage.

The increase in film accumulation occurs at times when low temperatures suppress the grazing fauna. Reduction in film occurs when the temperature is increasing, permitting increased grazing activity. Following the removal of the film there is a collapse of the grazing fauna population due to limited food supply; with the subsequent recovery in the film later in the summer the fauna commences to increase but the falling temperature suppresses the fauna population and the winter accumulation again results. The adverse effect on efficiency of the winter conditions is shown by the increase in 5-day B.O.D. and decrease in oxidized nitrogen in the effluent. The effects of introducing recirculation are also shown in the figure and will be discussed later.

Fluctuations in film accumulation in beds treating industrial sewages may be due to other causes (Hawkes[9]). Temperature effects on the bacteria fungi competition may be of importance in such beds. Even if they are not responsible for the seasonal fluctuation, the grazing fauna have an effective controlling influence on such growths and can limit the winter accumulation.

Practical Methods of Maintaining the Film—Fauna Balance at a Low Level

Having established the desirability of maintaining the film at a low level and having discussed the several factors influencing the degree of accumulation, it now remains to consider some operational methods by which such conditions can be maintained in practice. Consideration of the equation

Rate of Accumulation =

Rate of growth—Rate of removal

$$(R_a) = (R_g) - (R_r)$$

shows that to maintain R_a at zero, i.e. to prevent accumulation, two theoretical alternatives present themselves. One method is to operate the bed so that R_g is a maximum for the waste being treated and maintain conditions so that $R_r = R_g$. The alternative is to control R_g by operational means so that $R_g = R_r$ under the operating conditions imposed. The two alternatives are thus basically different and are, as we shall see, to some extent incompatible.

Of the two, the former, whereby maximum growth rate and activity of the film are encouraged but the accumulation is maintained at a low level by a dominant grazing fauna, is preferable. The low level of film accumulation would result in severe competition for the limited food by the grazing fauna. The percentage number of larvae which successfully pupate, before emerging as adults, decreases with decreasing food supply. Under conditions of limiting food much of the available food is wasted to the fly population by the death at different stages of development of larvae which had used some of the available food. This phenomenon, known ecologically as a "scamble", is attractive as a method of achieving the benefits of an insect population without involving nuisance of a large adult population. It is a self-regulating mechanism in that the fewer eggs produced by the reduced fly population would result in less severe competition and a resultant lower death rate of the larvae.

Unfortunately, it is only with lightly loaded beds treating weak sewages that conditions suitable to support this balance can be maintained throughout the year. In other beds, although at summer temperatures such conditions may prevail, the lower winter temperatures result in accumulation of film for reasons previously discussed. If the rate of accumulation is slight it may be that the resultant accumulation throughout the winter months is not sufficient to affect the efficiency of the bed before the spring unloading takes place. In other more heavily loaded beds or those in exposed sites, the greater accumulation of film results in decreased efficiency. In both cases the unloading in the spring, usually brought about by an increased grazing population, uncontrolled by the available food, is associated with a potential fly nuisance. A further aspect is that by permitting this winter build-up of film, the increased humus sludge produced during the resultant spring unloading imposes an increased load on the digestion plant when it is least able to cope with it (Winsor[30]).

Since low winter temperatures are probably the limiting factor in this method of film control, design of the plant to restrict the winter fall in temperature appears desirable. The choice of the site is important in this respect and sites exposed to the cold N.E. winds should be avoided. Enclosed beds are also obviously an advantage from this point of view.

In most beds, however, because of the nature and strength of the waste and the economic necessity of operating at high rates, the grazing fauna is not able to dominate the film and the alternative method by controlling the growth rate (R_g) has to be applied. Of the advantages claimed for the modified methods of filtration commonly practised, such as recirculation, alternating double filtration, and low frequency dosing, the control of film accumulation is common to all. The method by which this is achieved however has been variously described; some consider that the flushing action resulting from the higher rate of instantaneous application is the cause, others consider that the nutritional control is the operative factor. In the light of the results reported above it is considered that the flushing action can have little effect in removing film from within a bed at the usual rates of application practised in this country. An understanding of the controlling mechanism is not only of academic interest but essential for its successful application and for the diagnosis of the cause of failure should this occur. As a contribution to this understanding, these different methods of filtration will now be discussed as film controlling processes. This should in no way detract from the other advantages claimed for the different methods.

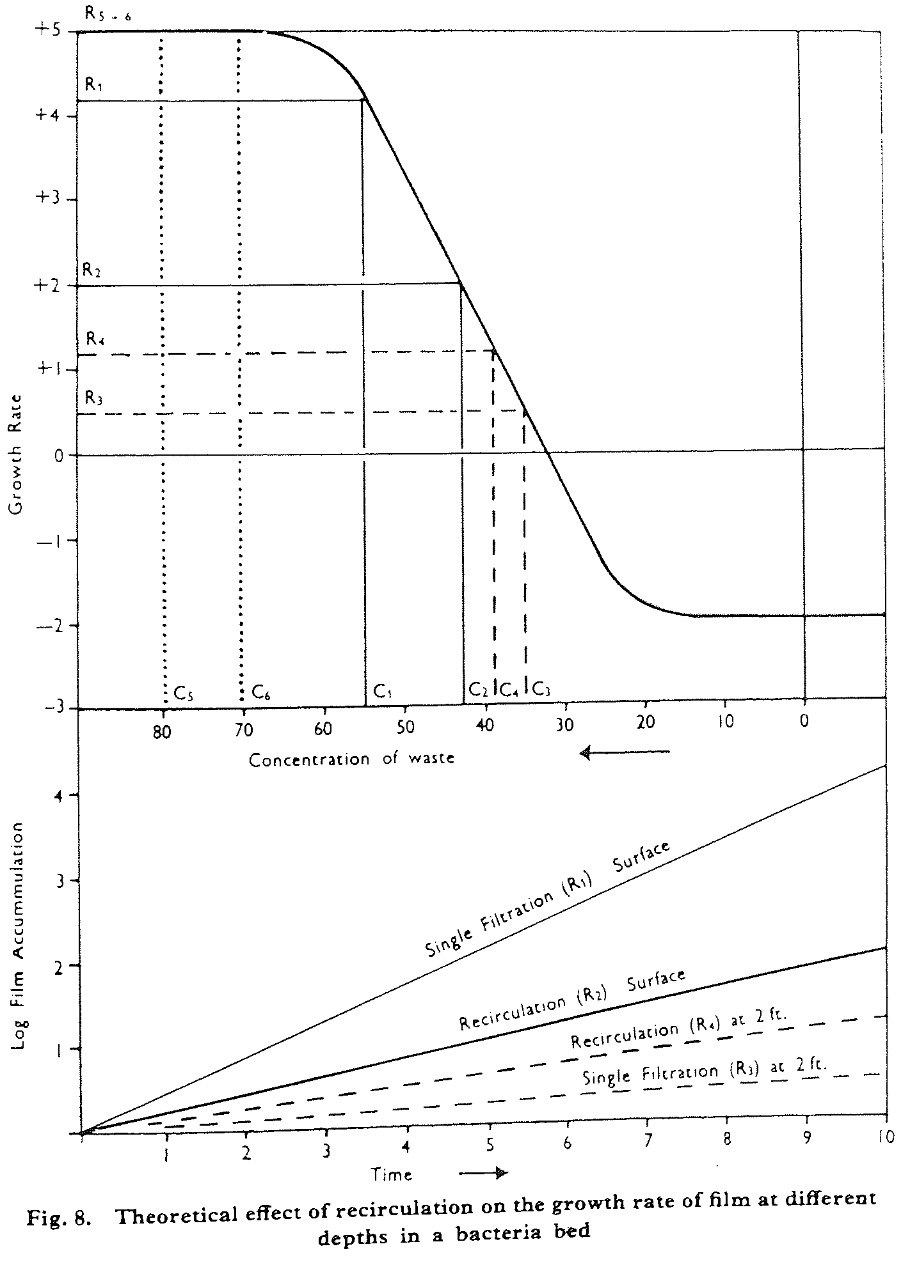

Fig. 8. Theoretical effect of recirculation on the growth rate of film at different depths in a bacteria bed

Recirculation

Ecologically the most important features of recirculation, whereby the waste is diluted with returned effluent before being applied to the bed, are (1) dilution of the feed and (2) corresponding increase in the hydraulic load. As shown in Fig. 8, these two factors influence the growth rate of the film and its distribution throughout the bed.

Assuming the waste has a concentration C_1 giving an arbitrary growth rate R_1 on the surface of a bed operating on single filtration, by introducing recirculation, reducing the concentration of the feed to C_2, the resultant growth rate is reduced to R_2. Consider now the growth rate within the bed, say at a depth of 2 ft. With single filtration suppose the concentration C_1 has been reduced to C_3, giving a reduced growth rate R_3. With recirculation, because of the higher hydraulic loading the reduction in concentration in the upper 2 ft. of bed is less than with single filtration and the resultant concentration C_4 may well be higher than the concentration C_3 at the corresponding depth in the bed operating by single filtration. This was in fact found to be so by Lumb and Eastwood[31]. As a result, the growth rate of the film within the recirculating bed at a depth of 2 ft. is greater than in the conventional bed. These results would account for the reduction in amounts of surface film and the more even distribution of

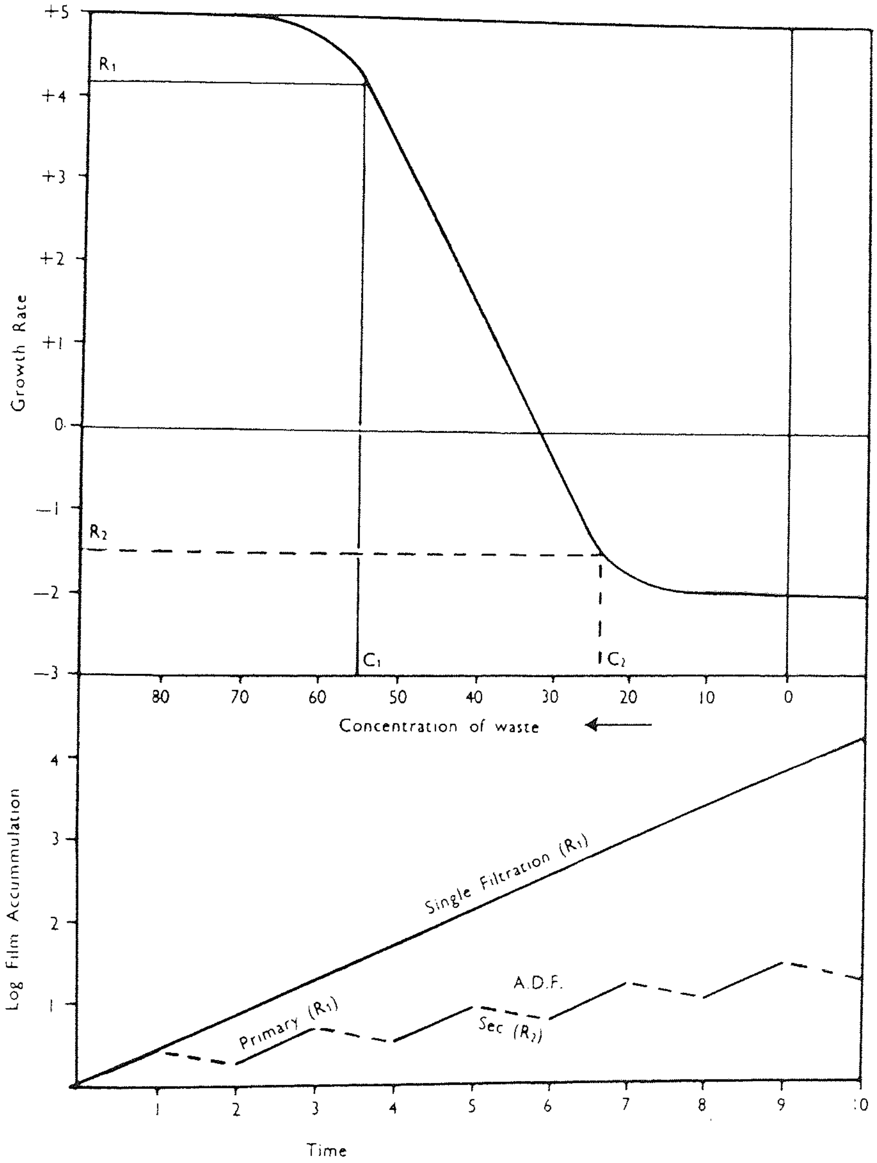

Fig. 9. Theoretical effect of alternating double filtration on the growth rate of film during the primary and secondary stages

film throughout the depth of the bed with recirculation. A greater depth of the bed is thus used for carbonaceous oxidation thus restricting the zone of nitrification.

To effect this reduction in film growth at the surface it is essential that the dilution of the feed is sufficient to result in a concentration which falls on the slope of the growth rate curve. It could be that with strong wastes C_5, and a low recirculation ratio the resultant diluted feed C_6 would have the same growth rate $R_{5,6}$, on the surface of the bed, the concentration of the feed C_6 not being growth controlling.

Besides this effect on the growth rate R_g, recirculation may also affect the removal rate R_r by changing the numbers and type of the grazing fauna. The increased hydraulic rate of application tends to reduce fly larvae such as *Psychoda*, although the more prehensile *Lumbricillid* worms persist and with the reduced interspecific competition they may increase in numbers, as mentioned by Lumb and Eastwood[31]. This change in dominance from fly larvae to worms took place when partial recirculation was introduced at Langley (Birmingham), as shown in Fig. 7. It will be seen that in this case recirculation did not prevent film accumulation and it would appear that the *Lumbricillid* worms were less active in removing film than the larval population they had replaced, for the spring unloading was slower. Although the beneficial results of film control were not achieved there was nevertheless a reduction in the B.O.D. of the effluent at times of film accumulation compared with previous winters ; nitrification was however less. During the following summer of 1959, which was hot, the stronger sewages made comparison with previous years difficult. Under such conditions almost complete nitrification was achieved with recirculation. The improved efficiency in spite of failure to control film accumulation suggests that there are other important factors involved in recirculation, as discussed by Lumb and Eastwood[31], and Wilson and Harrison[32]. It is considered, however, that had recirculation succeeded in controlling the film the results would have been better especially in terms of nitrification.

Alternating Double Filtration (A.D.F.)

The process of A.D.F., in which the waste is treated on a pair of beds in series, each bed alternately becoming primary and secondary in successive periods, was first conceived by O'Shaughnessy[33] as a means of controlling excessive film growth. He had observed that excessive accumulations on beds could be removed by applying the effluent from a bioflocculation plant. Thus from the beginning it was acknowledged that the control of film growth was an important feature of A.D.F. Tomlinson[34] demonstrated that this was due to a starvation effect during the secondary stage of the process during which the film decreased in amount. This is again explicable in terms of the growth curve (Fig. 9).

During the primary stage the growth rate at the surface R_1 is determined by the concentration C_1 of the waste and is the same as that on the surface of a conventional bed treating the same waste. During the secondary stage the film is subjected to the primary bed effluent of concentration C_2 giving a negative growth rate R_2. Thus, the resultant growth rate $\frac{R_1 - R_2}{2}$ is less than R_1, the rate on the surface of a conventional bed. Because of the higher hydraulic loading the film is distributed more evenly throughout the depth of the bed as in recirculation. The total amount of film however is less than in single beds treating the same waste, since with A.D.F. all the film is subjected to the negative growth phase in the secondary stage whereas in a conventional bed the bulk of the film in the upper portion of the bed is never subjected to starvation conditions and the resultant negative growth rate. Thus the principle of A.D.F. is based on a fundamentally sound theoretical basis.

Experience of Pilot Plant and Large-scale Operation of Alternating Double Filtration at Minworth (Birmingham)

The development of A.D.F. for the purification of sewage was carried out at Minworth by the W.P.R.L. and, as a result of long term investigations, Mills[35] concluded that it was possible to treat the industrial Birmingham sewage at a rate of 240 gal./cu.yd./day by A.D.F. On the basis of this success a section of the bacteria beds at Minworth (8·8 acres) were converted to operate on A.D.F. (Daviss[36]). Since completion in 1956 observations on the degree of film accumulation and efficiency of the plant have been studied, and comparisons made with the original experimental plant which continued to be operated as an A.D.F. unit. It should be pointed out that because of the increased strength of the sewage and the increase in trade effluents since the earlier work was done, the rate of 240 gal./cu.yd./day was no longer practicable. In the later work by the W.P.R.L. the average rate of application was 150 gal./cu.yd./day and this was the rate at which the unit was operated as a pilot plant for comparison with the large-scale plant. For the first year after maturing the latter was operated at approximately 100 gal./cu.yd./day with the intention of gradually increasing the rate ; however, it was not found possible to exceed the rate of 135 gal./cu.yd./day and obtain a satisfactory effluent throughout the year.

Comparisons of film accumulation and effluent quality of the pilot and large-scale plants are made in Fig. 10. It will be seen that the film accumulation in the large-scale plant was greater than in the pilot plant and the winter accumulation was sometimes greater, and when this occurred the final effluent was markedly inferior to that of the pilot plant especially in terms of nitrification. Thus the large-scale plant was not successful in achieving one of the objects of A.D.F., i.e. the prevention of excessive film accumulation. In diagnosing the cause of this shortcoming it is significant that the periods of excessive film accumulation occurred at times when the effluent from the primary bed was inferior. Under such conditions the film would not be subjected to starvation conditions during the secondary stage and thus no reduction in film would result. The deficiency in carbonaceous oxidation of the primary stage was to some extent made good by the increased efficiency of the secondary stage, but this was not so with nitrification which was most seriously affected under such conditions. To control film effectively using A.D.F. a primary effluent must be produced which will ensure that in the secondary stage the film is in the endogenous phase. With recirculation and A.D.F. an accumulation of film which results in a decrease in quality of the primary effluent causes a further increase in the film and thus conditions progressively deteriorate until eventually the process breaks down. To account for the lack of accumulation of film in the pilot plant another factor controlling film must be considered, i.e. the frequency at which successive doses of sewage are applied to the bed.

FREQUENCY OF DOSING

Early in the history of bacteria beds it was reported in evidence to the Royal Commission on Sewage Disposal[37] that intermittent dosing of

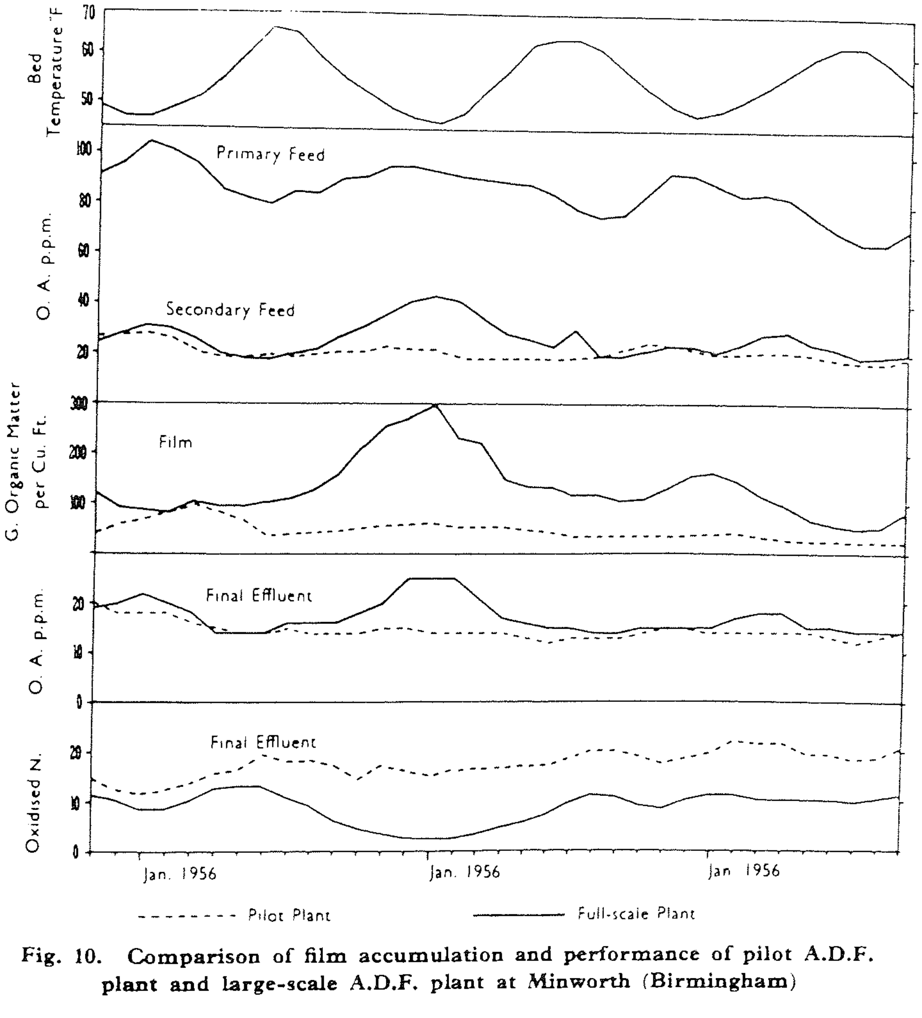

Fig. 10. Comparison of film accumulation and performance of pilot A.D.F. plant and large-scale A.D.F. plant at Minworth (Birmingham)

beds limited the growth of film. It is of interest to note that one of the first bacteria beds to be operated at the Lawrence Experimental Station, Massachusetts, (1890) was dosed intermittently at 20 min. intervals[38]. At the beginning of the century one of the early experimental circular beds at Birmingham had a distributor consisting of a long trough pivoted about a central supply pipe and mechanically driven to rotate once every 7 mins. by means of a 2 h.p. oil engine, the outer end of the distributor travelling along a circular mono-rail[39].

Lumb and Barnes[40] at Halifax found that by slowing down the speed of rotation of a 4-armed distributor, the condition and performance of the bed was improved. Tomlinson and Hall[41] investigated the effect of frequency of dosing on beds operating on A.D.F. They concluded that for the four-arm distributors the optimum speed of rotation under their conditions of experiment was between 15-50 mins. per rev. During the later period of these investigations comparisons of the seasonal fluctuations in film accumulation and fauna in low and high frequency dosed beds were made. The results of these are reproduced in Fig. 11 together with results of subsequent observations on these beds. Before 1957, when the beds A and B were dosed at high frequencies—the distributors being self-propelled—they accumulated excessive film each winter, whereas the low frequency dosed beds C and D on which the distributors were mechanically rotated at speeds between 30-35 mins. per rev. had a uniformly low film content. There was also a most remarkable effect on the fauna. The fly population was almost eliminated in the low frequency dosed beds (C and D) ; this was partly due to the decreased food supply and also to the greater downward rate of flow of the sewage suppressing the larval population within the bed. The more strongly prehensile *Lumbricillid* worms, however, were better able to withstand the flow of sewage and in the absence of competition from other species were more numerous in the low frequency dosed beds. Thus low frequency dosing created ecological conditions which not only maintained a low film accumulation necessary for efficient purification but also prevented fly nuisance by changing the fauna from one dominated by flies to one dominated by worms.

The difficulties of simulating on rectangular beds having reciprocating distributors the hydraulic conditions of a circular bed having a four-armed distributor with staggered jets has been discussed previously. It would appear that the frequency of dosing on the large-scale A.D.F. plant at Minworth, on which the distributors complete a travel dosing in both directions in approx. 6 mins., is too high to prevent film accumulation even on A.D.F. Consideration is being given to providing distributors with variable speed drives.

Towards the end of 1956 variable speed drives were fitted to the distributors on beds A and B so that they could be rotated for experimental purposes at 50 different speeds between 1 rev. per min. to 1 rev. in 60 mins. After maturing they were again operated as an A.D.F. unit under identical operating conditions as the C-D unit, both treating the same sewage at an overall rate of 150 gal/cu.yd./day; all four distributors revolved once every 15 mins. Fig. 11 shows that the reduction in speed of rotation of distributors A and B resulted in the control of film accumulation and a reduced fly population. The increased worm population in the C-D beds was probably due to the increase in frequency of dosing from 30 mins. to 15 mins.

Application of Low Frequency Dosing to Double Filtration

In comparing the different methods of filtration, several workers found that although under favourable conditions double filtration (D.F.) gave good results, the tendency of the primary bed to clog during the winter made it a less favourable process than recirculation or A.D.F. The success of low frequency dosing in controlling film accumulation suggests that this could be used to control the film in the primary bed of a double filtration plant. To investigate this possibility, beds A and B were operated as primary and secondary beds respectively of a double filtration unit ; the bed conditions and efficiency were compared with the A.D.F. unit C-D. The overall rate was the same, viz. 150 gal/cu.yd./day in the first attempt ; following the conventional operation of double filtration, the rate to the primary bed (A) was 450 gal./cu.yd./day and to the secondary (B) 225 gal./cu.yd./day—assuming two secondary beds and one primary bed. Even with low frequency dosing, however, there was a marked increase in the film in the primary bed as shown in Fig. 11 ; the test was therefore discontinued. After a short period of reconditioning a second attempt was made ; this time the flow to the primary and secondary bed was the same, i.e. 300 gal./cu.yd./day. As shown in Fig. 11, at this dosage low frequency dosing successfully controlled film accumulation throughout the two winters 1958-9 and 1959-60, the rate of rotation being 1 rev. in 20 and 30 mins. respectively in the winters and 15 mins. in the summer. The absence of ponding and the remarkably healthy condition during the winter of the primary bed treating strong industrial sewage at 300 gal./cu.yd./day (0·63 lb. B.O.D./cu.yd./day) was noteworthy. During the hot summer of 1959 the primary bed tended to become anaerobic and there was a marked decrease in the grazing fauna of worms. The film did not increase and the efficiency of the bed was not seriously affected. The secondary bed, with the distributor revolving once every 15 mins., remained very clear and acted chiefly as a nitrifying bed. The investigation is being continued and will be reported fully later; the results of 16 months operation, summarised in Table 1, show that the final effluents from the A.D.F. and D.F. units were very similar, the nitrification in the latter being superior for some periods. If low frequency dosing of the primary bed results in D.F. being as efficient as A.D.F. it could be that D.F. is preferable since it would then be possible to differentiate in design and operation between the two beds, e.g. in having smaller sized medium in the secondary bed and a more rapidly revolving distributor and the possibility of treating primary and secondary at different rates.

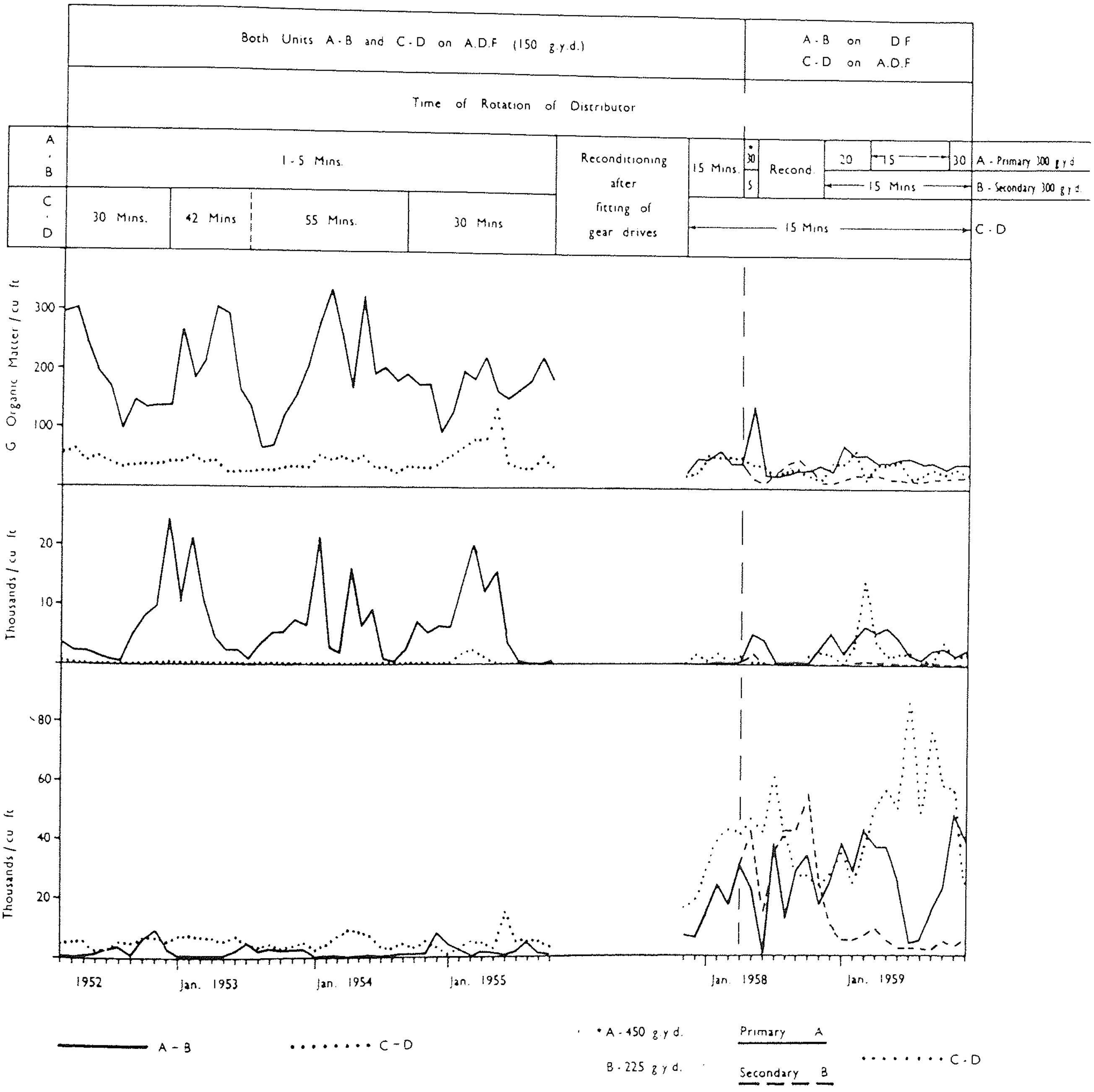

Fig. 11. Comparison of film accumulation and fauna in two pairs of beds A-B and C-D, operating under the range of different conditions shown

TABLE 1

COMPARATIVE RESULTS OF PRIMARY AND SECONDARY EFFLUENTS FROM A DOUBLE FILTRATION UNIT (D.F.) AND AN ALTERNATING DOUBLE FILTRATION UNIT (A.D.F.), BOTH TREATING THE SAME INDUSTRIAL SEWAGE AT 150 GAL./CU.YD./DAY

	4 Hr. O.A. p.p.m.							B.O.D., 5 Day, 20° C. p.p.m.						
	1958 Nov. Dec.	1959 Jan. Mar.	1959 Apr. June	1959 July Sept.	1959 Oct. Dec.	1960 Jan. Feb.	Av.	1958 Nov. Dec.	1959 Jan. Mar.	1959 Apr. June	1959 July Sept.	1959 Oct. Dec.	1960 Jan. Feb.	Av.
Primary feed	78·9	99·0	86·9	79·9	86·2	83·6	85·7	172·6	259·4	233·1	198·9	201·8	199·3	201·8
Primary tank eff (D.F.)	20·6	23·9	19·9	19·2	20·6	22·0	21·0	28·6	37·3	41·7	28·4	32·6	37·2	34·3
Primary tank eff (A.D.F.)	18·9	21·3	17·4	17·8	17·5	18·1	18·5	24·4	31·3	37·2	28·1	29·2	26·0	29·4
Secondary tank eff (D.F.)	16·0	17·2	15·8	14·4	14·5	14·5	15·4	21·3	20·5	24·6	15·1	17·7	15·9	19·2
Secondary tank eff (A.D.F.)	14·6	17·1	15·5	15·1	14·1	15·1	15·2	20·7	23·0	26·4	19·3	19·1	15·9	20·7

	Amm. N. p.p.m.							Oxidised N. p.p.m.						
	1958 Nov. Dec.	1959 Jan. Mar.	1959 Apr. June	1959 July Sept.	1959 Oct. Dec.	1960 Jan. Feb.	Av.	1958 Nov. Dec.	1959 Jan. Mar.	1959 Apr. June	1959 July Sept.	1959 Oct. Dec.	1960 Jan. Feb.	Av.
Primary feed	25·2	26·8	29·0	31·9	26·9	22·0	27·0	2·0	3·3	2·4	1·2	2·6	4·7	2·7
Primary tank eff (D.F.)	15·7	18·1	18·3	17·9	18·7	16·4	17·3	9·3	9·1	8·3	7·7	8·5	10·6	8·9
Primary tank eff (A.D.F.)	15·5	20·9	15·8	14·5	16·4	15·3	16·4	11·2	11·3	11·8	12·3	11·7	12·9	11·9
Secondary tank eff (D.F.)	5·3	6·7	5·4	4·9	9·8	8·1	6·7	20·8	22·7	20·3	20·2	19·2	20·0	20·5
Secondary tank eff (A.D.F.)	8·3	12·9	8·9	7·2	10·4	10·8	9·8	18·8	18·3	18·6	20·9	18·8	17·8	18·9

The results so far confirm those obtained by Peach[42] at Cheltenham and Tidswell[43] at Burton ; in the latter case the enhanced nitrification of the D.F. beds was even more marked.

Theory of Low Frequency Dosing

In many developments of biological filtration practice has led theory, and the practical success of low frequency dosing has since been explained by various theories. The resultant high instantaneous dosage rate is generally considered to be an important feature of the process. In view of the evidence reported earlier in this paper, however, the scouring effect of this high instantaneous rate is not considered to be an important factor in controlling film especially within the bed, although it probably does affect the fauna, the fly larvae being replaced by the more prehensile *Lumbricillid* worms. The film controlling mechanism of low frequency dosing is discussed later in this paper (after reporting some of the results of some tests carried out on the process).

Stanbridge[44] suggested that low frequency dosing may have advantages other than those attributable to the control of film. To investigate this possibility use was made of a circular bed which had a distributor fitted with variable speed drive. On several daily occasions the distributor was revolved at different speeds between 1 rev. in 3 mins. and 1 rev. in 60 mins., the speed on each occasion being chosen at random; the efficiency, as assessed by the percentage O.A. and B.O.D. removal and the amount of oxidised N. in the effluents, was determined. On the same occasion the efficiency of a similar bed receiving the same sewage through distributors revolving at a fixed rate was measured. The differences between the efficiency of the two beds on each occasion plotted against the rate of revolution of the distributor demonstrates any effect of frequency of dosing, apart from those resulting from film control, since during the short period of the tests the amount of film could be regarded as constant. As shown in Fig. 12 there was as expected, over the greater part of the range, between 15 mins. and 60 mins., a reduction in efficiency resulting from decreasing the frequency of dosing. There was however evidence that the optimum rate of revolution, for a clean bed, was between 10 and 15 mins. for a four-armed distributor with staggered jets. At speeds of revolution greater than these there appeared to be a lowering of efficiency. It is of interest to note that nitrification was only slightly reduced by low frequency dosing.

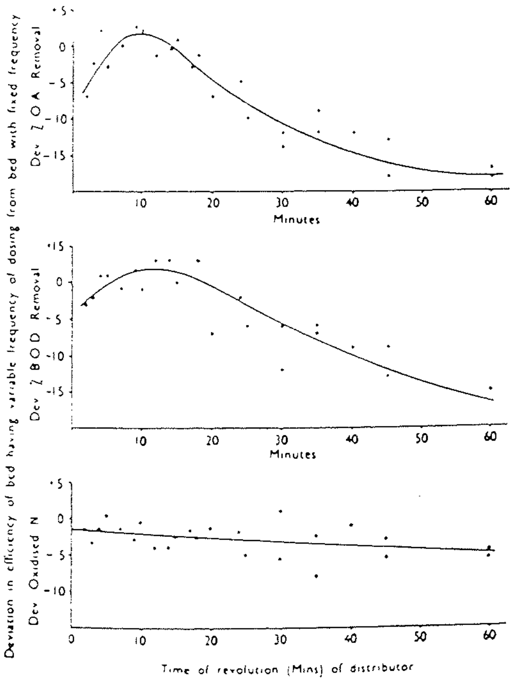

Fig. 12. Effect of frequency of dosing on the efficiency of a bacteria bed having only a low accumulation of film

It does not follow from these results that the optimum speed of rotation was 10-15 mins. per rev.; to control the film at limits which do not adversely affect the efficiency, it may be necessary to revolve the distributor at speeds slower than once every 15 mins., the resultant loss in efficiency more than being made good by the gain in efficiency resulting from the prevention of the film accumulation. The results nevertheless do indicate some advantages other than those attributable to film control, at least over the range 1-15 mins. per rev. Some such possible benefits of low frequency dosing have been discussed by Stanbridge[44]. He suggested that although the time of retention of some of the liquid is less with low frequency dosing this may be more than offset by the longer retention time of the liquid held interstitially between doses. Work reported by the Walter Pollution Research Laboratory[45] has shown that the mean retention time may be increased by decreasing the frequency of dosing. Below a certain frequency of dosing, however, the retention time is of course reduced. The results of times of contact on the beds at Minworth at different rates of revolution were somewhat inconclusive when determined by the salt method, using a sector of the bed.

It was observed that within a minute of the passage of the distributor arm over the section of the bed a flush of effluent was discharged from the bottom of the bed (Fig. 13). The peak concentration of the chloride appeared in the effluent within the first minute but was still being discharged in decreasing amounts three hours later. The reduction in chloride concentration in the effluent took place not at a steady rate but in a series of regularly timed steps; a drop in concentration coincided with the surges of effluent which immediately followed the passage of a distributor arm over the surface. It would appear that when sewage is applied to beds intermittently it passes into the bed as a surge mixing with the interstitial liquid; some of the mixed liquid is displaced in the form of a flush of effluent; the remainder is held interstitially until the next dose, only a small quantity draining away during this period. The amount held interstitially within the bed is therefore important in determining the efficiency of a bed intermittently fed, because whilst the liquid was held in the bed purification would be proceeding. It may well be that such a bed would be more efficient if constructed of medium smaller than the conventional medium used today; the low film concentration associated with the process would make this possible.

Low frequency dosed beds are thus quite different hydraulically and in the course of purification from conventional beds. In the

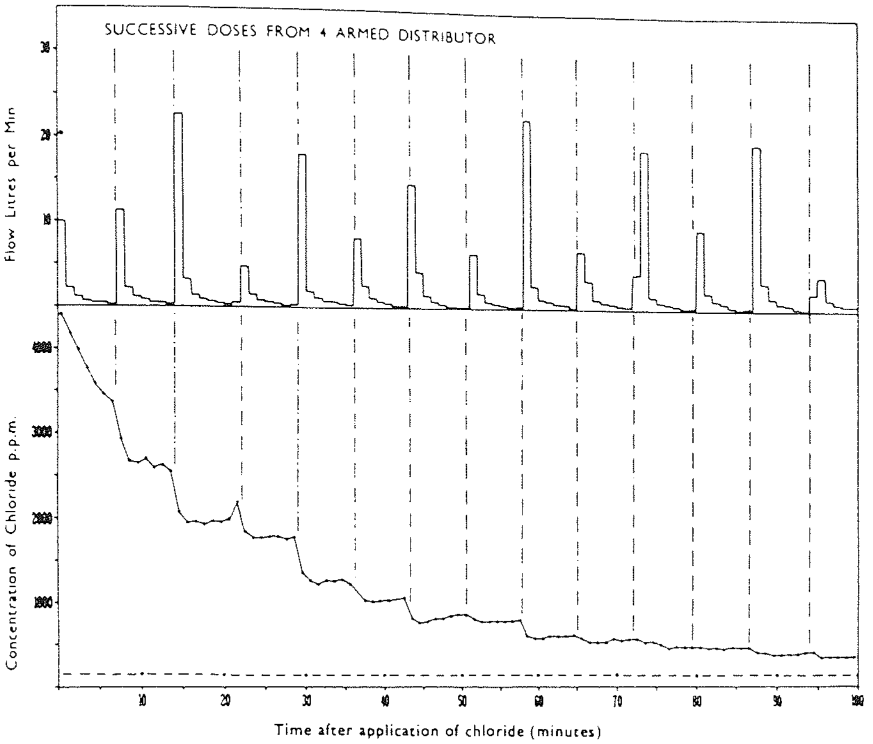

Fig. 13. The discharge of chloride from a sector of a bed for 120 minutes following one application of chloride to the surface, in relation to the frequency of dosing

latter the waste is considered to be oxidized as it percolates downward over the medium, this course of oxidation at different depths being expressed mathematically by Velz's equation[3]. In low frequency dosed beds the course of purification must be considered more in relation to time than depth. Certainly the concept implicit in the terms "percolating" or "trickling" filters is not applicable to low frequency dosed beds, which are better considered as surge filled aerobic contact beds. In view of the rapid mixing of feed and interstitial liquid they are in this respect homologous with the modern complete mixing activated sludge processes such as the Pasveer ditch[46].

Danckwerts[47] comparing the piston and complete mixing types of continuous flows through processing units generally, considered that because of the greater spread of the residence time with complete mixing and assuming the rate of the reaction falls off with the extent of the reaction, complete mixing types of reactor were less efficient than the piston flow type. With autocatalytic reactions (such as biological oxidation), however, it was considered that, because of the different rate of reaction curve, the completely mixed reactor may be superior. In applying these views to bacteria beds and activated sludge plants however it should be borne in mind that the log phase is probably absent.

A further advantage of low frequency dosing, it has been suggested, is that the higher instantaneous rate of dosage results in a greater volume of the bed medium being wetted and thereby the effective capacity of the bed is increased. To investigate this suggestion, the lateral spread of sewage applied to the surface of a clean bed as jets 12 ins. apart was assessed by collecting and measuring the sewage in twelve 2 in. wide adjacent trays placed parallel (tangential) to the travel of the jets so as to collect the liquid from an area 1 ft. × 2 ft. Measurements were made immediately above the surface of the bed and at three depths within the bed and at different speeds of revolution of the distributor arm. In each case the results were expressed on a percentage basis and are shown as histograms in Fig. 14. Most of the lateral spread occurred as the jet impinged on the bed surface ; there was however no indication that with slower speeds of revolution the lateral spread was greater.

Although other advantageous effects of low frequency dosing may exist, it is considered that the control of excessive film accumulation, with the resultant increased efficiency, is probably the most important effect. The means by which this is achieved remains to be discussed. Apart from the scouring effect, which is here considered not significant in controlling film, it has also been suggested that because of the infrequent applications of waste, the film is subjected to starvation conditions for some period between doses. To investigate this possible nutritional effect, samples were taken at minute intervals from side arm sampling channels collecting the effluents at 1 ft., 3 ft. and 5 ft. depths of the bed to measure the change in concentration between doses at 15 min. intervals as measured by the O.A. and B.O.D. Similar samples from the same bed being dosed at 1½ min. intervals were taken on the next day and the results of both tests, expressed as O.A. remaining per 100 p.p.m. O.A. applied, are shown in Fig. 15. Whereas only slight fluctuations in the strength of the liquid occurred at any one depth with the rapidly revolving distributor, when the distributor was revolved slowly there was a marked reduction in strength over the 15 min. period between doses, this being most marked at the 1 ft. level. Applying these results to the conventional growth rate curve, Fig. 16, it is found that at the 1 ft. level for more than two-thirds of the time the growth rate with low frequency dosing is considerably less than with high frequency dosing and may well pass into the endogenous phase towards the end of the period between doses. Within the bed at the 3 ft. level for half the time the growth rate would be higher with high frequency dosing, although at 5 ft. the growth rate would be higher with the low frequency dosing. This would account for the more even distribution of film throughout the depth of the bed with low frequency dosing. The results illustrate that with low frequency dosing the average concentration of nutrients available to the film in the upper layers is reduced. Thus the limitation of film in low frequency dosing could be accounted for by nutritional control as it is in recirculation and A.D.F.

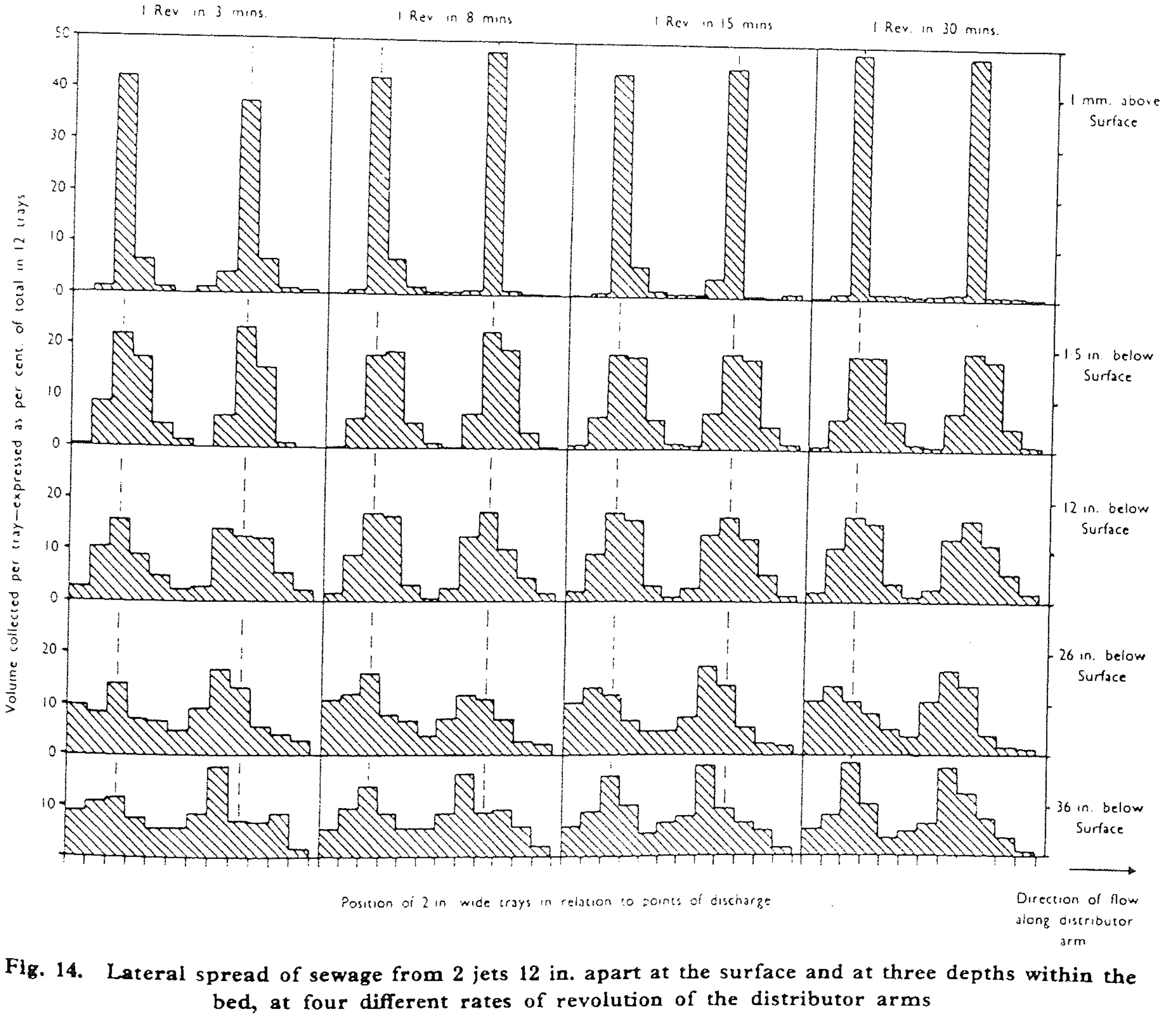

Fig. 14. **Lateral spread of sewage from 2 jets 12 in. apart at the surface and at three depths within the bed, at four different rates of revolution of the distributor arms**

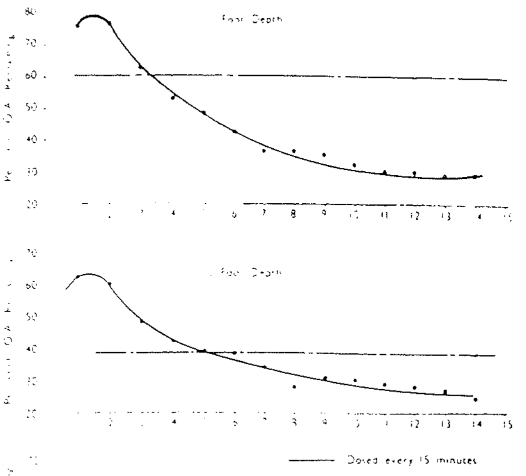

Fig. 15. Fluctuations in the strength of liquor between successive doses at 1 ft., 3ft. and 5 ft. depths of a bacteria bed dosed at 15-min. intervals compared with those when the bed was dosed at 1½-min. intervals

Although by these operational practices it is thus possible to limit the growth of the film (R_g) by nutritional means, it is not practicable to reduce it to 0 and it is necessary therefore to counter the resultant positive growth with some grazing activity (R_r). This however need not be so great as in a conventional bed. Thus although the methods of nutritional control involving high instantaneous rates of application create conditions adverse to the grazing fauna the latter should otherwise be encouraged.

Determination of Frequency of Dosing

In determining the frequency of dosing (expressed as 1 dose per *x* minutes) consideration should be given to unit small area representing one stone on which the film grows. Thus on a circular bed served by a four-armed distributor the jets of which are not less than 1 ft. apart and are staggered on the four arms, the frequency of dosing on the surface is the time for one full revolution of the distributor. Even at a depth of 1 ft. the amount of lateral spread (Fig. 14) results in the frequency of dosing at this depth being half the time of revolution of the distributor and only within the depths of the bed, where the flow has been more or less evened out, can the frequency of dosing be considered as a quarter of the time of revolution of the distributor—a figure sometimes quoted for the whole bed. Troublesome growths usually occur in the upper portion of beds and in this respect circular beds having distributors with staggered jets are capable of creating conditions of low frequency dosing in the upper layers of the bed, to prevent film accumulation, and higher frequency within the bed. Rectangular beds with conventional reciprocating distributors have the same frequency of dosing at all levels. By having arms with staggered jets which dosed alternately in opposite directions, such distributors could be modified to approach the condition of the circular ones.

THE ROLE OF BACTERIA BEDS AND METHODS OF ASSESSING THEIR EFFICIENCY

Throughout the foregoing discussion the yardstick by which the efficiency of bacteria beds has been assessed is the degree of oxidation of carbonaceous and nitrogenous compounds present in the waste as determined by the reduction in O.A. or B.O.D. and the extent of nitrification respectively. For beds treating purely domestic sewage these conventional tests probably assess the main function of the beds in removing oxidizable organic matter, although they are not necessarily a measure of the removal of pathogenic organisms[18]—a somewhat overlooked purpose of sewage purification. Since the adoption of these tests, bacteria beds have been called upon to treat increasing amounts of trade wastes either admixed with domestic sewage or separately. Considering sewage and waste treatment processes as means of combating river pollution rather than satisfying certain arbitrary standards, it is suggested that the above mentioned assessments of efficiency do not fully cover the different duties imposed on many bacteria beds today.

Apart from the deoxygenating effect, effluents from plants receiving toxic trade wastes may also be toxic. This toxicity is not assessed by the conventional tests. Toxic trade wastes may be divided into two groups. In the first group are those which are capable of biological oxidation, the final end products being relatively non-toxic. These substances are mostly compounds of non-metals such as phenols, thiosulphates, thiocyanates, cyanides, sulphides, etc. Such substances may necessitate a larger oxidation plant, either because of their slow rate of oxidation or because of their suppressing effect on the rate of biological oxidation of the more readily oxidizable matter or of each other. They are however capable of oxidation to such relatively innocuous products as water, carbonates, sulphates, phosphates and nitrates and could therefore be accepted, in controlled amounts, for treatment in biological oxidation plants. The second group of toxic compounds are

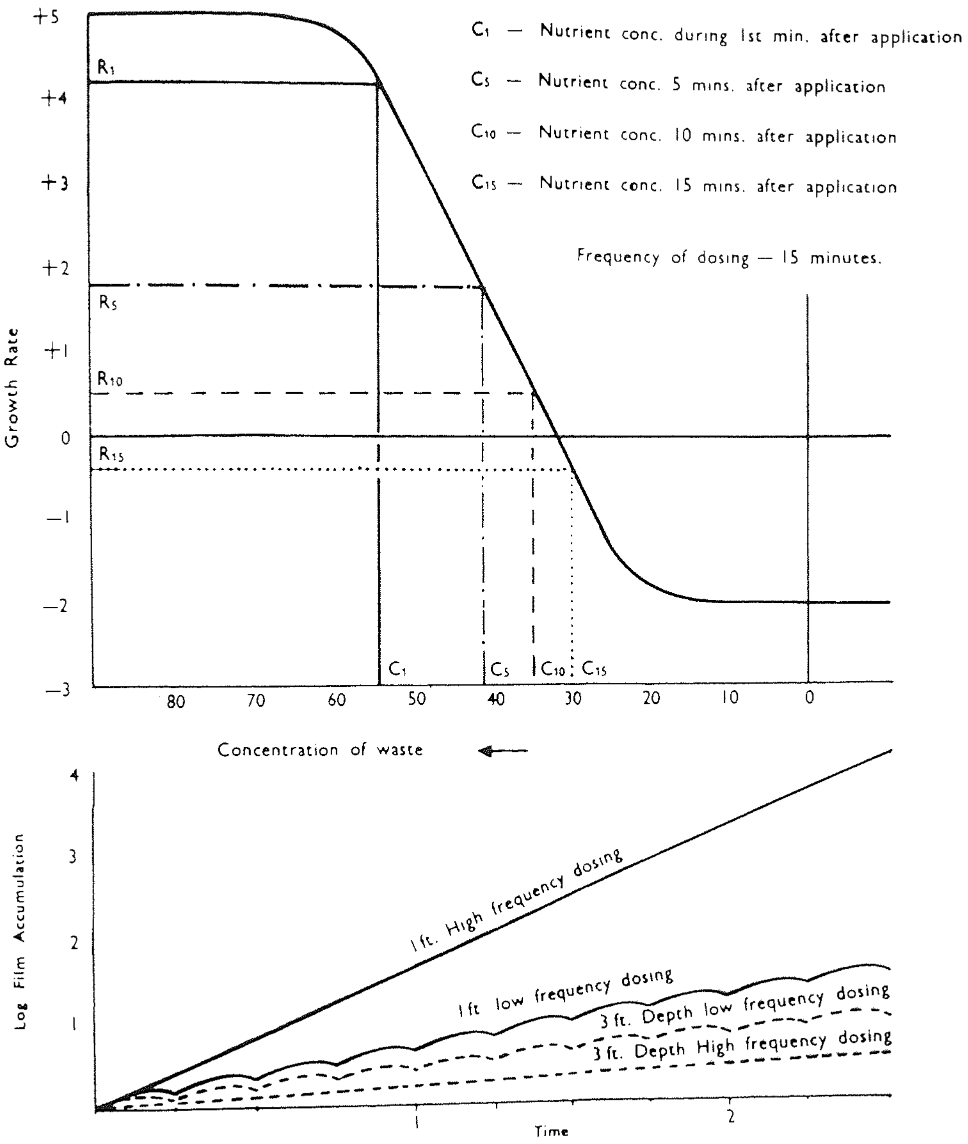

Fig. 16. Theoretical effect of low-frequency dosing on the growth rate of film at different depths

those which are either incapable of biological oxidation or if oxidized have end products which are toxic. This group includes the heavy metallic salts or organic compounds containing the heavy metals.

In accepting toxic metals for treatment in sewage treatment plants consideration must be given not only to their effect on the oxidation of carbonaceous and nitrogenous matter or to their effect on the anaerobic digestion of the sludge and its subsequent use as a fertilizer, but also to the possibility of their being removed or rendered less toxic to ensure that the final effluent is not toxic to stream life. The lethal concentration of these substances to stream life is probably much lower than to the micro-organisms in the biological oxidation plant. Thus even though the accepted concentration does not, after settlement, interfere with the biological oxidation, considerable reduction in toxicity may be needed to ensure a non-toxic effluent. In studies on the fate of metals during the treatment of sewage, Stones[49] has reported that different percentages (60-100) of the applied metal concentration appear in the effluent with different metals. Of this amount, different proportions were present in the humus and in solution; with copper, for example, approximately one-third was in solution whilst with nickel three-quarters was soluble. Thus a considerable proportion of the applied concentration of some metals may appear in the final effluent after the settlement of humus.

Theoretically, metals may initially be removed from the waste and be synthesised in the film. For continuous operation of a bed, however, the film must be removed and unless the metals are physically absorbed and accumulated on the surface of the medium itself, one might expect the overall discharge of metals to be equal to the amount applied, although the percentage would be expected to fluctuate seasonally. Ecologically, the only loss that could occur could be in the form of flies which left the beds or by the feeding activity of birds. It is possible however that in being synthesised into the film, metals are complexed with proteins and their toxicity thereby reduced. The overall effect on the receiving stream will then depend upon the readiness with which the proteins are broken down, liberating the metals.

The assessment of bacteria bed efficiency by the conventional tests does not measure the removal of such toxic substances and it may be that in this respect the processes discussed in this paper which proved superior in the oxidation of carbonaceous and nitrogenous compounds may not be the most efficient in the removal of toxic metals. The reduction in film under starvation conditions, for example, may release a higher proportion of stored metals in soluble form than if the film were removed as humus by grazing fauna.

Acknowledgments

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Paper No. 7

Factors influencing the seasonal incidence of fungal growth in sewage bacteria beds.

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FACTORS INFLUENCING THE SEASONAL INCIDENCE OF FUNGAL GROWTHS IN SEWAGE BACTERIA BEDS

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Abstract—The occurrence and seasonal incidence of fungal growths in sewage bacteria beds (percolating filters) is outlined and their effect on the efficiency of the process is discussed. The causes of the seasonal incidence were investigated in a series of laboratory culture work and ecological field studies. In pure culture *Sepedonium* sp. grew most rapidly at 25° C, at which temperature it was least abundant in the beds. The rate of lysis of the fungal mycelium was, however, higher at this temperature. By culturing film fed with sewage under controlled temperature conditions it was found that the amounts accumulating during three-week periods each month was related to the average sewage strength for the respective period. Field experiments showed that in the bacteria bed under varying temperature and nutritional conditions the amount of film accumulating each month, in the absence of grazing fauna, was more closely related to the average sewage strength for the period than to temperature. In culture the larvae of *Anisopus fenestralis*, which were common grazers in the bacteria beds, were found to devour fungal mycelium at a spectacular rate. This grazing activity was approximately 50 per cent higher at 20° C than at 10° C. Attempts to assess the importance of grazers in determining the seasonal incidence of the fungal growths by suppressing the macro-invertebrate grazing fauna in experimental areas of bed were not conclusive because of the effect of the suppressant on the microbial populations. The results, however, do indicate that the spring unloading of the beds is the result of biological activity and not mere mechanical or physical scouring.

The results of the different investigations support the hypothesis that in bacteria beds having film dominated by fungi the seasonal fluctuation in the standing crop of fungal mycelium is the result of seasonal changes in temperature and nutritional conditions. This is the outcome of microbial competition and predatism under different conditions of temperature and nutrition. Superimposed on these fluctuations are the effects of macro-invertebrate grazing activity. Although the grazers were not found to be the cause of the seasonal fluctuations in film it is considered that they play an important role in the economy of the beds in tending to prevent excessive accumulations of film.

1. INTRODUCTION

THE reclamation of water from waste waters such as sewage and industrial effluents involves the breakdown or removal of the organic content by bio-oxidation or biosynthesis respectively. One process, in common use, in which this is achieved is the bacteria bed or percolating filter. In this process the waste water is applied to the surface of the bed by means of a distributing mechanism and flows downward over the stones on the surface of which develops a microbial slime which, using the organic content of the waste as nutrient, brings about the purification of the water. In many beds treating domestic sewage the microbial film is composed of saprophytic bacteria and holozoic protozoa and is grazed by micro- and macro-invertebrates including nematodes, oligochaeta, collembola and dipterous larvae. In other beds, however, especially those treating strong industrial sewages, the film is dominated by fungi. The most commonly recorded forms are *Fusarium aquaeductum*, *Oospora* (*Geotrichum*), *Sepedonium* sp., *Ascoidea rubescens*, *Subbaromyces splendens*, *Sporotrichum* and *Penicillium*. Although the fungi are active agents in the purification process their higher assimilation efficiency results in a greater accumulation of film within the bed. This may eventually reduce the efficiency of the bed by preventing the even flow of liquid through the bed and by impeding the ventilation. Under extreme conditions the bed becomes completely "ponded" and the purification processes break down. Successive stages in the growth and spread of fungal mycelia near the surface of a bacteria bed and the resultant "ponded" conditions are shown in Figs. 1 (a–c and d). Besides these adverse effects on the process, the increased film may support a larger fly-population thus increasing the potential nuisance caused by the adult flies when they disperse from the works. Thus fungi are generally undesirable organisms in the bacteria-bed community.

In practice it has been found possible to limit fungal growths in bacteria beds by modified methods of operation such as recirculation and alternating double filtration (A.D.F.) Probably the most effective method is by reducing the frequency at which successive doses are applied to the bed. On circular beds this can be achieved by reducing the rate at which the distributor arms rotate. This method, however, may involve applying the waste at higher instantaneous rates of application than would otherwise be desirable if fungal control were not required. It was therefore considered useful to study the possible factors affecting fungal growths in beds. The work reported here forms the first part of this investigation and involved laboratory culture work and field experiments.

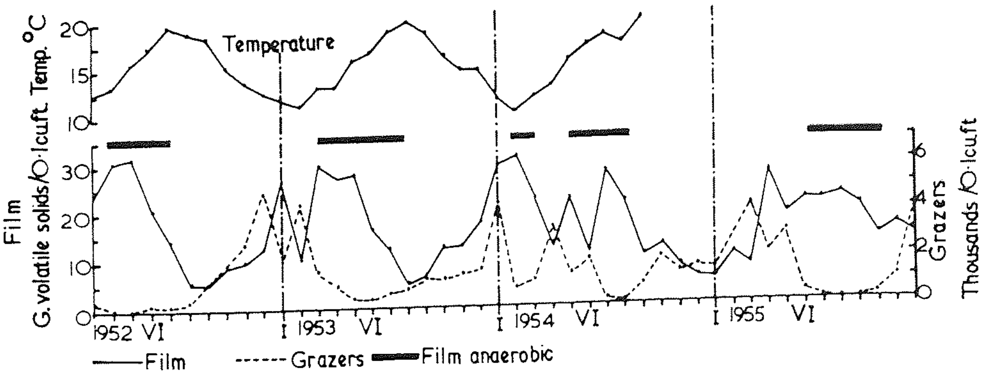

Fig. 2. Seasonal fluctuations in film accumulation and grazing fauna population in a bacteria bed treating industrial sewage—the film being dominantly fungal.

Previous observations have shown that there is a marked seasonal fluctuation in the amount of fungal film present in beds as shown in Fig. 2. Although the seasonal pattern is not as regular as that in beds treating domestic sewage in which an accumulation of solids occur each winter followed by an unloading the following spring (Fig. 3; Hawkes, 1965), the fungal growths are more profuse in the winter and spring than later, in the summer and autumn. Possible factors causing this seasonal fluctuation in the amount of fungal film were investigated. These were:

(i) temperature-direct and indirect effects;
(ii) strength of the sewage; and
(iii) grazing activity.

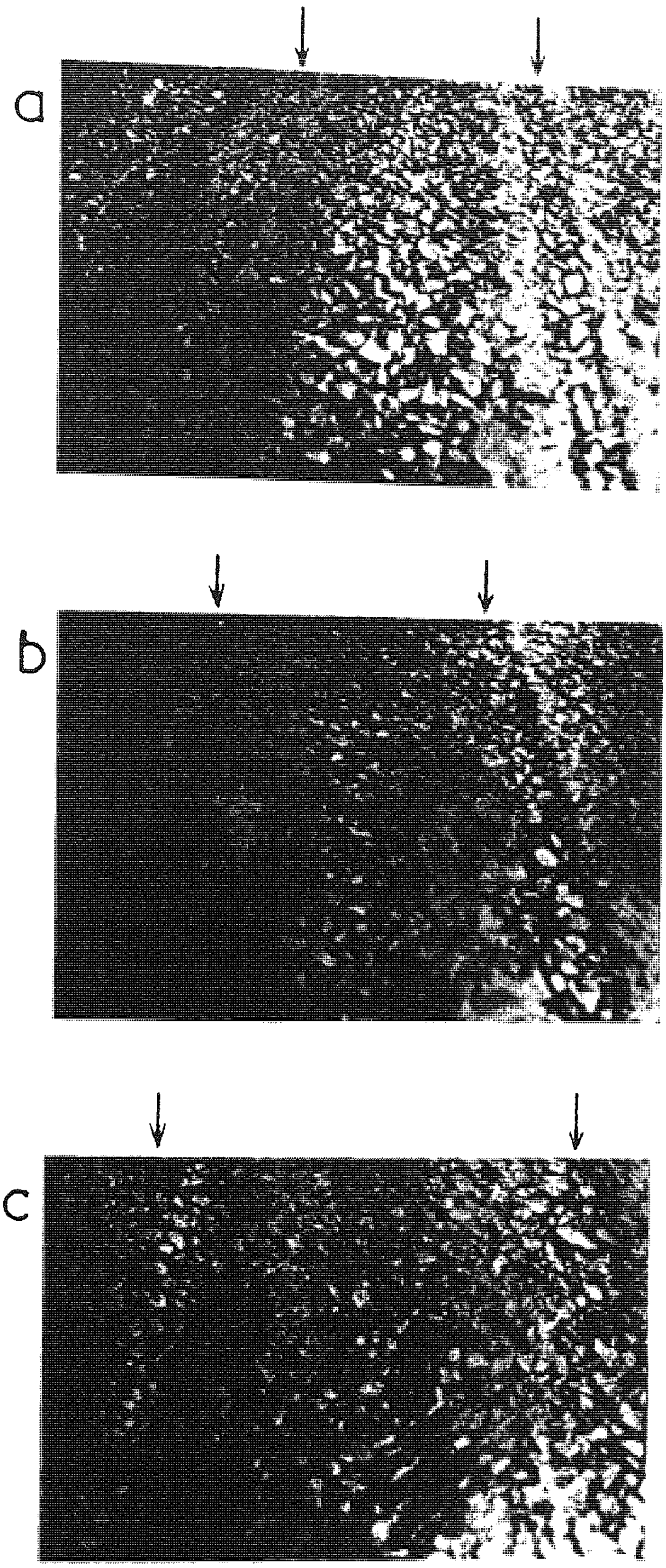

FIG. 1 (a–c). Progressive stages in the development of fungal growths near the surface of a bacteria bed. The path of the distributor jets indicated by arrows.

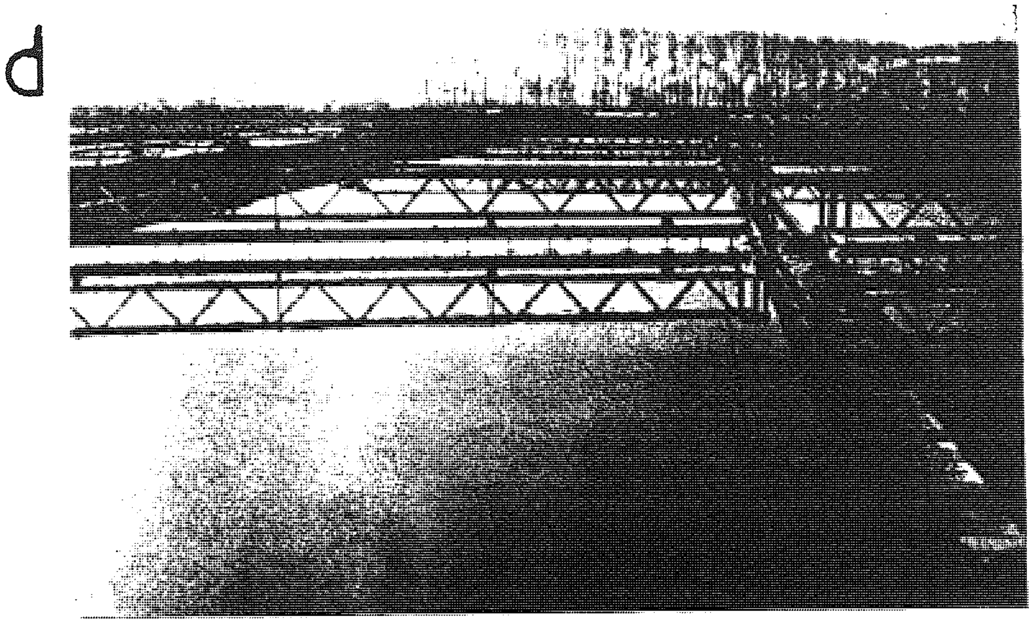

FIG. 1 (d). The resulting "ponding" of a bacteria bed due to the excessive growth of fungus.

2. METHODS

The several investigations described in the paper involved different experimental methods. The general methods used in the pure culture work and those used to assess the amount of film and fauna in the beds are described here; the detailed modifications of these methods are described in the sections dealing with the different investigations.

2.1. *Culture methods*

Observations on the beds showed that the most profuse growths were produced by *Sepedonium* sp. (Fungi imperfecti). This was isolated from the film and used in the culture work. *Fusarium aquaeductum* and *Geotrichum candidum* were also isolated and were found, on agar plates, to have similar temperature requirements to *Sepedonium*. After a series of initial tests using agar plates the growth rates were determined using *Sepedonium* in liquid medium. The nutrient liquid used in all cultures was 1 per cent peptone, 1 per cent glucose and 0·1 per cent yeastrel adjusting the pH to 7. 100-ml amounts of this medium contained in 250-ml conical flasks of uniform shape were used. The fungus was first cultured on 2 per cent agar plates containing the same nutrients, from these the liquid medium was inoculated by transference of hyphae on a small piece of nutrient agar taken from the edge of the colony.

2.2. *Assessment of film and grazing fauna populations*

The amount of film and numbers of grazers in the bed was assessed by removing samples of the bed medium contained in perforated canisters approx. 0·1 ft^3 in capacity which had previously been placed in the appropriate position of the part of the bed to be sampled. The film was removed from each sample of medium by washing twice in a revolving drum washing machine using 2 l. of water for each wash. By determining the volatile solid content on an aliquot of the resultant 4 l. the total amount of film per 0·1 ft^3 of bed was found. The macro-fauna was removed from a duplicate sample by washing the medium on a grid supported in a trough. The wash water with the removed organisms was strained through a fine mesh sieve to remove the macro-invertebrates, an aliquot of which were then counted over an illuminated counting chamber. When film and fauna were being assessed the canisters were placed in pairs in the bed and in calculating the film a correction was made for the grazers present on the basis of the numbers found in the fauna sample.

Sampling throughout the depth of the bed was made possible by the provision of vertical sleeves in which columns of the perforated canisters could be inserted.

3. INDIVIDUAL INVESTIGATIONS AND RESULTS

3.1. *The effect of temperature on the growth rate of* Sepedonium *in pure culture*

The direct effect of temperature on the growth rate of *Sepedonium* was investigated by culturing the fungus in nutrient broth at different temperatures between 0 and 30° C. Three flasks were used for each temperature and the fungus was harvested after 10 days' growth. The mycelial mats were filtered in a weighed Gooch crucible, washed and dried at 100° C and then weighed. The results, expressed graphically in FIG. 3, show that there was a steady increase in growth rate up to approx. 25° C, above which there was a sudden decline. This confirmed preliminary tests in which the growth rate on nutrient agar plates was measured.

The growth rate thus measured probably represents the log phase of growth under non-limiting nutrient conditions. In a bacteria bed the standing crop of fungus at any one time would be affected by the temperature in other ways. The effect of temperature on the rate of decay of fungal mycelium under starvation conditions, which at times exist in bacteria beds, was roughly assessed. Mycelial mats of *Sepedonium* developed in nutrient solution after 14 days' growth were removed, washed and after removing the surplus water their wet weight was determined. They were then placed in purified bacteria bed effluent in 200-ml flasks and incubated at different temperatures, three flasks being used at each temperature. After 16 days the remaining fungus was removed, washed and the wet weight determined after removal of the surplus water. The degree of decay of the mycelial mats was expressed as the percentage decrease in weight. The results, also shown in Fig. 3, show that there was a marked increase in rate of lysis with increase in temperature between 10 and 25° C.

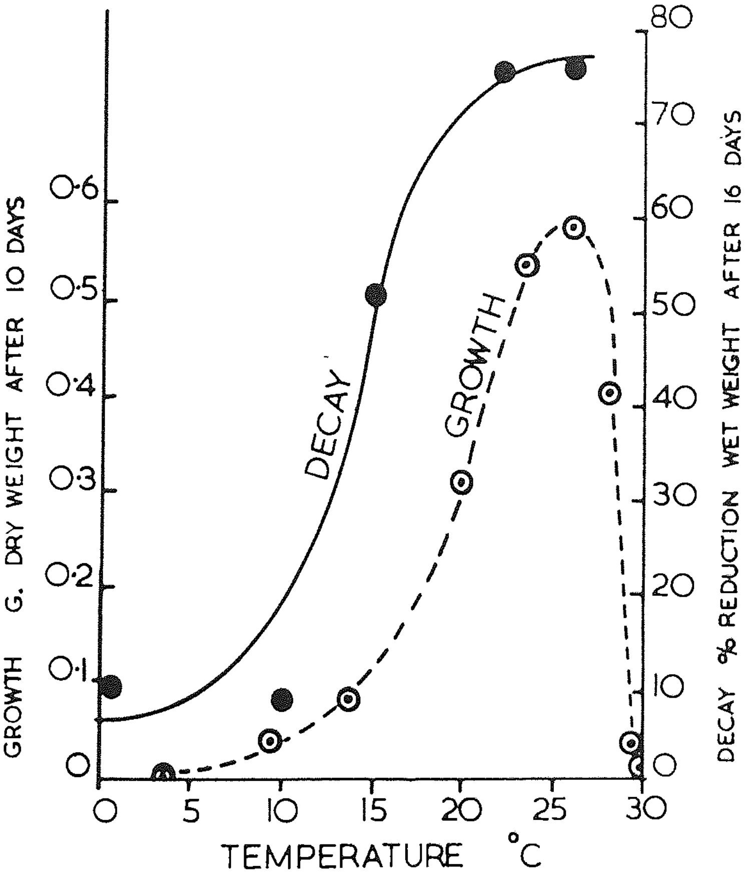

Fig. 3. Effect of temperature on the growth rate of fungal mycelium in nutrient solution and on the rate of decay under starvation conditions in sewage effluent.

3.2. *The effect of seasonal changes in the nature of the sewage on the growth rate of film*

It was realized that the nutrient and biotic conditions necessary in pure culture work were far removed from the natural conditions under which the fungus grew in the beds. It was, therefore, decided to measure the growth rate of the film under controlled conditions but more approaching the nutritional conditions prevailing in the beds.

Sepedonium was cultured in the nutrient medium for 3 days and the small mycelial mat which had then developed, approx. 0·5 g wet weight, was placed in the centre of a

6-in. square of stainless steel gauze, 10 mesh/in. This inoculum was then fed with settled sewage which had been strained through micro-straining fabric to prevent the inoculation of the culture with grazing fauna. During the first year of the experiment the strained sewage was applied by drip feeding from a Mariotte bottle at the rate of approx. 6·5 l./day, the bottles being recharged daily with fresh sewage. During the second year of the experiment a dosing device operating on the kinking-tube principle dispensed approx. 9 ml of sewage every 2 min to the culture. It was found that at this frequency of dosing the growth rate was the same as that using continuous drip feed. By using the dosing apparatus, however, the application rate was more easily controlled. After 21 days' growth on the gauzes, when the mycelial mat had in some cases reached the edge of the gauze, the growth was removed and its dry weight determined. All cultures were carried out in a thermally insulated room in which the temperature was controlled between 20–22° C.

To determine any effects of seasonal changes in the nature of the sewage, fungal mycelia were cultured, as just described, for three-week periods each calendar month for 2 yr. In each three-week period in the first year three cultures were grown in a dark chamber and another set of three in an illuminated chamber to investigate any effects of light. The light source used was two 16 in. 15 W tubes mounted approx. 12 in. above the cultures. A rectangular perspex tank through which water flowed was fitted between the light and the cultures to prevent the light affecting the temperature of the growth chamber. In the second year only three cultures were grown—in the dark chamber.

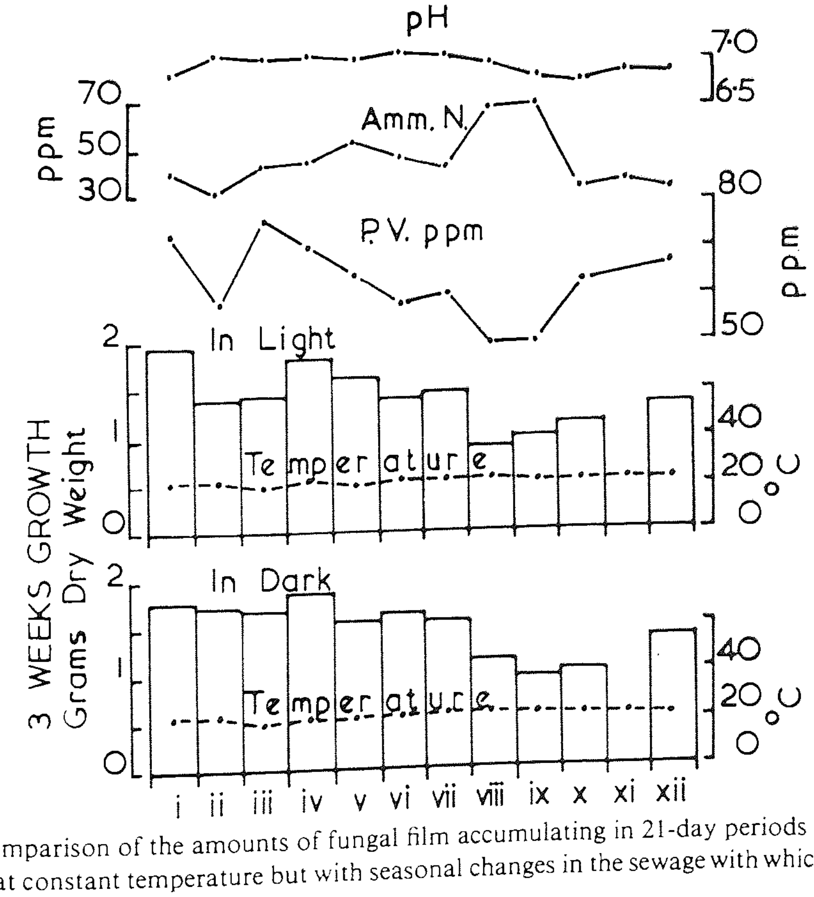

FIG. 4. Comparison of the amounts of fungal film accumulating in 21-day periods each month of a year, at constant temperature but with seasonal changes in the sewage with which it was fed.

Each day, samples of the feed liquor were taken, one of the fresh sewage and the other of the sewage at the end of the 24-hr period. The strength of the sewage was assessed by the "4-hr permanganate test". The ammoniacal N and the pH were also determined. The temperatures in the growth chambers were checked daily using a max.–min. thermometer. The averages of these data over each 21-day period were compared with the average amount of fungal film developed for each respective period. The results from the dark and light chambers for the first year are presented graphically in FIG. 4. The results for November were invalidated because of the failure of the initial cultures.

Although the seasonal differences in the accumulation rate of the film were not as great as seasonal fluctuations in film in the beds, the results indicate that at constant temperature the rate of accumulation of film is greater in the winter and spring than in the summer and autumn. Examining the corresponding analytical data it is seen that there was only slight differences in the pH values. There were, however, considerable seasonal fluctuations in the strength of the sewage as measured by the permanganate value and in the ammoniacal N values. There appears to be some positive correlation between the amount of growth and the sewage strength. The two smallest growths were associated with feed liquors having markedly high ammoniacal N concentrations. There was no apparent difference between the amounts of growths developing in the light and dark.

To investigate further the effect of seasonal differences in sewage strength on the growth rate, the experiment was continued for a further year using the dark growth-chamber only. The relationship between the average amounts of growth in the dark and the corresponding average sewage strength for 21-day periods over the two years is shown in FIG. 5. A significant positive correlation was found to exist between the amount of growth developed and the sewage strength.

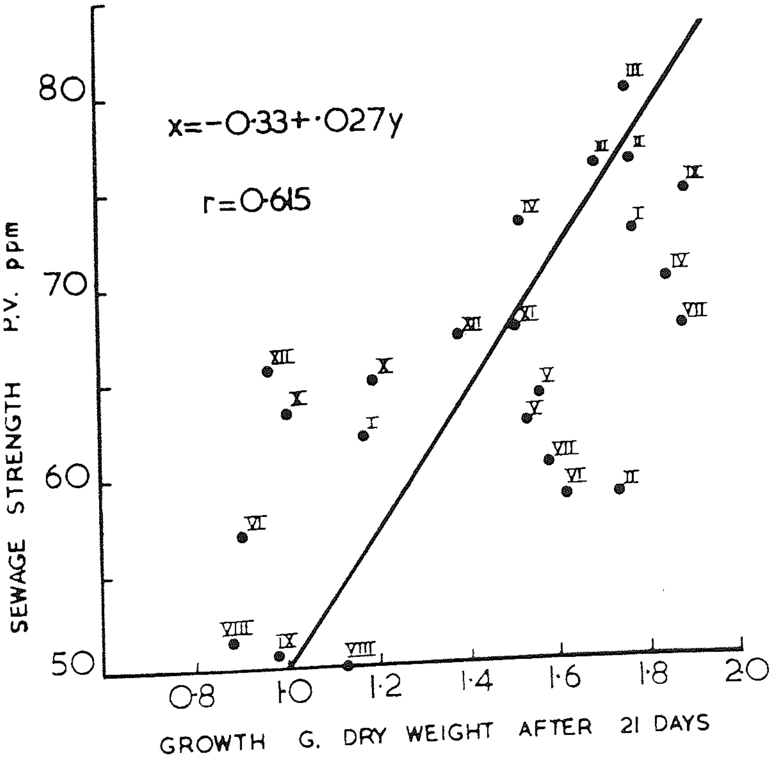

FIG. 5. Relationship between the amounts of fungal film accumulated in 21-day periods each month throughout two years at constant temperature and the average sewage strength for each period.

3.3. *Combined effect of seasonal changes in temperature and sewage strength on the growth rate of fungal film in the absence of grazers*

To determine the joint effect of seasonal changes in temperature and sewage strength on the growth rate of film, the rate of accumulation of film on clean media contained in canisters placed in isolation shafts in bacteria beds was measured each month. To ensure the absence of grazing insects and worms, the shafts were sprayed with B.H.C. and copper sulphate solution. In each shaft two canisters containing medium were supported on an empty inverted canister similarly treated, to isolate them from the bed below (FIG. 6). In one set of three shafts, each calendar month, canisters containing clean medium inoculated with a 3-day-old culture of *Sepedonium* were placed. In a second set of three shafts canisters containing medium, previously matured in another part of the bed, were used after killing the grazing fauna by immersing them in suspension of insecticide and copper sulphate. Duplicate canisters of media matured in close proximity to the ones transferred were also removed to determine the initial film accumulation.

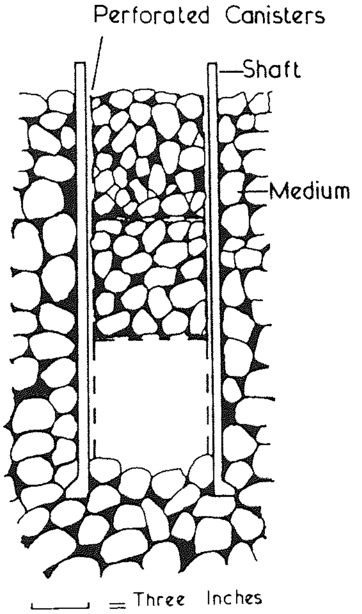

FIG. 6. Isolation shaft for the growth of film under normal bed conditions except for the exclusion of macro-grazing fauna.

All 6 isolation shafts were positioned so as to ensure similar dosage conditions. The bed used was one of an A.D.F. unit and received settled sewage and settled primary stage effluent successively on alternate days. The volumetric dosage rate remained constant throughout the experiment. The feeds to the beds were sampled daily and the strength assessed by determining the 4-hr permanganate value. The temperature in the surface layers of the bed, where the shafts were situated, was recorded on a Kent recording thermometer.

After 21 days' growth in the isolation shafts the canisters were removed and the weight of the accumulated film determined as previously described. In the case of previously matured medium, the increment in film was assessed by substracting the weight of film found in the duplicate sample previously determined.

The average amounts of film accumulated per canister in the two sets of shafts during 21-day periods in 13 consecutive months are shown as histograms in FIG. 7.

The corresponding average temperatures and sewage strengths for these periods are also plotted. The results show that differences in the amounts of film accumulated in the canisters containing clean medium inoculated with fungus during different 21-day periods are more closely related to differences in sewage strength than to differences in temperature. In the canisters containing previously matured medium, the differences in the incremental accumulation appear to be more related differences in strength of the secondary feed.

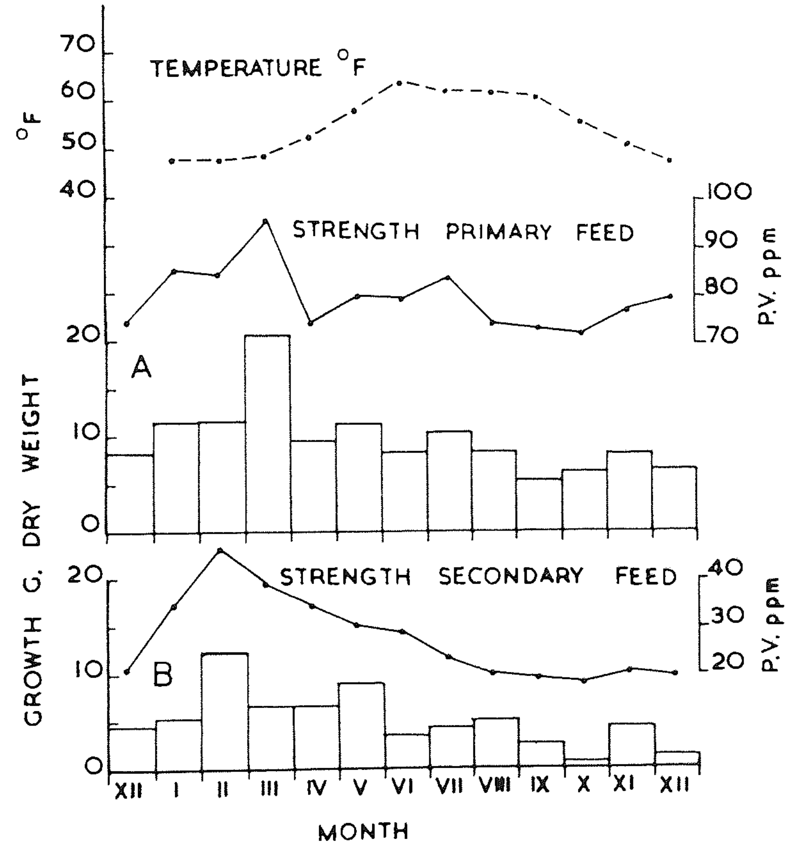

FIG. 7. Comparison of the monthly accumulations of film in the surface layers of a bacteria bed in the absence of grazers in relation to sewage strength and temperature: (a) clean medium inoculated with a culture of *Sepedonium*; (b) matured medium.

3.4. *Seasonal differences in the growth rate of film at different depths in the bed in relation to seasonal fluctuations in temperature and sewage strength*

Growth rates of fungal film at different depths in the bed could be expected to be affected by the strength of the sewage at that depth as determined by the stage of purification reached. The growth rates at different depths in the absence of grazers during 8 monthly periods from January to August were determined in a similar way to that used for the surface shafts. Three shafts were used allowing triplicate samples to be taken and there were 10 canisters in each shaft. After 28 days' growth the canisters were removed and the amount of accumulated film determined. The average amount accumulated at each depth during each of the eight periods are expressed as eight histograms in FIG. 8. Since the medium in the canisters is not matured the growth rates at different depths in the shaft do not represent the growth rate at the corresponding depth in the mature bed. Nevertheless, the results show that the relative amounts of film accumulated at different depths in the shafts differed at different periods. The total amount accumulated each month, shown by the graph, was again related to the average sewage strength. In May, June and July when the waste concentration was lower and the temperature higher there was markedly less accumulation in the lower half of the shaft. In August, at similar temperatures but with increased sewage strength, more film accumulated in the lower half of the bed. It is difficult to distinguish between the effects due to temperature and those due to sewage strength, but the results show that generally less film accumulates at times of higher temperatures and reduced sewage strength than at periods of low temperature and strong sewage feeds.

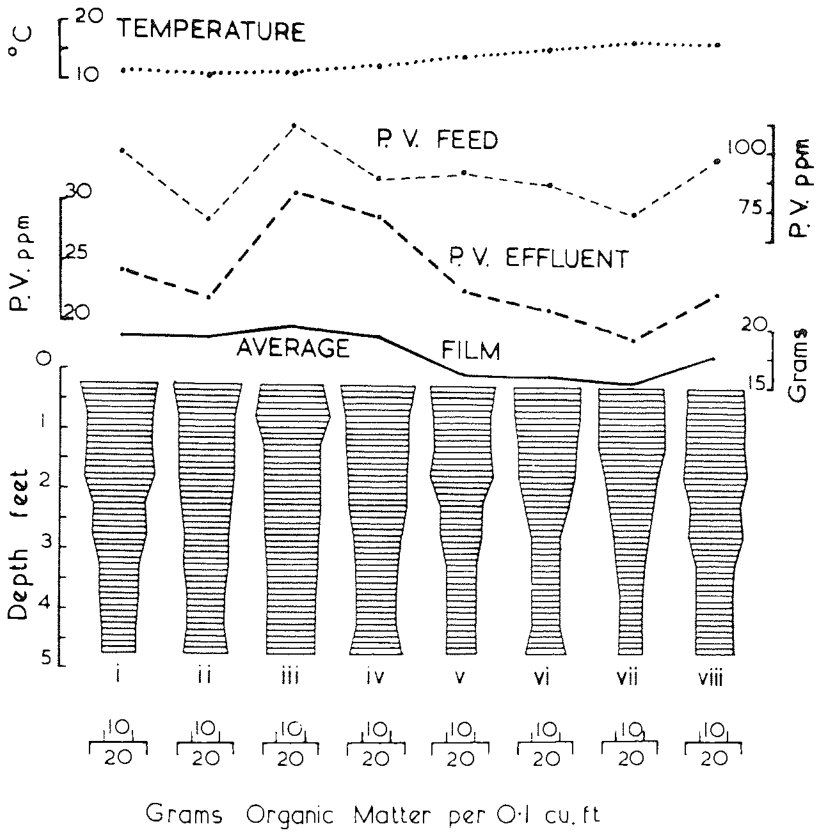

FIG. 8. Comparison of the monthly accumulation of film at different depths in a bacteria bed in the absence of grazing fauna in relation to temperature and strengths of feed and effluent.

The progressive accumulation of film at different depths in shafts over two four-month periods (January–April and May–August) was studied by a series of replicates. For each of these periods 8 shafts were filled with inoculated canisters of media, at 28-day intervals the canisters from two shafts were removed and the accumulated film in each canister determined. The average results are shown as histograms in FIG. 9, together with the relevant temperatures and sewage strengths expressed as graphs.

During both periods, after a rapid accumulation of film during the first month there was a much slower accumulation over the next 3 months. Although the initial rapid accumulation in May was somewhat greater than that at the lower temperature in January, the subsequent rate of accumulation was much the same for the 2 periods. In both periods also there was a similar progressive change in the vertical distribution of the film. On successive months a higher proportion of the film was found in the upper half of the shaft. This was presumably due to the increasing amount of organic matter removed from the waste by the maturing medium, leaving less to accumulate below. This trend was most evident in the summer period, when there was in fact a reduction in the film in the lower part of the shafts.

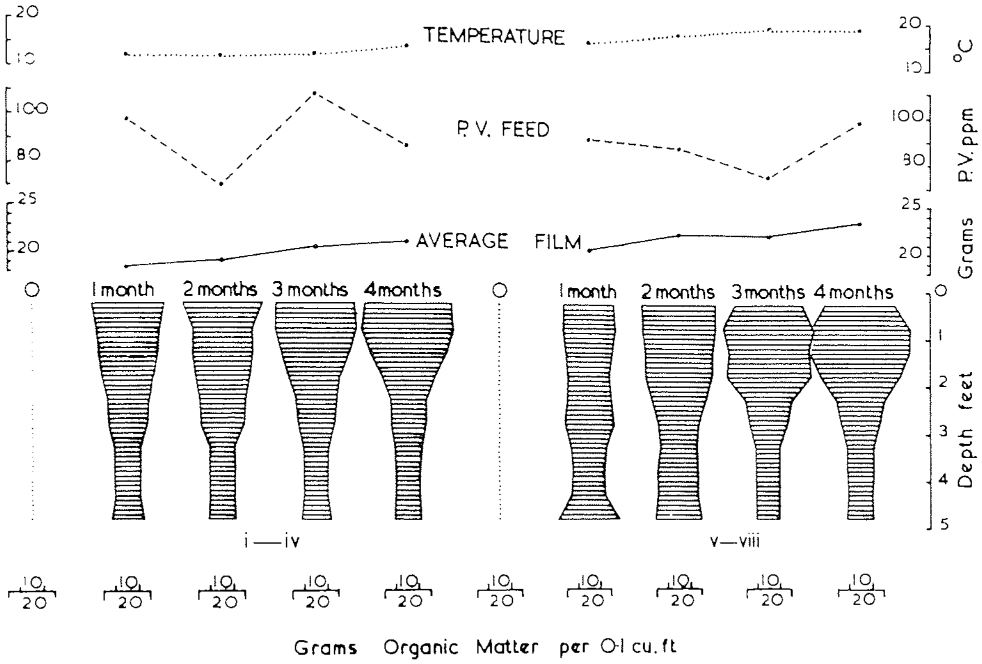

Fig. 9. The progressive accumulation of film at different depths in a bacteria bed in the absence of grazers throughout 2 4-month periods.

3.5. *The effect of macro-invertebrate grazing activity (laboratory culture studies)*

It has been suggested that the seasonal fluctuations in the amount of film present in beds is the result of changes in grazing activity of macro-invertebrates such as fly larva and worms, caused by changes in temperature. Apart from seasonal changes in the populations of the macro-invertebrates, changes in the individual grazing rates, due to seasonal temperature changes, could be involved. This possibility was investigated by comparing the grazing activity of a common bacteria-bed grazer—the larva of *Anisopus fenestralis*.

3.5.1. *Method.* The larvae were cultured on food prepared by centrifuging activated sludge and sterilizing it by boiling to produce a jelly-like paste. This was supported on a fine stainless steel gauze placed between two similar sized halves of Petri dishes, as shown in Fig. 10(a). The whole was held together by an elastic band. A thin layer of distilled water in the lower dish maintained a moist atmosphere in the chamber. As the larvae fed, the activated sludge was reduced in amount and faeces (humus) was produced. This was removed at approx. 5-day intervals by flushing with distilled water. This was accomplished by transferring the gauze with culture to a special shallow funnel (Fig. 10(b). This was supported in the bung of a conical flask so that when the air pressure in the flask was increased water in the flask rose up into the funnel and through the gauze. By using 50 ml of water and a pressure of 17 in. of mercury it was found that this rose up the funnel and the subsequent bubbling agitated the gauze thus assisting in the separation of the granular humus matter from the more jelly-like uneaten activated sludge. After bubbling for a period of one minute the pressure in the flask was reduced allowing the water and the removed humus to pass into the flask. After collecting the wash, the process was repeated using a second volume of distilled water. The two washes and the solids washed from the lower culture dish were bulked and the dry weight of the solids determined. Any larvae found in the humus were removed, the living ones being returned to the culture. A note was kept of dead larvae and the ones which had pupated, in order to assess the numbers of active larvae during each period. Food was supplied as required to ensure it was not limiting and at each feed a record was kept of the dry weight of the solids added, this being determined on a duplicate sample. The excess food remaining on the gauzes at the end of the experiment was determined and subtracted from the total amount supplied to assess the amount of food removed.

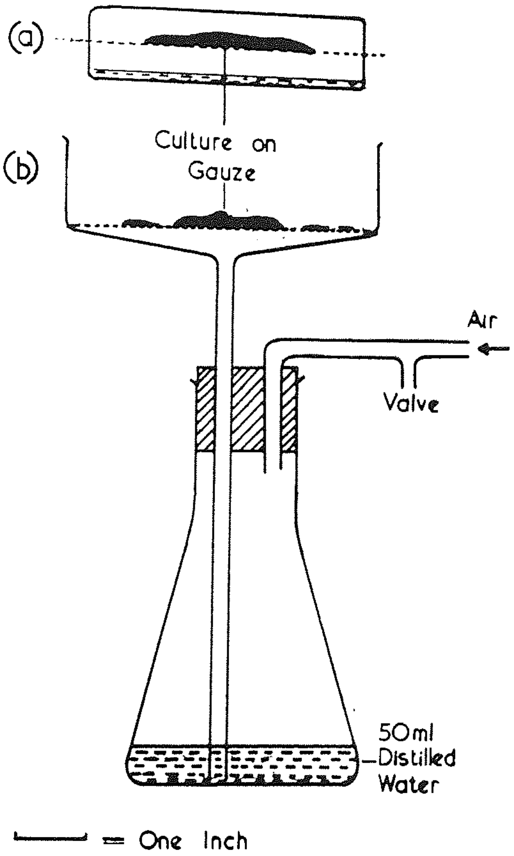

FIG. 10. (a) Culture chamber for measuring the grazing rate of larvae; (b) apparatus for the collection of humus solids produced by the grazing activity of fly larvae.

To assess the effect of temperature on grazing activity cultures were maintained at 5 different temperatures—approx. 3, approx. 10, 20, 22 and 26·5° C. At each temperature 3 cultures each inoculated with 50 5-day larvae were used. A fourth chamber, to which no larvae were introduced, served as a control, the same amount of food being added to all four chambers and all 4 being flushed at 5-day intervals. The amount of solids discharged from the control chamber was subtracted from the amounts collected from the inoculated cultures to assess the amount of humus produced by grazing activity.

3.5.2. *Results.* The amounts of humus produced during successive 5-day periods at the five different temperatures are shown as histograms in Fig. 11. Due to deaths and pupations different numbers of larvae were active during successive periods, the estimated mean number present each period is indicated by the graph.

At 3° C very little grazing occurred although it was increasing as the experiment was brought to a close. The larvae remained alive as shown by the spectacular increase in humus discharged after removing the cultures from the ice box. At 26·5° C also, little grazing occurred, but at this temperature all the larvae died before pupating.

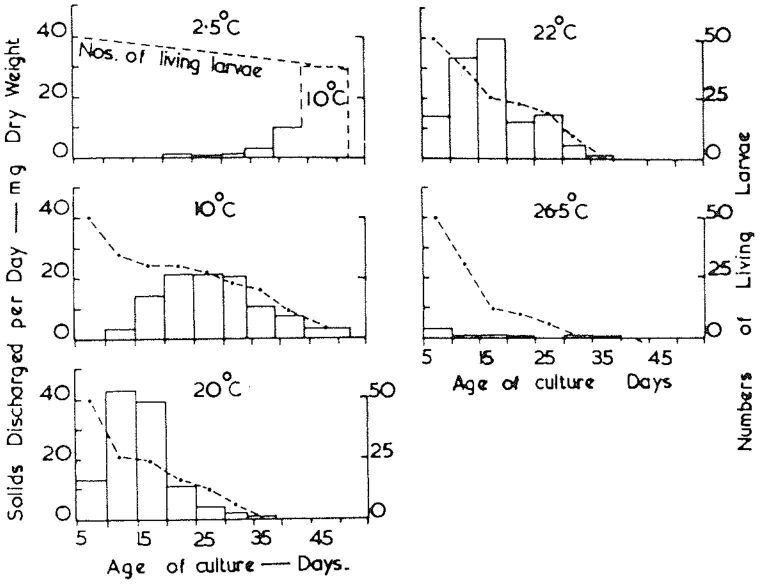

FIG. 11. Comparison of the amounts of humus produced by grazing *Anisopus fenestralis* larva at different ages and at different temperatures.

At 10° C there was a gradual increase in the amount of solids discharged as the larvae grew. Maximum grazing occurred after 15 days, i.e. when the larvae were 20 days old. This rate was maintained for 15 days, after which there was a decline associated with the successive pupation of the larvae. At 20° C there was a more rapid increase in the rate of discharge of solids, a peak being reached after 5 days, i.e. when the larvae were 10 days old. The duration of this heavy discharge, however, was shorter than at 10° C and was followed by a sharper decline. The results at 22° C were similar to those at 20° C.

Because of the different number of larvae surviving in the different cultures a direct quantitative comparison is difficult. In an attempt to overcome this difficulty approximate rates of discharge per larva were calculated using the estimated number of larvae present during each-5 day period. The average results obtained at 10, 20 and 22° C are summarized in TABLE 1.

Comparing first the results at 10 and 20° C, it is seen that although the total amount of solids discharged at 10° C was greater than at 20° C because of the longer larval phase, the average daily rate and the maximum rate was higher at the higher temperature. At 22° C, which is probably above the optimum for *Anisopus fenestralis*, the rate of discharge and the total amount discharged were somewhat less than at 20° C.

The amount of humus produced in relation to the amount of food disappearing was calculated and these results are also shown in TABLE 1. Something just less than half of the activated sludge removed appeared as humus, the remainder presumably was assimilated in the growing larvae or respired.

In the control chambers, in the absence of larvae the humus produced in relation to the activated sludge lost was much less. The percentage loss of activated sludge in the absence of larvae was higher at higher temperatures.

TABLE 1. AMOUNTS OF HUMUS SOLIDS PRODUCED IN RELATION TO THE FOOD REMOVED BY LARVAE OF *Anisopus fenestralis* GRAZING AT DIFFERENT TEMPERATURES

Temperature (° C)	Mean duration of stage (days)	Average total weight discharged per larva (mg)	Average rate of discharge per larva per day (mg)	Peak rate of discharge per larva per day (mg)	Humus produced / Reduction in food	Humus produced / Reduction in food in absence of grazers
10	50	25·4	0·51	1·09	0·40	0·135
20	30	21·6	0·72	1·72	0·49	0·130
22·5	30	20·1	0·67	1·54	0·49	0·130

3.6. *Comparison of the relative amounts of humus produced by grazing activity on different types of food*

Activated sludge, used for sake of convenience in the above experiments, differs in some ways from the film on which the larvae graze in bacteria beds. A comparison was therefore made between three different food materials—activated sludge, film removed from a bacteria bed and cultured *Sepedonium*. The methods used were similar to those described above; three cultures were used for each food and this time three controls were used in each case. All the cultures were carried out at the same temperature, 22° C. The average results are summarized in TABLE 2.

TABLE 2. AMOUNTS OF HUMUS SOLIDS PRODUCED BY LARVAE OF *Anisopous fenestralis* GRAZING ON DIFFERENT TYPES OF FOOD

Food	Average total weight of humus discharged per larva (mg)	Humus produced / Reduction in food	Humus produced / Reduction in food in absence of grazers
Activated sludge	17·7	0·42	0·10
Bacteria-bed film	7·8	0·31	0·11
Sepedonium mycelium	1·2	0·06	0·03

In comparing the results it is necessary to appreciate the differences in the compositions of the foods used. Activated sludge consists of flocculated bacteria, organic solids and some holozoic protozoa. The bacteria-bed film was mostly fungal mycelium with bacterial slime and accumulated organic solids. The *Sepedonium* was a pure culture of the fungus. The results show that larvae feeding on the *Sepedonium* produced appreciably less humus than those feeding on activated sludge. Presumably nearly all the fungus was utilized as food whereas the activated sludge contained much non-digestible matter which was passed as faeces. The bacteria-bed film also produced appreciably more humus than the fungus, but less than the activated sludge, presumably because of the dominance of fungus in the film. There were corresponding differences in the amounts of humus produced per food removed in the presence of larvae. In their absence, the amount of humus produced per food removed was less than in their presence. Less humus was produced from the lysis of *Sepedonium* than from a corresponding weight of activated sludge or bacteria-bed film.

3.7. *The effect of macro-invertebrate grazing activity* (*the experimental suppression of the grazing fauna population in a bacteria bed*)

In an attempt to assess the significance of grazing activity as a factor causing the seasonal fluctuations in the quantity of film, field experiments were carried out in which the grazing fauna populations in different sections of a bacteria bed were purposely suppressed for different periods of the year. For this purpose four narrow sections (approx. 1 × 100 ft) of a rectangular bed, each receiving sewage from a separate jet of one reciprocating distributor arm, were used. In each of these sections were placed 12 pairs of perforated canisters containing matured medium removed from that section of the bed. After a period of several months to ensure stabilization, each section was sampled at monthly intervals by removing three pairs of canisters from each section. One of each pair was used for the assessment of film and the second for fauna. By ensuring that the canisters were removed in rotation and refilled with the medium from the appropriate section, an adequate period of stabilization, 4 months, was ensured. The average monthly figures for grazing fauna, which was dominated by enchytraied worms and the larva of *Anisopus fenestralis*, and the amount of film for each of the four sections are shown as graphs in FIG. 12.

The bed used was one of an alternating double filtration unit, receiving settled sewage one day and the partially oxidized effluent of the primary bed on the next day. For experimental purposes the rate of flow was constant throughout the experiment. The average monthly strengths of primary and secondary feeds to the bed are also shown as graphs in FIG. 12. The temperature of the upper layer of the bed was recorded on a thermograph; the monthly average temperature is given in the lower graph of FIG. 12.

The macro-fauna was suppressed, when required, by the application of the insecticide B.H.C. together with a solution of copper sulphate which had been found to be highly toxic to enchytraied worms. These were applied as a suspension and solution respectively which was siphoned so as to mix with the feed discharging through the appropriate jet of the distributor to cover the required section. Section A was used as the experimental control and received no treatment. Sections B, C and D received treatments for the different periods indicated on the graphs.

3.7.1. *Results.* In Section A, the control, during the first winter there was an excessive accumulation of film followed by a spectacular unloading during May. Throughout the summer and autumn the film amounts were small and although there was some increase during the second winter the amount present was not excessive. These seasonal fluctuations in film are not, however, clearly related to fluctuations in the grazing

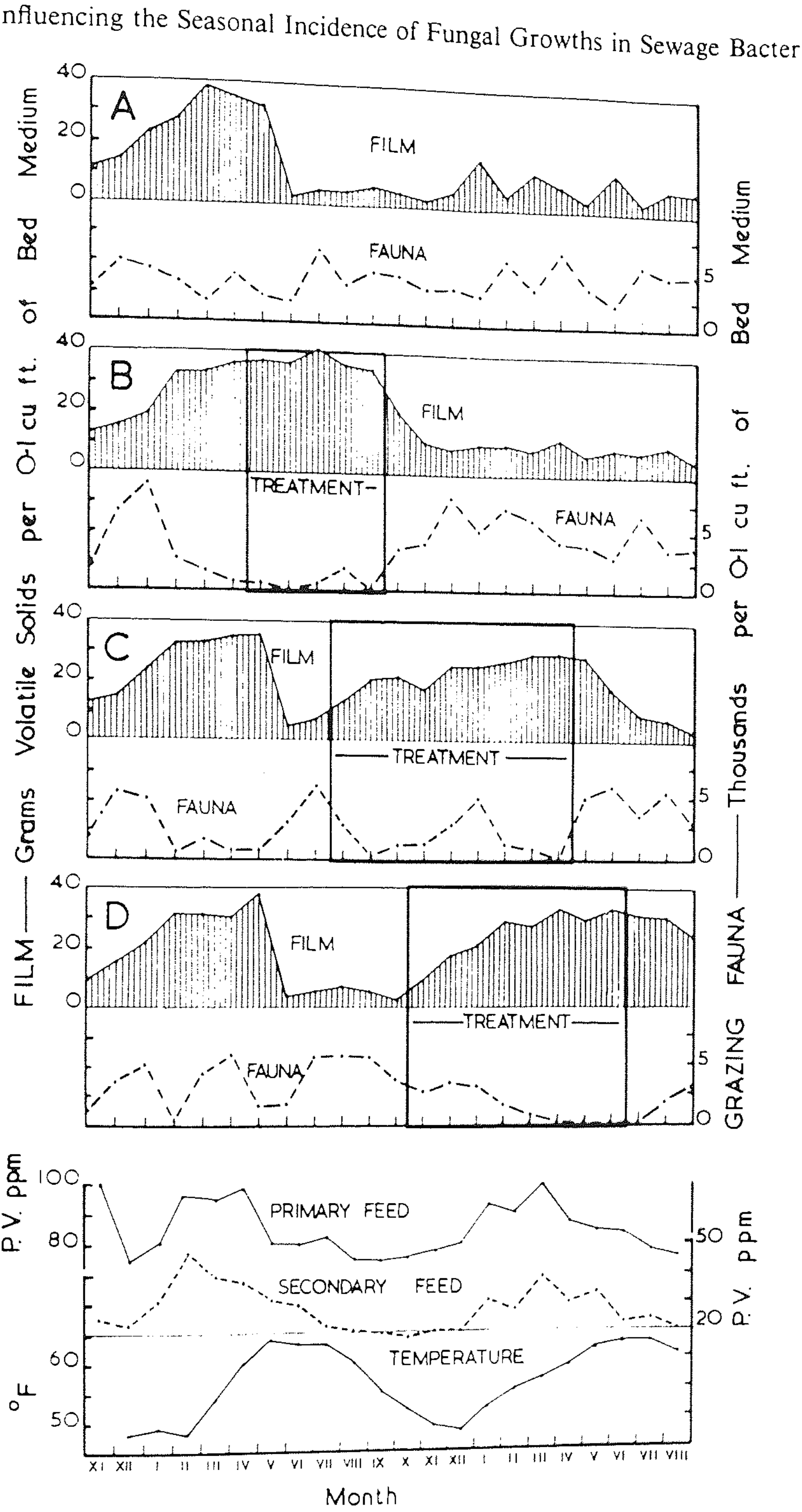

FIG. 12. Comparison of the natural seasonal incidence of fungal film in a bacteria bed with that induced by toxic applications for different periods of the year.

fauna population. The spectacular decrease in film occurred at a time of relatively low grazing fauna population. It did coincide, however, with a marked decrease in sewage strength at a time of high temperatures. Under such reduced nutrient conditions and high temperatures, lysis of the fungal film would be greatly increased, and could account for the marked unloading. There was a subsequent increase in the grazing population and throughout the summer this increased population grazing at higher temperatures could account for the smaller amount of film present throughout this period. With a fall in temperature and increase in sewage strength the following winter, there was an increase in the film. In accounting for the relatively small winter accumulation it is probably significant that this second winter was relatively mild as indicated by the temperature graph. There was also throughout the winter a somewhat higher grazing fauna population than during the first winter and probably significant was the fact that the insect larvae were much more abundant than during the first winter. Successive peaks in the populations, previously reported, probably caused the regular fluctuation in the film. If this is so, then it must be concluded that the grazers were at least partly responsible for limiting the accumulation of film during this second winter.

In Section B, the macrofauna was suppressed for a 5-month period commencing in April. As shown in FIG. 12, this prevented the marked decrease in film in May and the unloading only occurred after the treatments ceased in the autumn. The grazing fauna, which before the treatment started were low in numbers because of adverse conditions imposed by the excessive accumulation of film, were maintained at a low level throughout the period of treatment. The extent to which this suppression of the grazing fauna was responsible for the delayed unloading is difficult to assess. If, as suggested above, the unloading in the control section (A) was not attributable to grazing activity, the failure to unload in the case of the treated section (B) cannot be attributed to the absence of grazing fauna. Nevertheless the continued high level of film accumulation throughout the treatment period could be at least partly attributable to the suppression of the grazing fauna, which had they been present could have brought about a more gradual decline in the amount of film. The unloading, after the treatment ceased, coincided on this occasion with an increase in the grazers. At the same time, however, the sewage was relatively weak and the temperatures relatively high. It is therefore difficult to assess in this case the extent to which the different factors were responsible for the unloading. For the remainder of the period the grazing population, mostly enchytraeid worms, remained fairly high, greater than in the control section. The absence of an appreciable accumulation of film in the second winter in the presence of this grazing population suggests that the latter was responsible.

The failure to unload at the time of the control section unloading, if not due to the absence of grazers, needs to be accounted for. The unloading was prevented by the creation of toxic conditions. This suggests the failure to unload was caused by the suppression of biological activity. As a corollary it follows that unloading is due to biological activity either microbial or macrobial. The failure to unload, in this case, was probably due to the suppression of the bacterial lysis of the fungal mycelium or its autolysis by the frequent application of toxins, a possibility not anticipated in planning the experiment.

In Section C the accumulation of film during the first winter was similar to that in the control section (A) and there was a similar unloading in May. Following the commencement of treatment in July, however, there was a progressive increase in the film at a time when that in the control section (A) remained low, so that excessive amounts of film were present during the second winter, when in Sections A and B, not receiving treatment at this time, there was little accumulation as previously discussed. This accumulation of film during the period of treatment could have been due to suppressed grazing activity or to toxic effects on microbial activity. The fauna suppression was not completely successful in this section; the partial recovery in the grazing population in the middle of the period was due to successive invasions of the section by enchytraeids from adjacent untreated areas, rather than to reproduction within the sector. After treatment ceased there was a gradual unloading associated with an increase in grazing fauna population, mostly enchytraeids. Again a cause-and-effect relationship is difficult to establish.

In section D also the film accumulation followed a similar pattern to that in the control section (A) until treatment was commenced in the October. This resulted in a gradual increase in film so that, in contrast with the slight accumulation in the control section (A), excessive accumulations of film were present throughout the winter. After cessation of treatment there was only a gradual decline in the film and an associated gradual recovery of the macro-fauna.

Taking the results of this experiment as a whole it is concluded that the close relationship between the induced incidence of the film and the periods of toxic applications shows that fluctuations in the amount of film are due to changes in the rates of biological activity rather than to physical or mechanical forces alone. The extent to which these micro-organisms and macro-invertebrates were involved is difficult to establish from these results of field observations. However, it would appear that following heavy winter accumulations of fungal film, the spring unloading can occur as result of microbial activity under conditions of reduced nutrient concentrations and increased temperatures. The activity of macro-invertebrate grazers would appear to be more important in preventing excessive accumulations of film, especially at times of high nutrient concentrations and low temperatures.

4. SUMMARY OF RESULTS

Before discussing the results in relation to other workers' results and theories the chief results of the different investigations described in this paper will first be summarized.

(1) In pure culture the growth rate of *Sepedonium* sp. increased with increasing temperature up to 25° C, after which it rapidly declined.

(2) Under limiting nutrient conditions in sewage effluent there was an increase in the rate of lysis of *Sepedonium* mycelium with increasing temperature.

(3) Growth of mycelial mats of *Sepedonium* under laboratory conditions in the absence of macro-invertebrate grazers and at constant temperature by drip feeding with a sewage for 3-week periods each calendar month showed that the growth rate was directly related to the average sewage strength for the period. Seasonal changes in the strength of the sewage resulted in differences in the growth rate at constant temperature. Light had no direct effect on the growth rate.

(4) Growth of mycelial mats of *Sepedonium* for 3-week periods each calendar month under field conditions in shafts in the surface layer of a bacteria bed with seasonal changes in both temperature and sewage strength, but in the absence of grazers, showed that differences in the amounts of film accumulating in different periods were more closely related to differences in the average sewage strength than to differences in temperature.

(5) Comparing the growth rate of film at different depths in the bed at different seasons of the year in the absence of grazers, it was found that the differences in the

amounts of film accumulating in the depths of the shafts were greater than in the upper layers. Less film accumulated at times of high temperature and weaker sewage than at low temperature and strong sewage.

(6) Observations on the progressive accumulation of film at different depths over 2 4-month periods showed that after an initial rapid accumulation of film during the first month there was a much slower build-up during the subsequent months. There was also a progressive change in the vertical distribution of the film throughout each period. In successive months a higher proportion of the film was found in the upper half of the bed. This trend was more marked in the summer period during which there was a reduction in the amount present in the depths of the bed.

(7) A comparison of the grazing activity of *Anisopus fenestralis* larvae showed that at 10° C more material was grazed during their longer larval phase than at 20 and 22° C. At 3° C little grazing occurred but the larvae remained alive; at 26.5° C there was little grazing and the larvae died before pupation. The grazing rate was approximately 50 per cent higher at 20 than at 10° C.

(8) The experimental suppression of the macro-invertebrate grazing fauna in sections of a bacteria bed by toxic applications for different periods of the year resulted in marked changes in the seasonal abundance of the film. It is concluded from this that seasonal changes in the amounts of film are the result of differential changes in the rates of biological activities. The results do not clearly indicate to what extent microbial activity and macro-invertebrate grazing occur. It would appear, however, that the unloading of fungal film can occur as a result of microbial lysis under conditions of reduced nutrient concentration and increased temperatures. Grazing activity by macro-invertebrates appear to be important in limiting the increase in film at times of high nutrient concentration and low temperature.

DISCUSSION

The seasonal fluctuations in film in bacteria beds have been variously explained by different workers. British workers, HARRISON (1908), REYNOLDSON (1942), LLOYD (1945) and TOMLINSON (1946) concluded that the increased grazing activity of the macro-invertebrates at the higher temperatures was responsible for the reduced amount of film present in the summer. American workers, on the other hand, have tended to lay greater stress on the mechanical scouring of the liquid and on the activity of the micro-organisms in the film, the activity of the macro-fauna being considered incidental or at most have a minor role (LACKEY, 1925; HOLTJE, 1943; HEUKELEKIAN, 1945; COOKE and HIRSCH, 1958). In Britain also, TOMLINSON (1942) reported the importance of bacterial attack on the hyphae of starving fungi.

These conflicting views can be partially resolved by taking into account the different methods of operation, different hydraulic loadings and different types of film. For example, in America where the sewage is generally weaker, much higher hydraulic loadings are applied and recirculation is commonly practised. Under such conditions it is possible that the grazing fauna play a less important role than in the conventional beds more common in Britain. It is also necessary to distinguish between seasonal fluctuations in film in beds treating domestic sewage in which the winter accumulation of film consists of bacterial slime and flocculated solids and fluctuations in beds treating industrial sewages in which the winter film is dominated by fungi. The relative importance of the different factors involved probably differs with these two types of film. Here we are concerned with fluctuations in fungal film. It is also important to recognize that agencies which may be important in the removal of film throughout the year are not necessarily those responsible for the spring unloading.

The three factors listed in the introduction as possibly affecting the seasonal abundance of film will now be considered.

5.1. *Direct effects of temperature*

Although in pure culture there was an increase in growth rate with increase in temperature over the range normally experienced in beds, there was also an increase in the rate of lysis with increase in temperature when nutrients were limiting. With most sewages nutrient concentration is probably a limiting factor and it is therefore probable that the standing crop of fungus, as opposed to its growth rate, is less at high temperatures than low ones, independent of other factors such as grazing. LAMANNA and MALLETTE (1953) writing on the effect of temperature on micro-organisms state: "Temperature is a most important variable in determining total growth, and the greatest crops are obtained below the temperatures giving most rapid growth." The indirect effect on temperature will be discussed in relation to the other factors considered.

5.2. *Strength of the waste*

The results had shown that the strength of the sewage was an important factor determining the growth rate of film. TOMLINSON (1946) found that the growth rate of film was related to the sewage strength, quite apart from the rate of application. COOKE (1959) studied the relationship between climatic data such as temperature and precipitation and the nature of the sewage and the amount of growth developing on glass slides placed on the surface of beds at Dayton (U.S.A.). No correlation was found except in the case of B.O.D. removed, and this was slight and only accounted for "an insignificant portion of the variability in growth pattern of the organisms on the surface of the filter".

The effect of sewage strength on the rate of decomposition of the fungal mycelium must also be considered. Field observations showed that marked reductions in fungal growths occurred at times when the sewage was weak. TOMLINSON (1942) demonstrated that under starvation conditions in weak nutrient solutions fungal hyphae were destroyed by bacterial lysis. This effect was greater at higher temperatures.

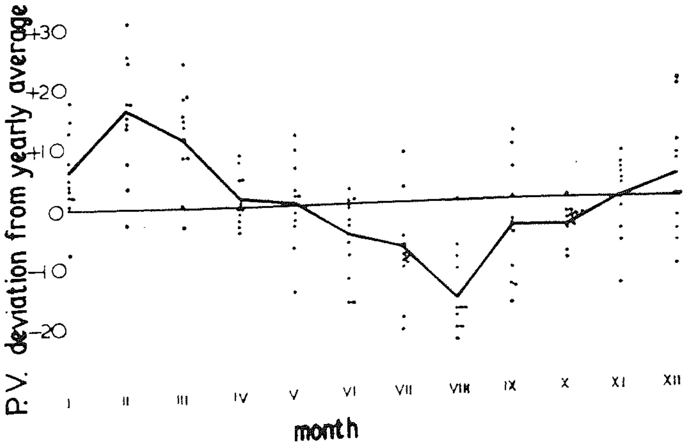

FIG 13. Seasonal fluctuations in the strength of an industrial sewage at Birmingham.

Thus the joint effect of temperature and sewage strength is probably a most important factor determining the seasonal pattern of fungal abundance. At Minworth (Birmingham) where these investigations were carried out, the sewage contains much industrial waste and the general seasonal fluctuations in strength are shown in FIG. 13. Each point represents the deviation of each monthly average permanganate value of the sewage from the yearly mean. The figures plotted represent the data for the 11 years 1954–1964 inclusive. The graph shows a definite seasonal fluctuation, the sewage being strongest in late winter and weakest in August.

5.3. *Grazing activity*

The laboratory culture work showed that *Anisopus fenestralis* larvae were able to devour fungal mycelium at a spectacular rate, and that this grazing activity increased with temperature over the range experienced in bacteria beds. The extent to which grazing activity was effective in influencing the seasonal pattern of fungal film in the beds, however, was difficult to assess by field experiments because of the effect of the suppressant on the microbial population directly. The amount of grazing is a product of the grazing fauna population and the individual grazing rate. The rate of grazing of *Anisopus fenestralis* at summer bed temperatures (20° C) was approx. 50 per cent higher than at winter temperatures (10° C). The populations, however, were many times greater in the winter. Thus, until the grazing fauna were suppressed by excessive accumulations of film, the overall grazing by *Anisopus* larvae was greater in the winter. It would thus appear that the incidence of the fungal film, as food, is more important in determining the incidence of grazers than *vice versa*. In stating this conclusion it is not intended to belittle the importance of grazers. It would appear that in the beds under observation at Minworth, the important role of the grazers, *Anisopus* larvae, was in limiting the winter accumulation of fungal film. Due to overloading or extremely low temperatures they were not always successful in this role and then the fungus growths produce adverse conditions which result in the death of the larvae. The subsequent unloading of the accumulated film then occurs in their absence. When the grazing population survive the winter they probably assist in the spring unloading because of their increased grazing rates at the increasing temperatures.

5.4. *The spring unloading of film*

The spring unloading, a common phenomenon in the activity of bacteria beds, has been variously explained by different workers. Most British workers have considered that the increased grazing at the higher temperatures is the most important factor. Systematic observations, over many years, on beds treating domestic sewage have shown that the spring unloading of the winter accumulation of solids is largely due to increased gazing activity of larvae of *Psychoda* and enchytraeid worms. In the case of film dominated by fungal hyphae, however, the present work shows that although grazing activity may contribute to the unloading, other agencies involving microbial activity are of major importance.

Most American workers consider that macro-invertebrates play no significant role in the unloading of solids from beds. HOLTJE (1943) found that the breakdown of fungal mycelium at higher temperatures was the major cause of the spring unloading. This conclusion is supported by the results of the present investigations. COOKE and HIRSCH (1958) observed that increased sloughing occurred following periods of excessive precipitation "when the filters receive an excessively high liquid loading". They concluded that, in the filters under observation, sloughing was related to the vigorous washing-out of excessive growths, i.e. the agency of removal was essentially physical. The results of the present observations also show a relationship between precipitation, as reflected by marked reduction in sewage strength, and spectacular unloadings in the spring. This, however, is explained in terms of nutritional changes by which the fungal mycelium under starvation conditions was more readily attacked by bacteria at times of increasing temperatures. Indeed, in the experimental beds under observation the flow remained constant, so increased hydraulic loading could not, in this case, have been a factor. Although the flushing action of the downward flow of sewage is necessary to carry away the dislodged solids as humus, the present work shows that the unloading of the film is essentially a biological phenomenon and is not the direct result of mechanical or physical agencies. In the case of film dominated by fungus this biological activity is mostly microbial although macro-invertebrates may contribute to it.

5.5. *A probable explanation of the seasonal fluctuations in populations in bacteria beds treating an industrial sewage*

Although the results do not conclusively prove the extent to which different factors are responsible for the seasonal fluctuations in the amounts of fungal film in bacteria beds, they all support the following general hypothesis accounting for the observed fluctuations.

As a result of the joint effect of seasonal changes in temperature and nutrient strength of the sewage there is a seasonal fluctuation in the standing crop of fungus. These fluctuations are the outcome of bacterial–fungal competition and bacterial attack. Low temperatures and strong wastes in the winter encourage the fungi, higher temperatures and weaker sewages of the summer favour the bacteria and limit the fungi. The decline from winter accumulation to summer sparsity can occur at a period in the spring of weak sewage and higher temperatures favouring the bacterial attack on the starving fungal mycelium. This can occur over a short period of reduced sewage strength.

The seasonal fluctuations in the macro-invertebrate grazers is largely determined by the abundance of their food—the fungal film. Thus those grazers which are able to thrive at winter bed temperatures 10° C, such as enchytraeid worms and *Anisopus fenestralis* larvae, are most abundant in the winter. Their effect on the film is superimposed on the fluctuations caused by microbial activity described above. This effect is greatest in the winter in limiting the accumulation of film, although they may also contribute to the unloading in the spring.

Although not responsible for the seasonal fluctuations in fungal film in beds the grazing fauna can have an effective controlling influence on such growths. For efficient operation, therefore, an ecologically balanced community including saprobic micro-organisms and macro-invertebrate grazers should be maintained.

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Paper No. 8

Comparison of four grades of sewage percolating filter media in relation to purification, film accumulation and fauna.

Hawkes, H.A., and Jenkins, S.H.

J.Inst.Sew.Purif., 88-112, 1955

PAPER No. 4

Comparison of Four Grades of Sewage Percolating Filter Media in Relation to Purification, Film Accumulation, and Fauna

By H. A. HAWKES, M.Sc. (Member), and S. H. JENKINS, D.Sc., F.R.I.C. (Fellow)

INTRODUCTION

In discussing aspects of sewage treatment on which information was needed, Hurley[1] included the size and arrangement of filter medium as one of the gaps in our knowledge. Reference to the literature reveals little fundamental work on the subject. Opinions as expressed in the 5th Report of the Royal Commission[2] varied as to the best size and nature of medium; generally, however, a finer grade medium than is advocated today was preferred, probably because of the treatment of effluents produced by prolonged settlement or by septic tank treatment. Because a high proportion of the cost of medium is due to haulage, most of the investigations on the subject have been concerned in determining whether locally available materials were suitable as media. For example in Florida[3], which has no hard igneous stone, investigations were carried out to compare locally available limestone, river gravel, and wood wastes, the first proving most satisfactory. In this country also, several such investigations have been made [2], [4], [5], [6]. The work reported here gives the results of observations carried out on a large scale under ordinary operating conditions.

Plant

In 1954, reconstruction of eight separate filter beds at the Minworth works of the Birmingham Tame and Rea District Drainage Board was completed. The eight beds were made into two blocks of four; the beds were fitted with travelling power-driven distributors; and the plant was designed to operate on the alternating double filtration principle[7]. In the process of reconstruction it became necessary to use an additional quantity of filter medium. Advantage was taken of this requirement to choose three different grades of medium and place them in the outside bed of a block of four beds, together with some of the medium originally present in the bed. This arrangement facilitated separate sampling of the four effluents from the four sections of the bed. These were known as A, B, C and D. The mechanical analysis of the different sizes of medium is given in Table 1.

For the purpose of this investigation the bed was operated as a single filter. Although the four sections were of different areas because of the different amounts of media available, the areas used for the collection of the four effluents were equal. They were so situated as to be equidistant from the middle point of travel of the two pairs of travelling distributors serving some or the whole of all four areas from one central trough (see Fig. 1); this ensured equivalent periodicity of dosing. The four effluents were collected into small subsidiary channels which discharged to the main bed effluent channel running alongside the bed. To prevent any mixing of the effluents, dividing walls were built up from the floor of the bed to a height of 2 ft. To enable the medium from different depths to be examined for film accumulation and fauna density, eight perforated cylindrical shafts, into which a column of 6 in. diameter perforated canisters closely fitted, were incorporated in each area. These were situated in two rows within the collecting areas and under the jet lines of the normal flow arm of the distributor. The jets were 24 in. apart. In one area, A, eight similar additional shafts were situated between the jet lines.

TABLE 1

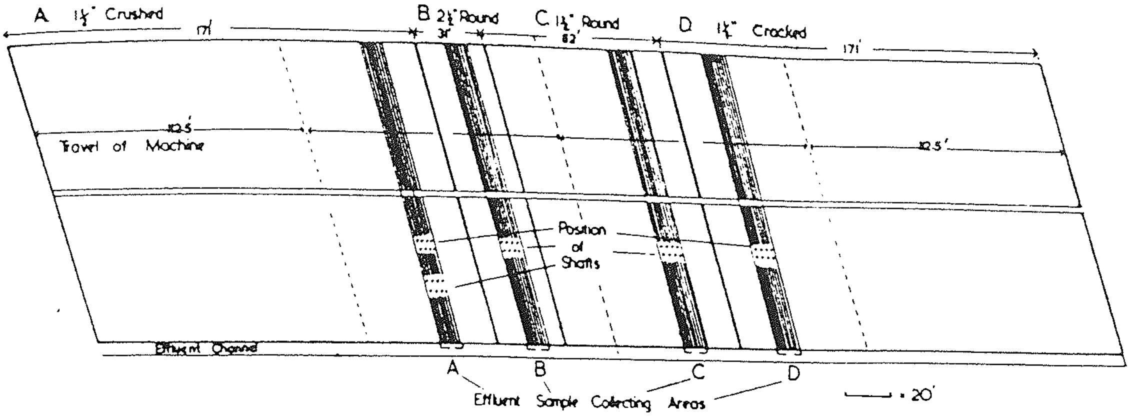
MECHANICAL ANALYSIS OF MEDIA: PERCENTAGE COMPOSITION BY SIZE

Grading	A	B	C	D‡
	Cracked	Round	Round	Cracked
Under ½"	0.2	0	0	9.9
½"—¾"	7.2	0	7.9	24.0
¾"—1¼"	64.5	0	40.5	50.0
1¼"—1¾"	28.1	30.0	49.4	16.1
1¾"—2¼"	0	49.7	2.2	0
Over 2¼"	0	20.3	0	0

‡Previously used medium containing some organic matter which dried out before the bed was put into operation.

Methods

To compare the relative efficiencies of the four sections, samples of the sewage feed and of the four bed effluents were taken every 2 hours throughout a 24 hour period each week. The 5 day B.O.D. (20°C), 4 hrs. O.A., ammon. N., and



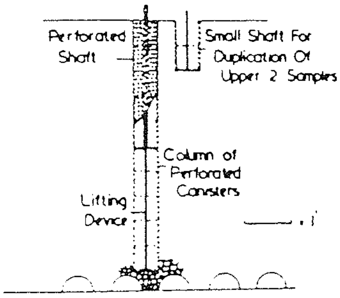


Figure 1

Above Plan of Experimental Bed showing 4 sections of different sized media with position of sampling shafts and effluent collecting areas

Left Diagram showing column of perforated canisters in shaft together with lifting device.

nitrite plus nitrate nitrogen were determined on these samples. The suspended solids figure for each was determined on daily samples taken hourly during the working day and bulked for weekly periods.

Each month a column of perforated canisters containing matured medium was lifted from one shaft in each area (two in area A) by means of a lifting device comprising a rod which passed through the centre of the core to a plate under the bottom canister and a tube which fitted over the rod and which was attached to a perforated plate under a canister half way down the shaft (Fig. 1). By this means the column could be raised at two lifts. The upper two canisters were duplicated; medium from one was used to determine the number of grazing fauna, from the other film was removed in a revolving drum washing machine[8] and the film content determined. Below the upper foot, alternate canisters in the shaft were used for fauna and film determinations.

RESULTS

The analytical results of the sewage and the four effluents were calculated as monthly averages and are expressed graphically in Fig. 2., together with the temperature of the bed surface and O.A. loading during the sampling period. Because of a faulty distributor arm the flow to the two rows of

TABLE 2

PERCENTAGE VERTICAL DISTRIBUTION OF FILM AND GRAZING FAUNA IN 4 SECTIONS OF A SEWAGE PERCOLATING FILTER HAVING DIFFERENT SIZED MEDIA; NOMINALLY, A 1½ IN. CRUSHED GRAVEL; B, 2½ IN. ROUND GRAVEL; C, 1½ IN. ROUND GRAVEL; D, 1¼ IN. CRACKED GRANITE

Depth ft.	Film				*Anisopus* larvae – pupae				*Psychoda* larvae – pupae				*Lumbricillus*			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
0.5	26.2	33.9	28.1	25.0	28.2	19.6	12.8	24.7	18.9	7.4	14.9	16.5	18.7	18.8	31.4	12.4
1	18.8	17.8	22.1	23.0	36.3	16.4	40.5	39.9	29.4	13.8	25.8	36.9	26.7	25.6	25.7	19.8
2	17.0	15.8	19.6	18.2	24.6	24.3	30.8	16.2	28.4	27.5	28.6	26.2	24.9	21.7	22.9	35.5
3	14.5	14.5	13.6	12.5	9.5	20.4	14.2	15.0	16.8	39.2	19.9	15.1	19.3	18.4	12.3	16.4
4	11.0	9.5	9.3	11.4	1.4	11.9	1.2	3.0	6.5	9.8	6.5	4.8	10.4	9.6	4.4	9.7
5	12.5	8.5	7.3	9.9	—	7.4	0.5	1.2	—	2.4	4.4	0.5	—	5.9	3.4	7.2

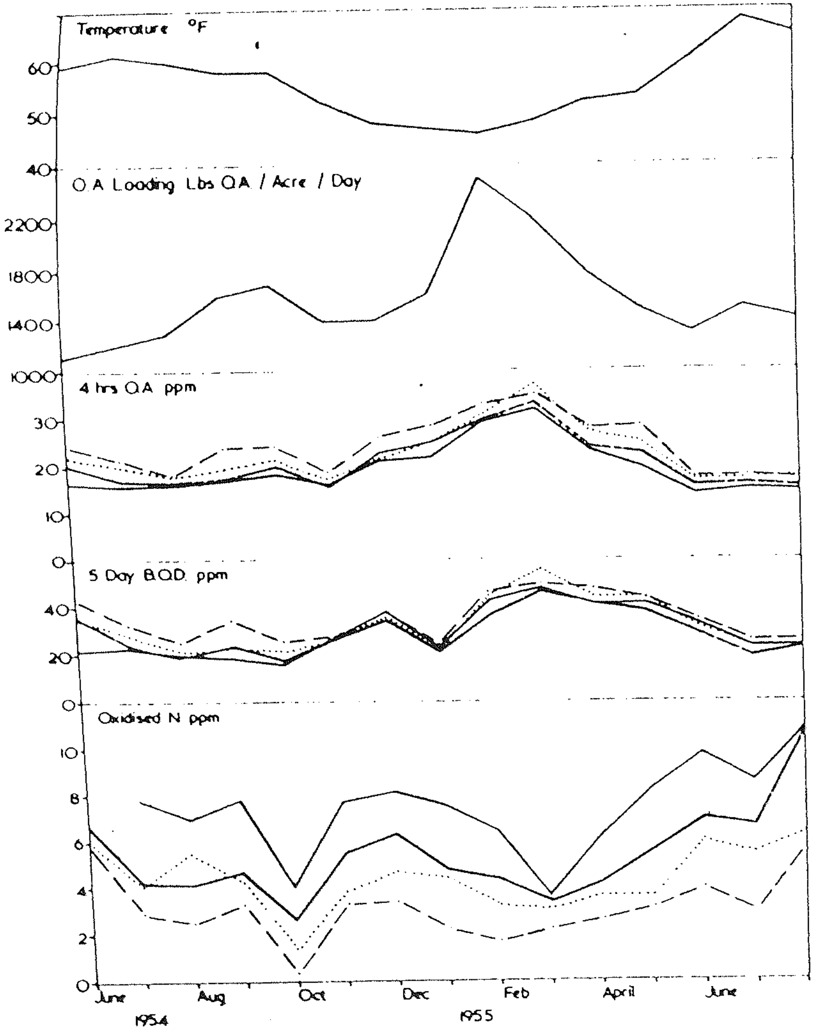


Figure 2
Comparison of effluent quality from 4 sections of sewage percolating having different sized media.

A - 1½" Crushed ———
B - 2½" Round — - —
C - 1½" Round ……
D - 1¼" Cracked ———

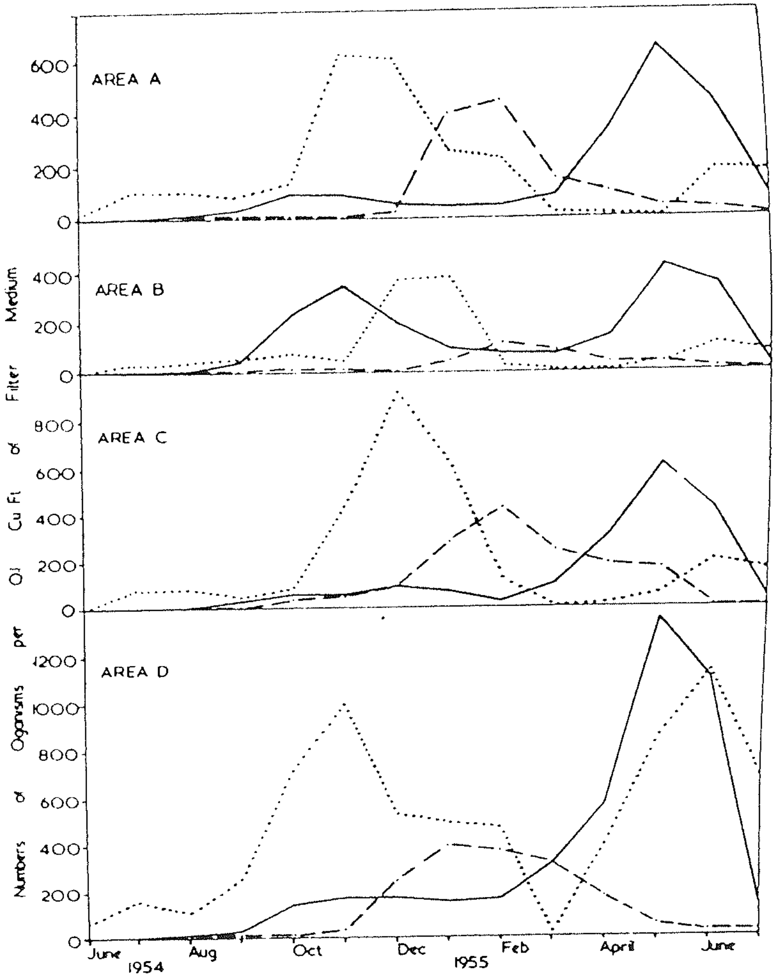


Figure 3
Grazing fauna population in 4 sections of sewage percolating filter having different sized media

A - 1½" Crushed
B - 2½" Round
C - 1½" Round
D - 1¼" Cracked

Lumbricillus ———
Anisopus — - — - —
Psychoda ……

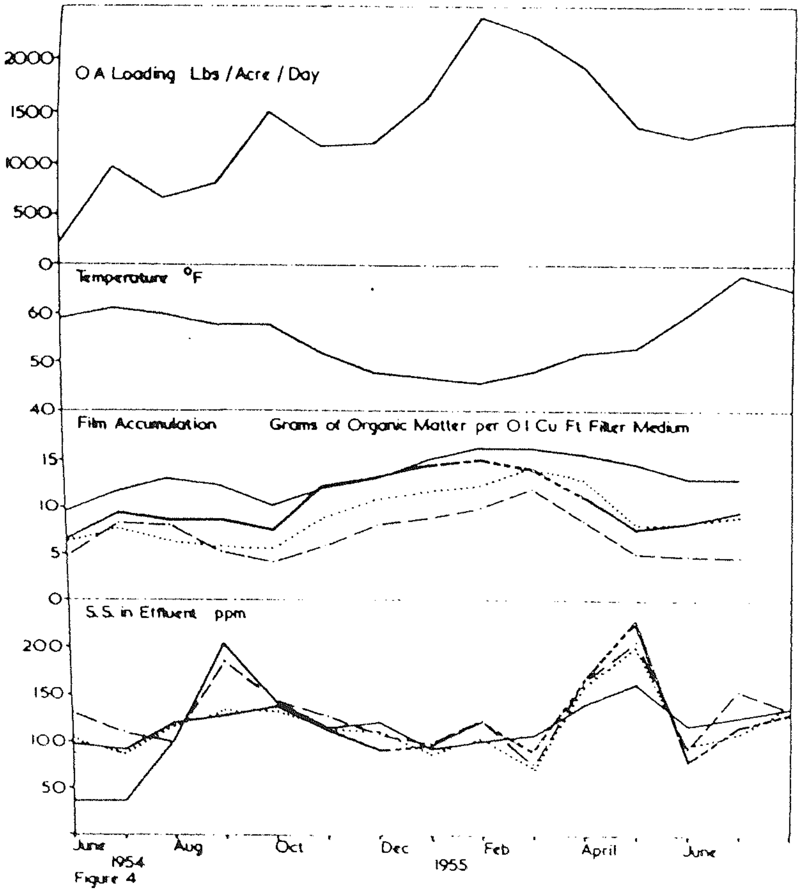


Figure 4
Film accumulation in and humus discharges from 4 sections of sewage percolating filter having different sized media.

A - $1\frac{1}{2}''$ Crushed ————
B - $2\frac{1}{2}''$ Round — · — ·
C - $1\frac{1}{2}''$ Round · · · · · ·
D - $1\frac{1}{4}''$ Cracked ————

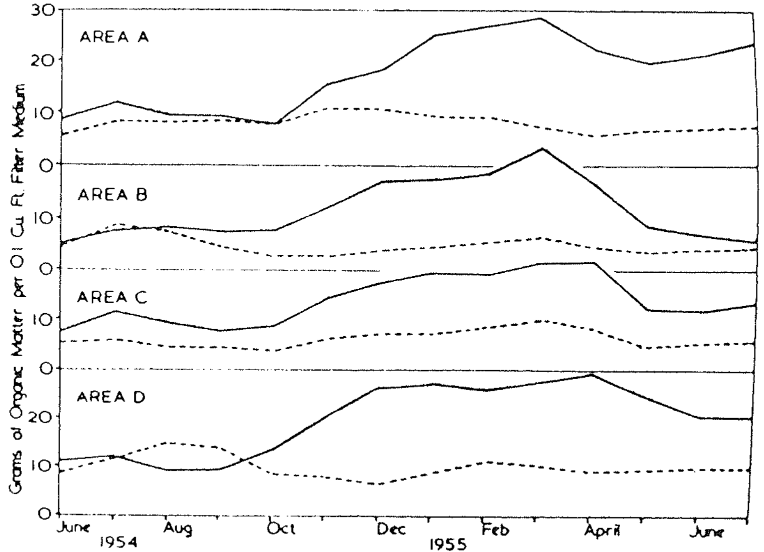


Figure 5
Concentration of film in upper foot of percolating filter compared with that in in lower 4 feet.
Film concentration 0-12" ————
" " 1'- 5' - - - - - -

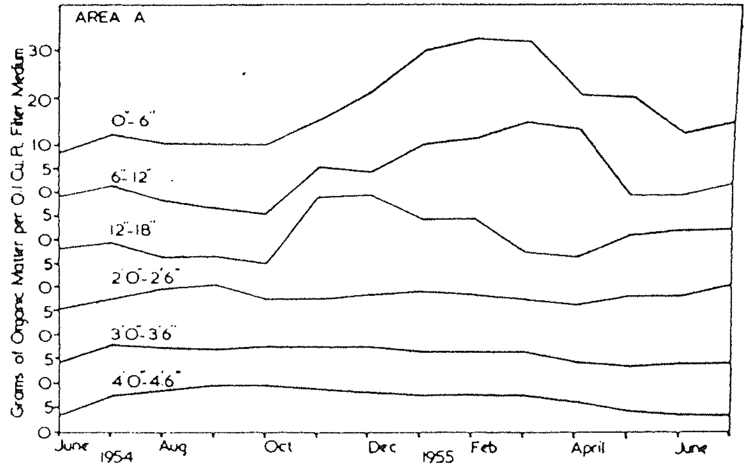


Figure 6
Seasonal fluctuations in film accumulation at 6 levels in sewage percolating filter

shafts on area A was unequal, and as the shafts were sampled from the two rows alternately the film accumulation and fauna showed a series of peaks and troughs on successive months. To overcome this, and since only the general seasonal trends were being compared, a two-point moving average was used. The comparative fluctuations in populations of the dominant grazing fauna are shown in Fig. 3. Fig. 4 shows the relative film accumulations in the four areas in relation to the O.A. loading and temperature. A measure of the humus discharge is given by the suspended solids in the bed effluents. The vertical distribution of the film and fauna was investigated, and the monthly figure for the different depths was expressed as a percentage of the total. The averages of these percentages for the four areas are given in Table 2. The seasonal fluctuations in the amount of film in the upper foot of the bed and in the remainder of the bed in the four sections are given in Fig. 5. For section A the seasonal fluctuations at different depths are shown in Fig. 6.

DISCUSSION AND CONCLUSIONS

It was not possible, due to operational requirements, to maintain a uniform flow to the bed, as shown by the O.A. loading graph (Fig. 2). After a period of maturation it was intended to dose at a rate of 150 g.y.d., but this was exceeded during the winter months. By comparing the bed effluents, it is seen that on the basis of the O.A. the original medium in area D gave the best effluent, followed by area A with crushed medium, and then area C with 1¼ in. round medium. Area B with the large round medium produced the worst effluent. The oxidised N results are in agreement with this order of efficiency. Although the average B.O.D. figures are also in agreement, on several occasions effluent A was superior to D, which on some occasions was as bad as B; likewise, effluent C was superior to A and at other times inferior to D.

A comparison of the fauna populations in the four areas (Fig. 3) shows that throughout the period there were successions of dominant grazers in all areas, but the relative abundance and total populations differed. Although the populations in areas A and C were very similar, *Psychoda*, *Anisopus* and *Lumbricillus* being successively the dominant grazers area B, with the largest medium, supported a smaller population, with *Lumbricillus* as the dominant grazer for most of the period, with *Psychoda* subdominant and *Anisopus* comparatively rare. Area D, with the small cracked medium, supported the largest population, there being a similar succession to that found in A and C, but later in the period both *Lumbricillus* and *Psychoda* were very abundant. The fluctuations in film accumulation (Fig. 4) in all areas showed the typical winter accumulation; after the initial increase of film during maturation there was a slight autumn unloading, and a more marked one in the spring. The heavier discharges of humus at these periods are evident from the suspended solids graph (Fig. 4). The average amounts of film throughout the depth of the bed differed in the four sections, with most being present in D and least in B. As shown in Fig. 5, the winter accumulation of film in all sections occurred in the upper foot of the filter, whereas below this there was an almost uniform film concentration through the year. This fact is further illustrated in Fig. 6, showing fluctuations at different levels in area A.

The percentage distribution of film and grazing fauna given in Table 2 shows that there was a reduction in film content as depth increased in all four sections; the relatively higher percentage distribution of film in the surface of section B could be correlated with the lower percentage of grazing fauna in this position. The vertical distribution of the fauna, which were at a maximum at the 1 ft. level in sections A, C and D and even lower down in section B, was probably determined by the availability of food, the flushing action of the applied sewage, and the temperature. The greater abundance of fly larvae in section B at a greater depth was presumably due to the greater flushing action of the sewage between the large voids; *Lumbricillus*, however, whose setae enable it to withstand considerable flushes, was more abundant nearer the surface in this section. In addition to these environmental factors, interspecific competition was probably of importance. Thus, the relatively lower percentage of *Lumbricillus* in the upper foot of D, compared with the other areas, may be correlated with the higher percentage of fly larvae in this position.

In general, the quality of the effluent was related to the size of the medium, the smallest medium producing the best effluent. Theoretically, the finer the medium the greater the surface area in relation to unit volume, the longer the retention period, and the greater the purification efficiency, provided that aeration is adequate. The aeration in relation to the percentage of voids is, however, greater the larger the medium. These factors are discussed by Goldthorpe[9]. Investigations have shown that in practice although the smaller medium, when fairly clean, does produce better results than the coarser medium[4, 10] the relative increase in efficiency is not as great as might be expected from theoretical considerations. This view is confirmed by the work reported here. Work on the purification of beet sugar wastes[11] in which liquors containing large quantities of suspended matter (about 300 p.p.m.) were treated at equivalent rates in filters of different media, viz :— $\frac{3}{4}$ in.-1$\frac{1}{2}$ in. gravel, $\frac{3}{8}$ in.-$\frac{3}{4}$ in. slag, $\frac{1}{8}$ in.-$\frac{1}{4}$ in. gravel, and $\frac{1}{8}$ in.-$\frac{1}{4}$ in. clinker, showed that although the finer medium immediately produced a well purified effluent, the efficiency decreased as the solids accumulated and choked the filter; the coarse medium, however, at first provided only a moderate degree of purification, but as the film developed the purification improved until a good quality effluent was produced. In the present work, although accumulation of film was greatest in the smallest medium (D), and during the winter resulted in surface ponding, the effluent remained superior to the others derived from larger medium. It would appear that the surface accumulation of film and resultant ponding did not, in this case, seriously affect the aeration of the lower depths of the filter.

The optimum size of medium for any given circumstance will be the smallest grade which, whilst providing the largest surface area per unit volume, at the same time provides sufficient volume of voids in which solids can accumulate without impeding aeration to the point where it limits the rate of oxidation. Apart from size, the shape, ratio of dimensions, and tendency to "pile" must also be taken into consideration[12]. The best type of medium will probably vary with different sewages and different operational conditions such as loading, method of distribution, periodicity of dosing, and method of operation. In practice, the choice of medium is probably best determined by large-scale tests under operating conditions, and it is along these lines that the present investigation is being continued.

SUMMARY

The results are summarised in Table 3.

TABLE 3

Medium Size (Nominal)	1¼" Cracked Granite (D)	1½" Crushed Gravel (A)	1¼" Round Gravel (C)	2½" Round Gravel (B)
O.A. p.p.m.	20.4	21.9	23.6	25.3
B.O.D. p.p.m.	30.9	30.9	34.8	37.5
Oxidised N p.p.m.	7.4	5.1	4.1	2.9
Amm. N p.p.m.	25.5	28.4	29.7	30.3
Anisopus Nos. per 0.1 cu. ft.	104	76	96	21
Psychoda Nos. per 0.1 cu. ft.	429	159	181	76
Lumbricillus Nos. per 0.1 cu. ft.	269	125	117	125
Volatile Matter, mg. per 0.1 cu. ft.	12.4	9.8	8.4	6.6

ACKNOWLEDGMENTS

The authors wish to thank Mr. M. R. Vincent Daviss, Engineer to the Birmingham Tame and Rea District Drainage Board, for permission to publish this paper, and to the members of his staff in the Laboratory and at Minworth Works who have co-operated with the work.

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Paper No. 9

Comparison of four grades of media in relation to purification, film accumulation and fauna in sewage percolating filters operating on alternate double filtration.

Hawkes, H.A., and Jenkins, S.H.
J.Inst.Sew.Purif., 221-5, 1958

Paper No. 2

Comparison of Four Grades of Media in Relation to Purification, Film Accumulation, and Fauna of Sewage Percolating Filters operating on Alternating Double Filtration

By H. A. HAWKES, M.Sc., M.I.Biol. (Associate Member), and S. H. JENKINS, D.Sc., F.R.I.C. (Fellow)
(*Birmingham Tame and Rea District Drainage Board*)

INTRODUCTION

In reconstructing a portion of the filtration area at the Minworth Works of the Birmingham Tame and Rea District Drainage Board it became necessary to use additional filter medium. Advantage was taken of this requirement to construct one bed just over 1 acre in area, using four different grades of media and arranged in four sections so that the effluent from the different sections could be sampled separately. Initially the new bed was operated on single filtration and a comparison was made of the four effluents and corresponding biological conditions within the filters. The results of these observations have previously been reported[1]; the present paper reports on the continuation of these observations during a period when the filter was operated on alternating double filtration. The sewage treated is of an industrial nature. It receives inadequate settlement at Saltley Works and additional settlement at Minworth before biological filtration.

PLANT AND METHODS

A more detailed account of the plant and methods has been given previously.[1] The nominal sizes of the four grades of media on Bed No. 4 in the sections known as A, B, C and D, were respectively 1½ in. crushed gravel, 2½ in. round gravel, 1½ in. round gravel and 1¼ in. cracked granite. The mechanical analysis of the different media is given in Table 1. To compare the relative efficiencies of the four sections, samples of the sewage feed and the four bed effluents were taken every 2 hours throughout two successive 24 hour periods each week, when the beds were successively primary and secondary. Routine tests were carried out on these settled bed effluents; suspended solid determinations were also carried out by taking the shaken hourly samples throughout the working day, mixing them to make a single weekly sample from each bed, and analysing the mixed sample.

TABLE 1

MECHANICAL ANALYSIS OF MEDIA: PERCENTAGE COMPOSITION BY SIZE

GRADING	A	B	C	D
	Cracked	Round	Round	Cracked
Under ½"	0·2	0	0	9·9
½" — ¾"	7·2	0	7·9	24·0
¾" — 1¼"	64·5	0	40·5	50·0
1¼" — 1¾"	28·1	30·0	49·4	16·1
1¾" — 2½"	0	49·7	2·2	0
Over 2½"	0	20·3	0	0

The biological conditions of the sections were observed monthly by removing from each section of the different media a column consisting of a number of perforated canisters containing the appropriate medium. The film was removed and its solid content determined[1]; the contents of corresponding canisters were used to determine the grazing fauna population.

RESULTS

The analytical results for the sewage fed to the filters and the settled bed effluents were calculated as monthly averages, which are expressed graphically in Figs. 1 and 2. A three point moving average was applied to the results as comparison was only being made on the general seasonal trends. Although during the period of observation the filters were operated on the alternating double filtration (A.D.F.) principle, it was not possible to isolate each area as a complete A.D.F. unit and thus although each area received primary and secondary feeds on alternate days, the secondary feed was the mixed primary bed effluents from four filters each the size of Bed No. 4. For this reason it is necessary to consider the results as two separate processes, *i.e.*, primary filtration and secondary filtration. Fig. 3 shows the relative accumulations of film and comparative fluctuations in population of the dominant grazers.

PRIMARY FILTRATION DISCUSSION

Examination of the comparative O.A. and B.O.D. graphs of the primary effluents from the four areas, Fig. 1 shows that the relative efficiencies of the four grades of medium were not at all seasons in the same order. During the first winter in 1956 for example, area D with the smallest medium produced an effluent having an O.A. and B.O.D. considerably higher than the other areas, whereas area B, with the largest medium, produced the best results. Throughout the following summer however Area B produced the worst effluent. In the next winter (1956-57) the smallest medium continued to produce a better effluent than the larger medium B, although there was some indication that during mid winter the graphs converged—this was especially evident in the case of the B.O.D. The results for the Spring of 1957 again diverge, area D with small medium giving the best results and B again the worst.

It is considered that these differences are due to seasonal changes in biological conditions within the filters. Although during the first winter the fauna in all four areas was depleted due to previous enforced resting of the bed, the accumulation of film was by far the greatest in the smallest medium (Area D) where it caused severe ponding and a marked decrease in efficiency. The accumulation of film in the largest medium (B) although of the same order as that in A and C had less effect in the large medium where no ponding occurred. In the spring of 1956, after unloading of the filters, although the film concentration was greatest in the smallest medium (D), it was not sufficient to cause ponding and in fact this area produced the best primary effluent presumably because the smaller

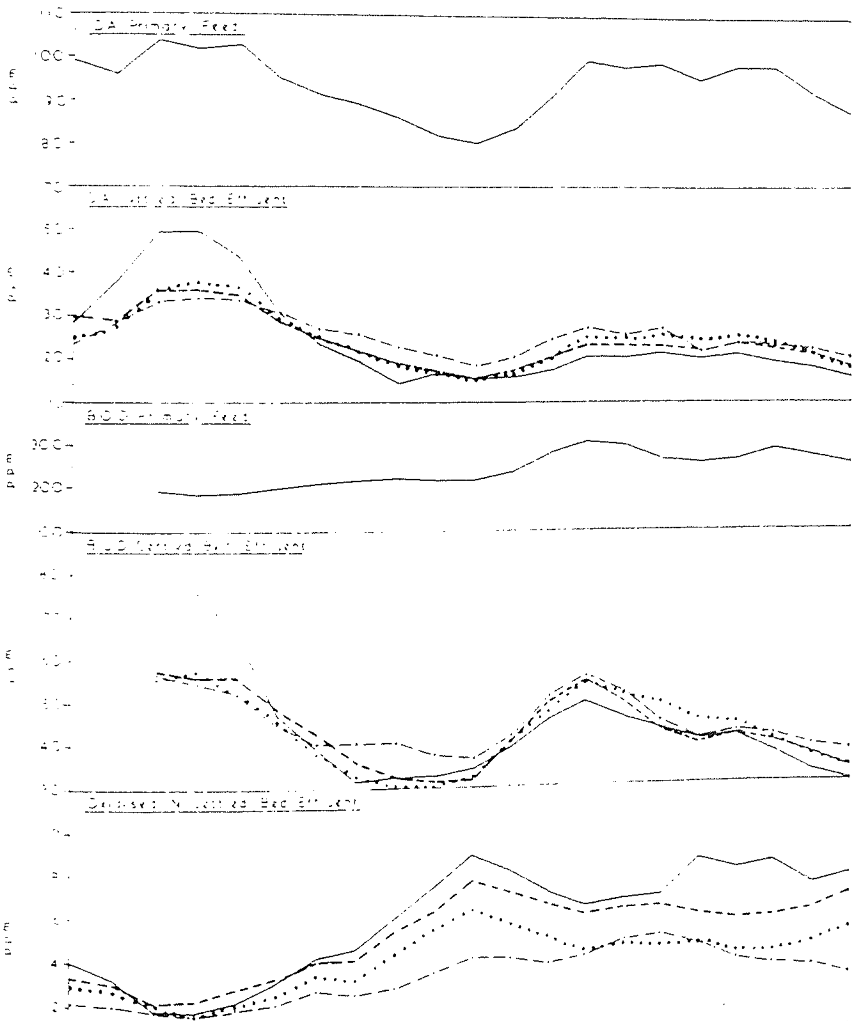

Figure
Comparative analysis of effluents from four areas of a sewage percolating filter having different sized media —
A 2 Crushed — — —
B 2 2 Round —·—·
C 2 Round · · · · ·
D 4 Crushed ———

medium provided a larger surface area per unit volume and a larger retention period. In contrast the largest medium which no doubt was able to endure film accumulation during the winter, produced the worst effluent in the summer, when all areas contained less film. During the second winter (1956-57) not only had an effective grazing fauna population become established in all areas but the winter was unusually mild and the winter accumulation of film, even in area D, was not excessive. No serious ponding occurred and no corresponding marked decrease in efficiency was observed. As a result the effluent from D during the second winter continued to be the best.

Except for the first winter when little nitrification occurred in any area, the smallest medium (D) also produced the most highly nitrified primary effluent and for the most part the largest medium (B) the least. In between these extremes there was also a marked difference between (A) the crushed gravel and (C) the round gravel of similar size; the former produced the more highly nitrified effluent. On the basis of O.A. and B.O.D. results the effluents from A and C were for long periods much alike but at other times, especially during the winter, A gave a superior effluent.

SECONDARY FILTRATION

During the secondary stage of alternating double filtration less work is done in reducing the O.A. and B.O.D. than in the primary stage, especially when the primary effluent is of fair quality (Hawkes 1957).[2] Since the secondary feed to all four areas was the same, as previously stated, the differences in the secondary effluents from the four areas were only slight. Even so, the relative O.A. values for the secondary effluents followed a similar pattern to the primary effluents; the small medium (D) produced the worst effluent during the

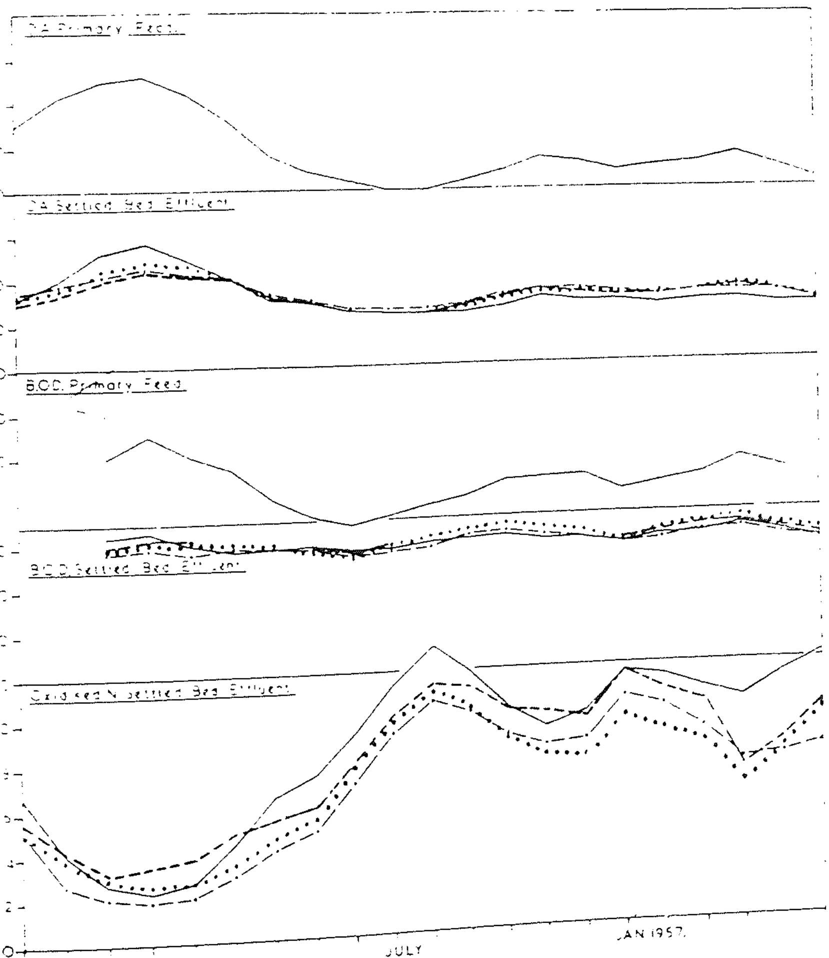

Figure 2
Comparative analysis of secondary effluents from four areas of a percolating filter having different sized media —

A 1½ Crushed — — —
B 2½ Round —·—·
C 1½ Round ······
D 1¼ Cracked ——

severe first winter but thereafter it produced the best. In the case of the B.O.D's. this pattern was less clear, and little difference was observed between any of the effluents. Comparison of the graphs giving the content of oxidized forms of nitrogen in the primary and secondary effluents shows that the differences between the four effluents were of the same order in both stages of filtration.

As shown in Figs. 1 and 2 the differing biological conditions in the four filters affected their relative efficiencies, the largest medium (B) which under clean conditions produced an inferior effluent, proving to be less affected by the excessive accumulation of film under severe winter conditions. The relative accumulations of film and grazing fauna populations in the four areas are shown in Fig. 3. It will be seen that in all areas there was a seasonal fluctuation in the amount of accumulated film, the greatest accumulation occurring during the winter months. The greatest fluctuations took place in the area (D) having the smallest medium, and the least in areas C and B. In all areas the greatest accumulation occurred during the first severe winter when the populations of the grazing fauna are shown to be the lowest. Fig. 3 shows that the seasonal fluctuations in the populations of *Anisopus* larvae followed a similar pattern in all four areas, the numbers being greatest during the second, milder, winter. The *Anisopus* population in the two areas having the smaller medium (A and D), was greater than in the other areas, and was least in the largest medium B.

In the case of *Psychoda* also a similar pattern of incidence may be seen. The *Psychoda* population in area A was somewhat higher than those in C and D but all three showed a similar pattern. In Area B, with the largest medium, there was, except for a short period during the initial spring unloading, no effective *Psychoda* population. The *Lumbricillid* worm population was very similar in A, B and C but the small medium of area D supported a *Lumbricillid* worm population which for periods was far greater than in the other areas.

On the whole the smallest medium D, supported the largest grazing population and the largest medium, B, the lowest. At the same time it appears that the smaller the medium the more essential is an effective grazing fauna to maintain the efficiency of the filter.

CONCLUSIONS

The results, although not giving a clear answer as to which of the four media investigated was

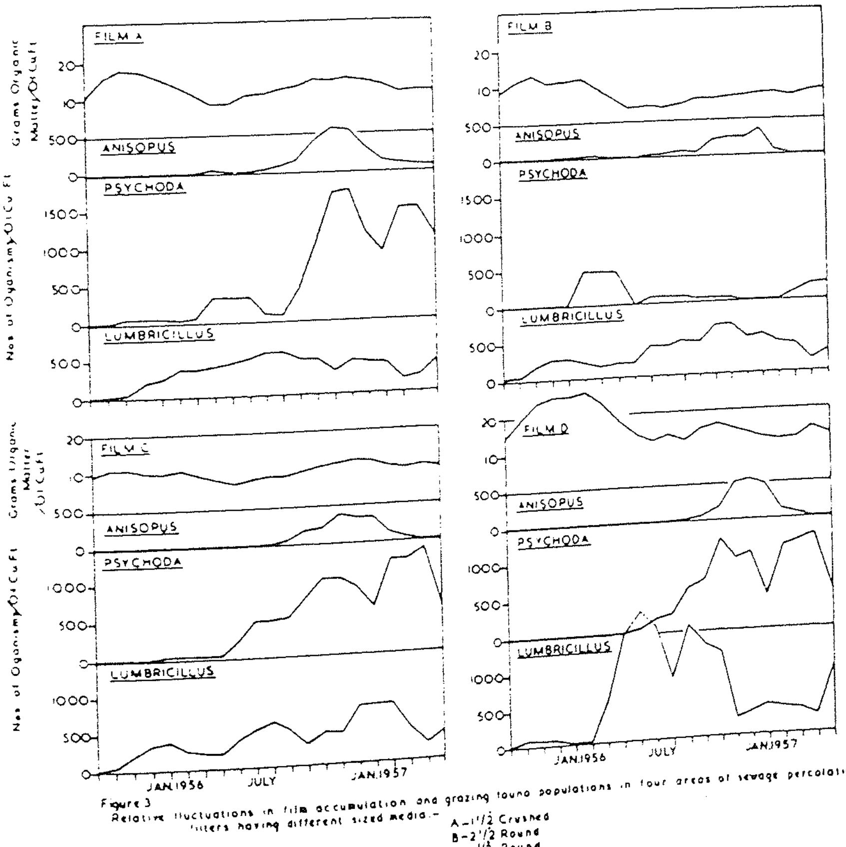

Figure 3
Relative fluctuations in film accumulation and grazing fauna populations in four areas of sewage percolating filters having different sized media.–
A–1½ Crushed
B–2½ Round
C–1½ Round
D–1¼ Cracked

superior under all seasons and conditions, illustrate that the efficiency of different filter media is not determined only by the physical characteristics, such as surface area per unit volume or percentage of voids per unit volume, but is also affected by the various biological conditions such media create under varying seasonal conditions. Thus it is to be expected that the best medium for any filter will depend not only upon the rate and nature of the sewage being treated but also upon the method of operation of the filters, *e.g.*, single filtration, recirculation, double filtration or alternating double filtration and such other factors as the method of distribution and periodicity of dosing, all of which affect the biological conditions. For example, when operating the four experimental areas as single filters it was found that although the smallest medium, D, accumulated more solids than the other areas and ponded more seriously during the winter months, the effluent was at all times superior to those from the larger media. (Hawkes and Jenkins 1955).[1] When operating as an alternating double filter as shown above the effluent from area D during severe winter conditions was inferior to the other areas. This difference may be connected to the fact that with A.D.F. there is, at the same rate of treatment, twice the volume of sewage applied to the surface of the filter at any one time than with single filtration and, presumably, a correspondingly increased volume of sewage within the filter. Under these conditions the ponding may be aggravated.

Because of the different conditions under which filters have to operate at different works, with different sewages, it is unlikely that a single standard medium could ever be prescribed for all sewage works. Generally the choice of media is limited by the material available locally; of those available the most suitable is best determined by tests under actual operating conditions, such as are described in this paper. When the results are not conclusive, as in this case, it would appear most practicable to chose the medium which shows least deterioration in efficiency under severe winter conditions, and also produces a well oxidized effluent at other times. In the present investigation, for example, although the smallest medium, area D, produced the best results under favourable conditions it was subject to serious reduction in efficiency under severe winter conditions. Of the other media, although the largest medium area B, withstood the severe winter conditions best, the deterioration in the efficiency of area A, having the nominal 1½ in. crushed gravel, was only slightly greater and its efficiency throughout the remainder of the period was superior to that of B and for most of the time was also superior to that of area C with the slightly larger medium. On this basis it is considered that, of the four media investigated, the nominal 1½ in. medium, area A, was preferable.

SUMMARY

1. In comparing the relative efficiencies of four grades of filter media, nominally 1½ in. crushed gravel, 2½ in. round gravel, 1½ in. round gravel and 1¼ in. cracked granite, in primary and secondary stages of alternating double filtration it was found that the relative efficiencies of the four grades varied seasonally, the smallest grade being superior under summer conditions and the largest under severe winter conditions.
2. These variations were explained by the varying biological conditions within the filters. The largest medium was least affected by the excessive accumulation of film during extreme winter conditions, which caused serious ponding and a marked fall off in efficiency in the smallest medium.
3. The seasonal fluctuation in film accumulation was greatest in the smallest medium which also supported the largest grazing fauna population. The smallest grazing fauna population was found in the largest medium.
4. Because variations in biological conditions affect the relative efficiencies of the different filter media and since these conditions are determined by such factors as the nature of the sewage, the rate and method of application and the system of filtration it is not considered practicable to prescribe one type and grade of medium for all sewage filters.
5. Of the four media tested it was concluded that the 1½ in. crushed gravel was best suited to operate on Minworth sewage by alternating double filtration treatment at an approximate overall rate of 135 g.y.d.

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Paper No. 10

The effects of methods of sewage application on the ecology of bacteria beds.

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THE EFFECTS OF METHODS OF SEWAGE APPLICATION ON THE ECOLOGY OF BACTERIA BEDS

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(With 3 Text-figures)

Two difficulties in treating sewage in bacteria beds—namely, the choking of the beds by excessive growths of micro-organisms and the nuisance from flies breeding in the beds—are considered as one ecological problem. The effect of the manner in which the sewage is applied to the bed through different types of distributor nozzle on the film and fauna populations was studied. It was found that nozzles which provided a strong flushing action on the surface did not prevent excessive growth of film below the surface but did limit the grazing fauna, as a result of which the amount of film was greater than under jets in which the flushing action was reduced. Where this reduction was effected by allowing the sewage jet to first impinge on a splash plate, uniform conditions were produced in the medium below, where the species were in direct competition for food in the one ecological niche. As a result the fly larvae (*Anisopus fenestralis* and *Psychoda* sp.) suppressed the population of *Achorutes subviaticus* (Collembola) during the winter. Where the flushing action was reduced by allowing the sewage to flow through an increased number of holes of smaller bore, two niches were provided, one wet region, subject to some flow of sewage, and the other drier region between the jets. Under this method, two populations existed side by side, *Achorutes* being present throughout the year in the drier zone and *A. fenestralis* larvae occupying the sub-jet zones.

Introduction

The purification of settled sewage in bacteria beds (sewage percolating filters) involves the activity of both micro-organisms and macrofauna. Micro-organisms, including bacteria, protozoa, fungi and, on the surface, algae, grow as a slime or film on the stones and feed on the nutrient organic matter in the sewage, thus purifying it. The macrofauna such as fly larvae, worms and Collembola graze on the film which would otherwise increase and choke the beds. Experience has shown that only a very thin slime is required for efficient purification, whereas an excessive accumulation of film adversely affects the efficiency (Hawkes, 1957). The flies present in the filters, although beneficial in the larval stage, may produce a nuisance when they leave the filters as adults. Thus the two problems inherent in operating sewage bacteria beds, the prevention of excessive accumulation of film and the prevention of fly nuisance, may be considered as one ecological problem.

The fly population of bacteria beds has been studied by previous workers (Lloyd, 1945; Tomlinson & Stride, 1945) and Reynoldson (1939) studied the enchytraeid worm population; film accumulation studies have also been carried out by

Heukelekian (1945) and Tomlinson (1946). At Minworth the ecology of *Anisopus fenestralis* has been studied in relation to its control by insecticides. A full ecological study including the investigating of the factors influencing both the growth of the film and the macrofauna populations is, however, necessary to explain the results obtained.

The artificial habitat of bacteria beds necessitates a study of the effects on their ecology resulting from the different practices of operating the beds. Hawkes (1955) showed that the periodicity of application of the successive doses of sewage affects the nature and amount of film and the nature of the grazing fauna. A slower rotation of the revolving distributors resulted in a marked reduction in the amount of film, accompanied by a fauna dominated by lumbricillid worms, whereas in the control bed, having rapidly rotating distributor arms, thick fungal growths developed each winter and fly larvae were the dominant grazers. Similarly, Tomlinson & Hall (1955) showed that beds with the slowly revolving distributors were more efficient in oxidizing organic matter. However, it is difficult to apply these results to rectangular beds having reciprocating distributors. As the manner in which the sewage is applied to the bed through different types of distributor nozzle might also affect the film accumulation this factor was investigated. The present paper describes the results obtained.

METHODS

The bed chosen for the test received settled sewage by means of a mechanical travelling distributor which traversed the bed, dosing in both directions, once every 6 min.; the areas selected were about the centre points of travel and thus received an application of sewage every 3 min. Before modification the machine discharged sewage to the bed through two horizontal pipes, one of which operated only at times of high flow. Each pipe had $\frac{7}{8}$ in. diameter nozzles so spaced that the jets discharged vertically downwards on to the bed surface, approximately 9 in. below, at approximately 24 in. spacing: the jets on the two pipes were staggered so that at high flows when both pipes were working, jets were discharging at 12 in. intervals. For the purpose of the test, however, only one pipe was used. Each nozzle delivered sewage at an approximate rate of 380 gal. per hour. Equally spaced about the middle of the pipe alternate nozzles were modified to give different methods of distribution along six strips of the bed, each strip being 24 in. wide, i.e. the width served by one jet. The modifications were as follows:

(A) Open fish-tail, in which the jet from the $\frac{7}{8}$ in. diameter nozzle discharged over a triangular tray slightly inclined from the vertical to produce a sheet of liquid approximately 24 in. wide at the surface of the bed.

(B) Closed fish-tail, whereby the sewage discharged through a rectangular orifice 9 in. long and $\frac{1}{4}$ in. wide to produce a sheet of liquid approximately 24 in. wide but with a somewhat stronger impinging force.

(C) Splash plate—a circular disk $2\frac{1}{2}$ in. diameter on to which the jet was first allowed to impinge, producing a circular sheet of approximately 24 in. diameter.

(D) The unmodified nozzle producing a cylindrical jet of liquid approximately 1 in. in diameter.

(E) Twin jets—whereby the jet was divided into two by means of a horizontal pipe having two ¾ in. holes through which the sewage discharged downwards on to the bed as two jets 12 in. apart; the total volume being equal to that discharging through one unmodified nozzle.

(F) 'Quad' jets—similar to E but having four ½ in. jets, each 6 in. apart.

To assess the amount of surface growth, areas 12 in. × 24 in. of clean stones were so placed on similar areas of steel mesh as to extend 12 in. to either side of the original jet line and to cover a distance of 12 in. of the travel of the distributor, the depth of stones being approximately 1½ in. The steel mesh rested on the medium below. Eight such areas were situated along the paths of each of the six jets under observation. In the medium underneath the meshes there were three rows of two cylindrical cans 6 in. in diameter and 6 in. deep, the base and sides of which were perforated with seven and sixty ¾ in. diameter holes respectively; each can containing about 0·1 cu.ft. of medium. These were so placed that the centre ones were in line with the original jet and the others to either side of it. One in each pair was used to assess the total amount of film below the surface and the other to assess the fauna. One surface area 12 in. × 24 in., was removed monthly from each of the six jet lines; by means of a frame of similar size across which elastic bands could be stretched at 2 in. intervals the whole area was divided into 2 in. strips running parallel to the jet line, the central strip being directly under the original jet. The stones and film were removed monthly from each of the strips and shaken with approximately 200 ml. of water in metal containers in a shaking machine. The resultant wash was made up to 500 ml. and the organic matter determined. By this means it was possible to plot eleven transects across the jet lines and thus compare the amount and distribution of film on the surface. The amount of film and numbers of grazing fauna in the circular perforated cans below the surface layer were determined by methods previously described (Hawkes, 1952); these although not corresponding directly to the surface strips gave some measure of the distribution of film and fauna below the different jets.

RESULTS

Eighteen monthly results were obtained for each of the six types of jet between August 1956 and February 1958. During the winter of 1956–7 the normal luxuriant surface growth of fungus did not occur—probably due to the exceptionally mild winter. To ensure its development during the following winter the loading to the bed was increased and this, and probably the more severe winter, resulted in luxuriant growths. Unfortunately it caused such severe surface ponding that the sewage flowed laterally from ponded to non-ponded areas, and interfered with the observations. Consequently the experiment had to be terminated.

The results are considered for three different periods: (1) the winter and early spring season (November 1956–April 1957) following a 3-month period of maturation; (2) the summer and autumn period (May 1957–October 1957);

and (3) the conditions prevailing following heavy loading of the beds under winter conditions and before the extent of the ponding brought the observations to an end.

The average conditions during these three periods of the areas under the six different types of nozzle are shown as histograms in Figs. 1–3 respectively.

The surface growths during the first winter (Fig. 1 *a*) show that different growth patterns were developed under the different jets. The most uniform distribution of film was under the splash plate (C) and a slightly less even distribution occurred under the open fish-tail (A). The closed fish-tail (B) showed a fall-off in growth towards the edges, presumably due to the spread of the jet being restricted by the length of the aperture. Under the unmodified 1 in. jet (D) a ridge of fungal film developed approximately 10 in. wide and having a furrow in the middle where the jet of sewage impinged on the surface. The twin jets (E) had two ridges of growth but without furrows. With the four jets four lines could be discerned, although the two pairs tended to merge, probably as a result of the outward flow of the sewage due to the flow along the horizontal pipe (F).

The distribution of film on the surface could thus be correlated with the distribution of the sewage. Considering the areas actually wetted by the sewage there were only slight differences in the amounts of growth per unit area under the different jets, suggesting that at the overall rates of application used, the volume applied per unit area was not the most important factor in determining the amount of growth. It had been thought that the amount of surface growth is restricted by the scouring action of the impinging sewage jet. Although the growth immediately below the straight unmodified jet was slightly suppressed (D), this effect was less important than had been thought, as shown by comparing the growths under jets A and C. There was little difference in the amounts of surface growth under jet A, where the sewage impinged with considerable force on passing through a rectangular nozzle, and jet C, where the force of the jet was broken by first impinging on a disk before passing on to the filter as a mushroom-shaped sheet. The amount of surface growth during this winter period was not excessive under any of the jets and was not as great as experienced in previous winters.

The distribution of film in the 6 in. thick layer below the surface layer of stones, as measured by the three perforated cans, showed a similar pattern to the surface distribution under the different jets. By contrast, however, there was a marked difference in the relative amounts of film at this depth under the wetted areas of the different jets; more film was accumulated under the open fish-tail (A) than under the splash plate (C) or under the wetted middle area of the 1 in. circular jet (D), and appreciably less under the twin jets (E) and the four jets (F). These differences are correlated with the marked differences in the grazing fauna populations under the different jets. Under each jet area the distribution of the fauna was affected by the sewage distribution on the surface; the fly larvae and lumbricillid worms were more abundant under the wetted areas, whereas the collembolan *Achorutes subviaticus* was found in the drier regions (Fig. 1 *c–f*).

Apart from the distribution of grazing organisms the numbers of the different grazers was affected by the type of jet. Beneath the wetted areas *Anisopus fenestralis* larvae were most abundant under the splash plate (C) and under the two split jets (E, F) and least under the fish-tail jets (A, B). This would appear to be due to the differences in the force of impact of the sewage on to the bed, the larvae being suppressed under the more powerful fish-tail jets (A, B). Probably for the same reason the *Psychoda* larvae were only common under the splash plate jet (C). Lumbricillid worms, however (Fig. 1*e*), were more abundant below the more powerful jets (A–D), probably because of the effect of interspecific competition, since there was less competition from the suppressed fly larvae population. By far the greatest number of *Achorutes* were found in the areas not subjected to a strong flow of sewage and this species was therefore abundant in the jet areas having alternating areas of wet and dry, i.e. D–F. Under the areas directly receiving sewage *Achorutes* were more frequent wherever the force of the jet was reduced, as with the splash plate (C). The *Achorutes* present in the two outer cans beneath the fish-tail jet B, were there because they were adjacent to drier areas, on the fringe of the wetted area. Nozzle B gave a spread somewhat less than that from the open fish-tail A, under which no *Achorutes* existed.

Thus the differences in the amounts of film accumulating in the subsurface layers under the different jets reflect the different grazing fauna populations; and although the scouring action of the fish-tail was not sufficient to prevent the accumulation of the tenacious fungal film it did limit the fly larval population, with the overall result that more film accumulated under such jets.

The results throughout the following summer and autumn (May–October) are shown in Fig. 2. Although there was little change in the amount and distribution of the surface film (Fig. 2*a*), by comparison with the period November–April there was a marked reduction in the amount of film in sub-surface layers (Fig. 2*b*). The relative proportions of film under the different jets, however, was much the same in the summer and autumn as in the winter, except that under the splash plate jet the film was greatly reduced (Fig. 2*b*, C). The cause of the reduced amount of film present under summer conditions is not fully understood, for under laboratory conditions the growth of film was greater at summer temperatures. Moreover, the numbers of grazers was on the whole considerably less during the summer although it may be that at the higher temperatures their activity was greater. During the summer *A. fenestralis* were present in greatly reduced numbers under all the jets, the higher histogram for the quad jets (F) (Fig. 2*c*) being due to a single high count for the end of the period (October). Lumbricillid worms were similarly reduced in numbers throughout the summer period. The reduction in numbers of these two grazing species may be correlated with the increase in numbers of the other grazing fauna—*Psychoda* larvae becoming more abundant in areas subject to stronger sewage flows from A, B, D and E and *Achorutes* in the zone beneath the more gentle sprinkle of sewage from the splash plate of C. It is of interest to note that whereas the *Achorutes* occupying the drier zones were reduced in numbers during the summer period the population under the splash plate increased. The reason was presumably that whereas in the drier zones they occupied a separate niche to

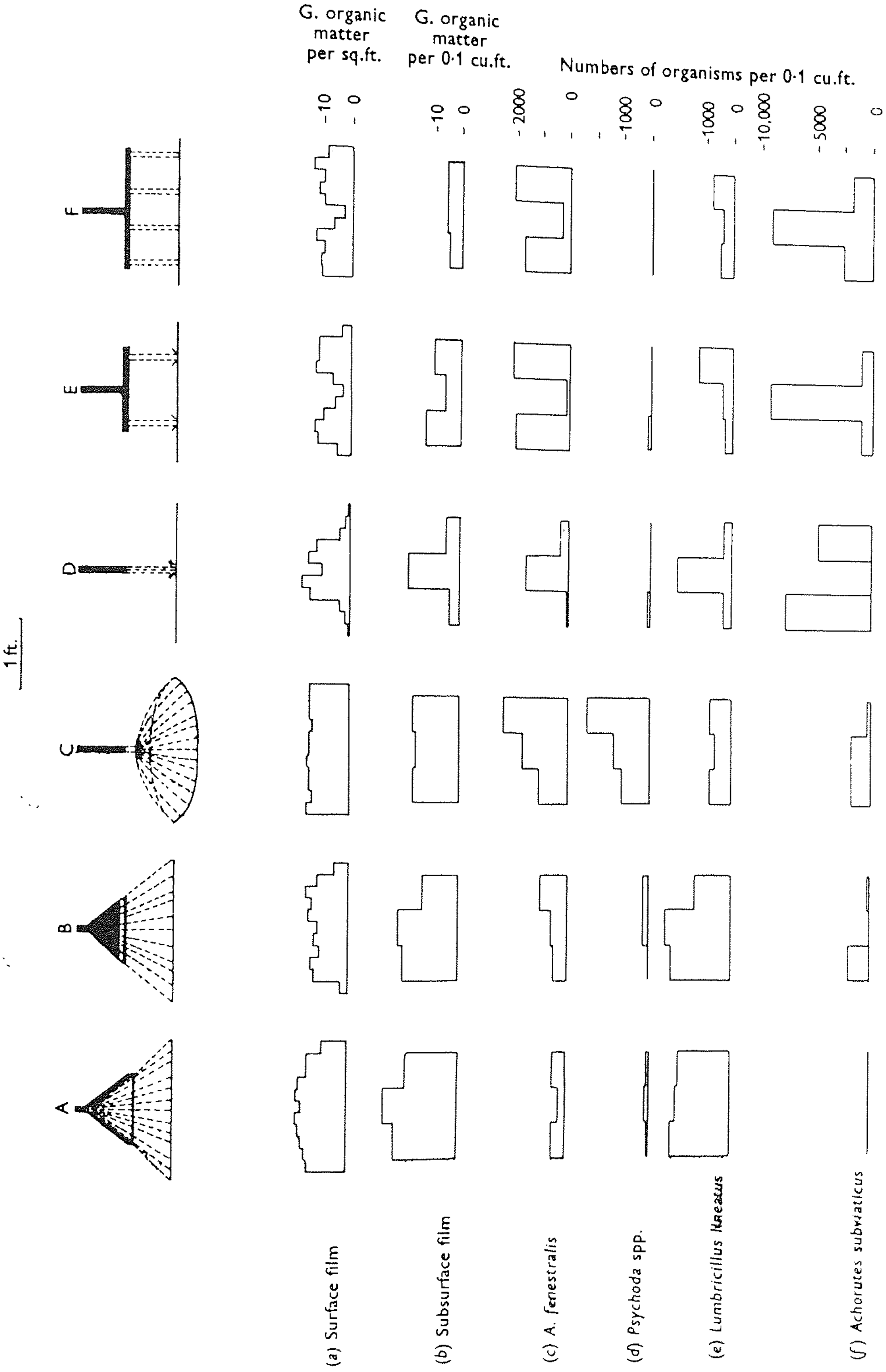
G. organic matter per sq.ft.
G. organic matter per 0·1 cu.ft.
Numbers of organisms per 0·1 cu.ft.
-10
0
-10
0
-2000
0
-1000
0
-1000
0
-10,000
-5000
0
A
B
C
D
E
F
1 ft.
(a) Surface film
(b) Subsurface film
(c) A. fenestralis
(d) Psychoda spp.
(e) Lumbricillus lineatus
(f) Achorutes subviaticus

Fig. 1

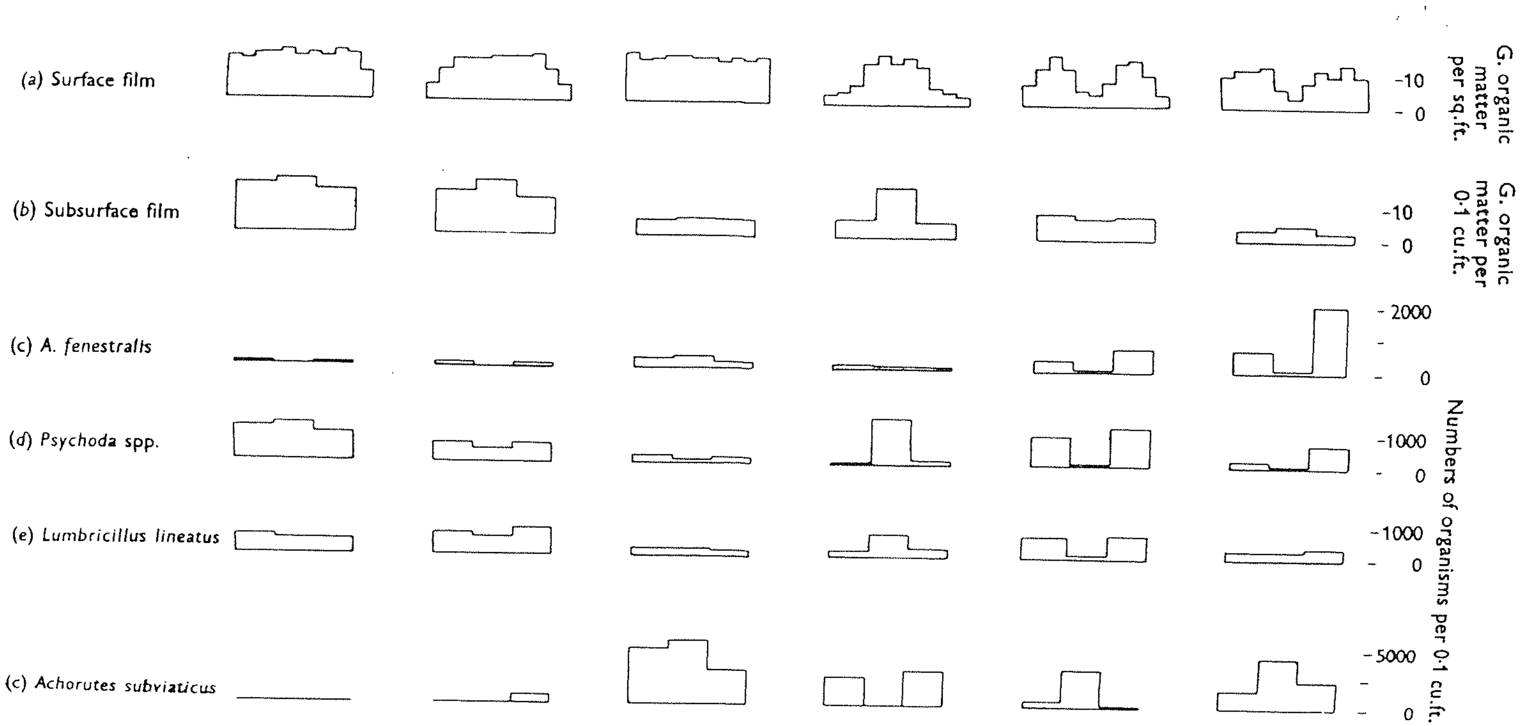

Fig. 2

Figs. 1, 2. Comparison of film accumulation and fauna under six different distributor nozzles each applying equal volumes of sewage to 2 ft. wide strips of bacteria bed. A, Open fish tail; B, closed fish tail; C, splash plate; D, straight nozzle; E, twin nozzle; F, quad nozzle. Fig. 1. Winter conditions: Fig. 2. Summer conditions.

the *Anisopus* larvae, under the splash plate they competed in the same niche and in the absence of competition from the fly larvae and in the presence of abundant food, limited in the drier regions, they increased in numbers.

The conditions at the end of February 1958 after the organic loading had been increased and following a more severe winter period are shown in Fig. 3, which indicates that there was a general increase in the amount of surface growth below jets A–D, and a smaller increase under E. Under F, however, no increase took place. In the subsurface layers there was a marked increase under all the jets. Expressed on the graphs by the shaded areas are the different conditions of the film under the different jets. Under the jets impinging with considerable force, i.e. A, B and the wetted areas under the jets on D and to a smaller extent on E, the fungal growths were tough and leathery in texture and in these zones ponding occurred producing anaerobic conditions. However, under the splash plate (C) and under the four split jets (F) the fungus was more foam-like in texture and was aerobic. These different conditions of the film probably account for the differences in fauna present.

With the low temperature and heavy loading *A. fenestralis* was virtually the only effective species (Fig. 3, *c–f*). Under the splash plate jet (C) and four split jets (F), where conditions were aerobic, food plentiful, and there was no strong flushing action, *A. fenestralis* larvae were abundant (Fig. 3*c*); under the other jets the numbers appeared to be limited by less favourable conditions. For example, comparing the distribution of *A. fenestralis* larvae under the straight jet D during the two winter periods (Figs. 1*c* and 3*c*), in the first winter the larvae were most abundant in the sub-jet position where most food was available; in the second winter they were more numerous on either side of the sub-jet zone, presumably because conditions in the sub-jet position were less favourable due to the ponding.

It is considered that the amount and distribution of surface growth, as opposed to the growth within the bed, is determined partly by the flushing action of the sewage jet and partly by the degree to which the sewage flow into the bed is impeded by subsurface growths. Under the two fish tail jets A and B, although the scouring action tended to limit the surface growth, the time taken for the sewage to enter the bed gradually increased (incipient ponding) until a stage of continuous ponding was reached when successive applications of sewage were made before the previous dose had percolated into the bed. Under these conditions the surface fungal growths, predominantly *Sepedonium* sp., were encouraged. Previous work has shown that the growth of fungal film can be limited by lengthening the period between successive applications of sewage at the same overall rate of application. Under conditions of ponding described above the period between doses could be considered as zero—i.e. the optimum conditions for growth.

In the case of the splash plate (C), although no ponding existed because of the condition of the film, growth developed below the surface because of the absence of any flushing action. With the straight jet (D), although the powerful flushing action prevented excessive growth immediately below the jet, the growths below

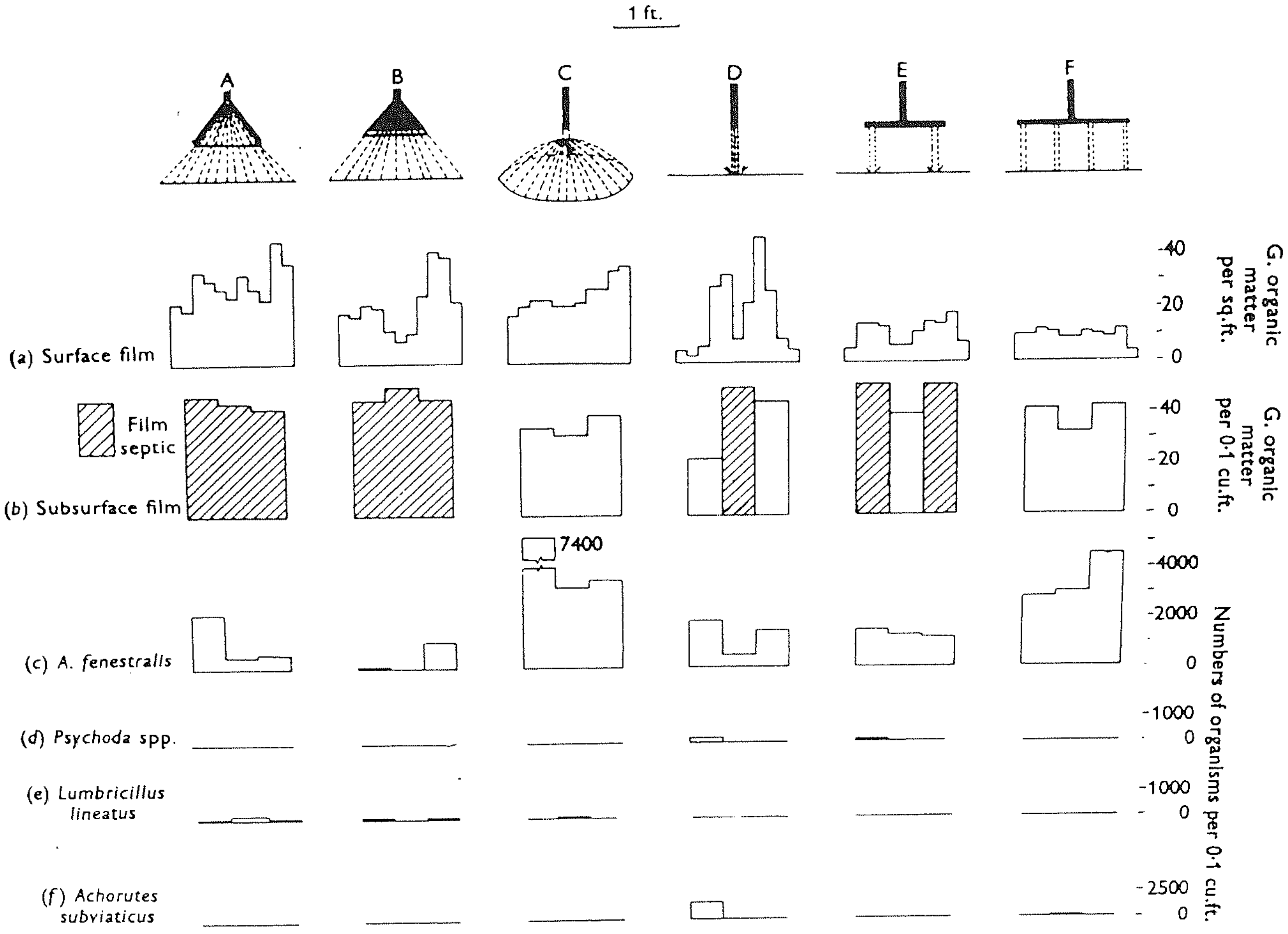

Fig. 3. Comparison of film accumulation and fauna under six different nozzles each applying equal volumes of sewage to 2 ft. wide strips of bacteria bed operating under severe winter conditions.

the surface caused the sewage to flow laterally; the generally ponded conditions encouraged excessive fungal growths as ridges on either side of the jet line. During previous years it had been observed that as conditions deteriorated these ridges widened until by meeting with neighbouring ridges they formed a continuous sheet over the whole surface of the bed, even though the sewage was being applied at 24 in. spaces. With the twin-jets (E) the less powerful flushing action did not produce troughs immediately below the jets but because of the smaller volume per unit area below each jet the growth on either side of the jet lines was less. Under the quad-jets (F) this trend was carried a stage further and because of the condition of the film below the surface and the resultant lack of ponding the surface growth under this jet was less than any of the others.

DISCUSSION AND CONCLUSIONS

It would appear reasonable to postulate that the more even the distribution of the sewage on the surface of the bed the higher the proportion of the bed capacity that would be effectively used. At the same time the satisfactory operation of the bed requires the maintenance of an effective grazing population and the prevention of excessive accumulation of film. Of the nozzles tested the two fish-tails (A) and (B) and the splash plate all gave even distribution. With the two fish-tails, however, the possible suppression of the film by the scouring action of the jet was more than offset by the reduction in the grazing fauna, thus resulting in the greatest accumulation taking place under these jets. In the case of the splash plate, although the lack of scouring action permitted surface growth to develop, conditions below the surface were far superior to those under the fish-tail nozzle. The split jets (E and F) obviously improved the evenness of the distribution and with the four jets (F) better bed conditions were established even under extreme loading. Comparing the splash plate and the quad-jets, the former gives the more even distribution, whereas the latter creates a more suitable environment for the establishment of a mixed grazing fauna. For example, by providing two niches—the alternate wet and dry zones—Collembola and fly larvae are able to co-exist under the split jet zone (F), whereas under the splash plate (C) *Achorutes* became abundant only when the *A. fenestralis* population was reduced during the summer. (Figs. 1 and 2*c*, *f*). In severe winter conditions the fauna under all nozzles was restricted to *A. fenestralis*, and it is considered that where favourable bed conditions were maintained during this period it was due to the activity of the fly larvae. Thus the prevention of fly nuisance by insecticide treatment could only be secured by adversely affecting the beds. For this reason the maintenance of a mixed fauna, whenever possible, is to be preferred to a fauna dominated by one species and consequently the jets at 6 in. spacing are preferable to the splash plates. Under certain operating conditions, however, the hydraulic design of distributors having small closely spaced jets to ensure even distribution along the arm over a wide range of flows involves difficulties, and more widely spaced jets fitted with splash plates would provide a practicable substitute.

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(*Received* 3 *October* 1958)

Paper No. 11

The effects of periodicity of dosing on the amounts of film and numbers of insects and worms in the alternating double filters at Minworth.

Hawkes, H.A., and Jenkins, S.H.
J.Inst.Sew.Purif., (1), 48-50, 1955

The Effect of Periodicity of Dosing on the Amount of Film and Numbers of Insects and Worms in Alternating Double Filters at Minworth, Birmingham

By H. A. Hawkes, M.Sc. (Associate Member)

The paper by Tomlinson and Hall[1] describes the effect of slowing down the speed of rotation of the distributors on the performance of circular filters at Minworth, Birmingham, operated by alternating double filtration. Opportunity was taken during the latter part of this investigation to observe the effect of periodicity of dosing on the macrofauna and on the accumulation of film by a method which had previously been used on other filters at Minworth[2]. During this period the distributors on Filters C and D were mechanically driven at constant speeds of one revolution in 42 minutes and one in 55 minutes. The speed of the self-propelled distributors on Filters A and B varied with the flow from one revolution in 1 to 5 minutes. Both pairs of filters were operated at the same rate of application. This was changed three times a day, the average rate being 150 gallons of settled sewage per day per cubic yard of filtering medium.

Experimental Methods

72 perforated canisters containing approximately 0.1 cu. ft. of matured filtering medium were buried in pairs below the surface of each of the four filters in the path of a distributor jet. Half of them were placed just below the surface of the filter, a third between 12 and 18 inches, and a sixth between 24 and 30 inches below the surface. The position and sequence of removal of each canister was indicated by holes punched in metal flags stuck in the filter. A period of at least 12 weeks was allowed for equilibrium to be established before the canisters were removed. During the first 18 months some of the canisters were removed every two weeks and after that every four weeks. On each occasion 6 pairs were removed from each filter, 3 at the surface, 2 at 12 inches, and 1 at 24 inches below the surface. From the medium in one of each pair, the film was removed by washing the medium on a grid in a trough and the insects and worms were counted on a sectored illuminated counting chamber as previously described.[2] The film was removed from the medium in the other canister of each pair in a rotary washing machine. The total weight of solid matter and organic matter (by loss on ignition) were determined and a correction was made for the numbers of insects and worms present in the film.

Results

The results from Filters C and D were very similar, and differences between Filters A and B could be attributed to the smaller sized medium in Filter B. Comparison is therefore confined to Filters A and C, which contained medium of about the same size. The speed of rotation on Filters C and D was decreased in June 1953 from one revolution in 42 minutes to one revolution in 55 minutes. This alteration, however, produced no marked change in the biological condition of the filter. The temperature of the filters was not recorded and seasonal fluctuations in temperature

FIG 1 VARIATION IN AMOUNT OF FILM AND IN NUMBERS OF WORMS AND INSECTS IN THE UPPER 2′6″ OF FILTERING MEDIUM IN ALTERNATING DOUBLE FILTERS AT MINWORTH, BIRMINGHAM

FILTER A. SELF-PROPELLED DISTRIBUTOR, 1-5 min per rev

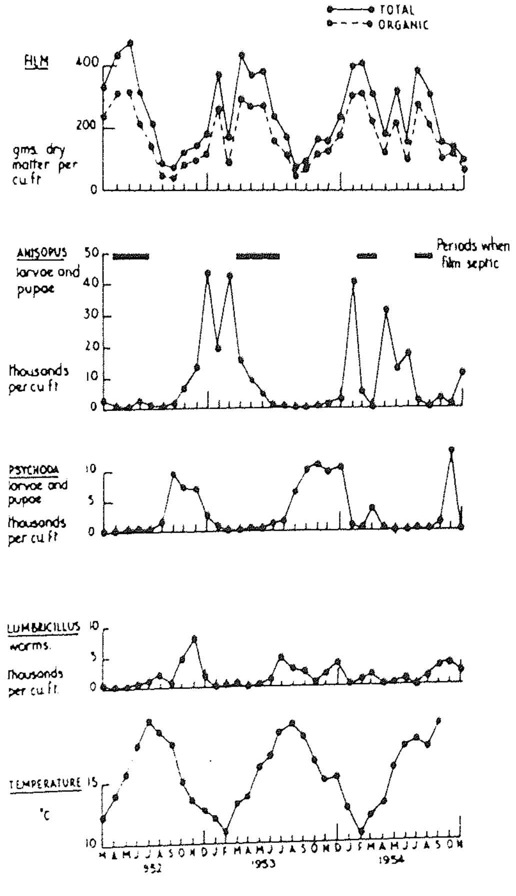
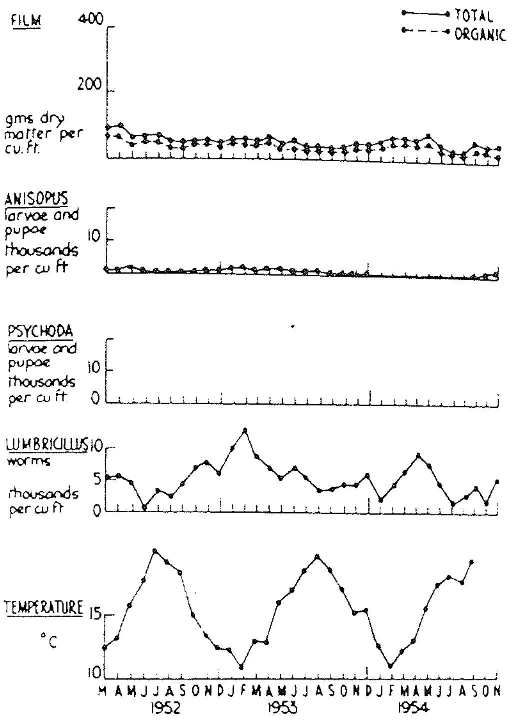


FIG 1 contd VARIATION IN AMOUNT OF FILM AND IN NUMBERS OF WORMS AND INSECTS IN THE UPPER 2'-6" OF FILTERING MEDIUM IN ALTERNATING DOUBLE FILTERS AT MINWORTH, BIRMINGHAM

FILTER C. MECHANICALLY DRIVEN DISTRIBUTOR 42-55 min per rev.



are indicated by the average of the sewage and filter effluent temperatures. In Fig. 1 each point represents the monthly average of the samples removed from the upper 2½ ft. of filter. The film removed from canisters in Filter A was black and anaerobic during the periods indicated by the shaded rectangles. Numbers of *Anisopus* and *Psychoda* in Filter C were too small to record on most occasions.

The vertical distribution of film, insects, and worms is shown in Table 1. The amount of film, or number of organisms per canister, was found for the three levels for each month and the value for each level expressed as a percentage of the total of the three levels. These monthly percentages were then averaged over the whole period and the standard deviation of the mean calculated.

DISCUSSION

From the results it is obvious that periodicity of dosing had a marked effect on the accumulation of film and on the grazing fauna. Whereas Filter A developed a thick fungal growth during the colder months and supported a large fly population, Filter C contained only a small amount of film which remained constant during the year and maintained a very small fly population. Filamentous algae belonging mostly to a species of Ulotrichales covered the surfaces of Filters C and D and contributed considerably to the weight of film in the canisters at the surface. *Lumbricillus* was the dominant grazer in Filters C and D.

The reduction in film in the upper layers of the filter, caused by increasing the time between doses of sewage, may be attributed partly to starvation and partly to the increased scouring action of the high instantaneous rate of application of sewage to the surface. The abundance of the filter metazoa is determined by several factors such as food and oxygen supply, temperature, and the flushing action of the sewage, to which the adult fly is particularly vulnerable. Larvae of both *Anisopus* and *Psychoda* have a burrowing habit, and the absence of sufficient film for this to be possible and also the considerable flushing action of the sewage would account for the low numbers in Filters C and D. It is noticeable that of the few *Anisopus* larvae present in Filter C, 75% were recovered from a depth of about 2 ft.

TABLE 1

VERTICAL DISTRIBUTION OF FILM AND GRAZING FAUNA IN RELATION TO DOSING PERIOD

Filter A—Distributor revolving once in 1-5 minutes
Filter C—Distributor revolving once in 30-55 minutes

Insect Larvae and Pupae

	Depth	Film Accumulation		A. Fenestralis		Psychoda spp.		Lumbricillid Worms	
	(ins.)	A	C	A	C	A	C	A	C
Number of Samples		31	31	27	3	19	—	23	31
Percentage of total at three levels	0—6	31 ± 1.4	38 ± 0.93	17 ± 2.75	6 ± 2.1	29 ± 6.7	—	25 ± 4.1	33 ± 1.35
	12—18	35 ± 1.0	31 ± 0.75	43 ± 3.8	19 ± 8.5	38 ± 5.15	—	34 ± 4.1	32 ± 1.35
	24—30	34 ± 1.45	31 ± 0.69	40 ± 4.9	75 ± 10.5	33 ± 6.1	—	41 ± 4.45	35 ± 1.98

Lumbricillus lineatus, on the other hand, was more numerous in Filters C and D. These worms are strongly prehensile by virtue of their setae. Moreover, the vulnerable early stages of development are protected by a cocoon which is normally firmly attached to the filtering medium and are thus able to withstand the downward flow of sewage. The relatively slow rate of reproduction which is most active during the colder months would be favoured by the uniform conditions of Filters C and D where, in the absence of competition from fly larvae, it established a large population on the limited food available.

Collembola, which are active grazers on other filters at Minworth, were very rare in both Filters A and C although present in fair numbers in the smaller medium of Filter B.

Filter A showed marked fluctuations in the accumulation of film. In June and July of 1952 and 1953 film disintegrated and was washed through the filter. It is not clear how this was carried out, since the canister counts show that the rise in population of larvae of *Psychoda* and *Anisopus* took place later in the season. It appears however that septic conditions in the early part of the year prevented colonization by these insects. In 1954 unloading was only partial and the peak in the development of *Psychoda* was delayed until October.

Table 1 shows that film is evenly distributed in the upper 30 inches of both filters ; the slightly greater proportion in the top 6 inches of Filter C may be attributed to the growth of algae on the surface. The concentration of the sparse *Anisopus* population in Filter C at the lowest level is contrasted with the uniform distribution of *Lumbricillus*.

Increasing the period between doses has a beneficial effect on the condition of filters and, up to a certain time, on the purification efficiency. Also, by reducing the amount of film, and thereby maintaining the fly population at a low level, the possibility of nuisance from adult flies is very considerably reduced.

ACKNOWLEDGMENTS

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REFERENCES

[1] TOMLINSON, T. G., and HALL, H. Effect of periodicity of dosing on the performance of percolating filters. *J. Inst. Sewage Purif.*, 1955, (1), 40.

[2] HAWKES, H. A. The ecology of *Anisopus fenestralis* Scop. (Diptera), in sewage bacteria beds. *Ann. appl. Biol.*, **39**, 1952, 181.

The foregoing Papers were presented at a meeting of the Midland Branch held in Birmingham on February 9th, 1955.

MR. TOMLINSON, in introducing his paper, said it was the last of a series giving the results of experiments on alternating double filtration which were begun at Minworth in 1938. This process originated from observations and experiments made by Whitehead and O'Shaughnessy of the Birmingham Drainage Board. The object was to prevent the excessive accumulation of film in the surface layers of medium which characterises single filtration on circular filters and thereby to increase the rate at which sewage can be treated. Over a period of years it was found that, whereas with single filtration 60 gal./cu. yd./day was the maximum safe load, with alternating double filtration it was possible to treat 240 gal./cu. yd./day at a constant rate throughout the 24 hours to give about the same quality of final settled effluent. Later, in order to test the process under more natural conditions of flow, the rate of application was changed three times a day while maintaining the average well within the capacity of the filters at 150 gal./cu. yd./day.

The need for investigating the effect of increasing the period between doses arose from the decision of the Birmingham Drainage Board to adopt alternating double filtration for the extensions of the main works at Minworth, when the application of the results of experiments with circular filters to rectangular filters with travelling distributors had to be considered. They had no preconceived ideas about the effects of slowing down the speed of rotation of the distributors. The large-scale experiment carried out by Lumb and Barnes increased the period of one revolution of a 4-arm distributor to only 4 minutes and therefore did not apply to the problem at Minworth where the travelling distributor would dose at much longer periods.

The effect of slowing down the speed of rotation of the distributor on the appearance of a circular filter during the winter was striking. Perhaps the shortest way to describe it was to say that the filters maintained their summer condition the whole year round. The improved purification efficiency was no doubt largely attributable to the improved condition of the filter. Decreasing the speed of rotation beyond a certain limit affected the time of contact and therefore also affected the average quality of the effluent adversely, so there was an optimum period for each set of conditions. In the case of the Minworth experiments the optimum period corresponded to a speed range of one revolution in about 15-30 minutes.

In the small-scale experiments at the Finham works of Coventry Corporation it was decided to see whether it would be possible to operate single filters at a high rate of application with a controlled dosing period. The rate of treatment of settled sewage was maintained constant at 360 gal./cu. yd./day and the single-arm distributors were driven electrically at constant speeds ranging from one revolution in ¼ to 26 minutes. The optimum period seemed to be in the region of one revolution in 12 minutes. From May to October, 1954, the filter with the distributor revolving at this speed produced effluents which after settlement for 1 hour had, on average, a 5-day B.O.D. of 21 p.p.m. and a 4 hrs. O.A.

of 25 p.p.m. and contained 7 p.p.m. of oxidised nitrogen. The settled sewage treated had, on average, a 5-day B.O.D. of 190 p.p.m. and a 4 hrs. O.A. of 69 p.p.m.

Introducing the supplementary paper, **Mr. Hawkes** said the results of the observations made during the later stages of Mr. Tomlinson's investigations were based on samples of medium removed from near the periphery of the filters where the jets were closer together than near the centre. The results needed little further explanation, though the reasons for them were more complex.

Discussion

Mr. S. J. Roberts (Leicester) proposing a vote of thanks, said that the Midland Branch in particular was indebted to the authors for a series of papers extending over a number of years. These papers had greatly increased the knowledge of the inner working of the percolating filter and had given particulars of methods for increasing the efficiency and loading of filters. Perhaps the results given in the present papers were more surprising than those obtained from the earlier experiments, where surface growths of fungi had been controlled by alternating double filtration or by recirculation of effluent. The present papers described how similar control and results could be obtained by regulating the periodicity of dosing. Mr. Roberts wondered, however, if it were correct to say that the fungal growths were starved when there was no decrease in the quantity of organic matter applied to the filter. From the results given for Minworth and Coventry, it appeared that there was an optimum periodicity of dosing for each sewage and Mr. Roberts asked if there was a different optimum for each rate of application, *e.g.*, if the optimum was 12 minutes at 150 gal./cu. yd./day, would it also be 12 minutes at 300 gal./cu. yd. day ? Finally, he asked Mr. Hawkes if the chemical control of flies on a large scale at Minworth would eventually become unnecessary because of a progressive decline in their numbers brought about by the adoption of a long dosing cycle.

Mr. R. D. Raybould (Wolverhampton), seconding the vote of thanks, congratulated the authors on the amount of work which had gone into the papers and on the graphical presentation of the results, which greatly aided comparisons. Methods of improving the performance of filters were of particular importance at a time when synthetic detergents were causing difficulties in activated sludge plants.

Experience at Wolverhampton supported the authors' findings. Over the last 25 years, six large rectangular filters dosed at 10-min. intervals had consistently given better results (without winter ponding) than four circular filters dosed at much more frequent intervals. The circular filters, in spite of taking a smaller dose, ponded to such an extent each winter as to require forking. It was thought that the infrequent heavy doses of sewage had a scouring effect and so kept the surface of the rectangular filters open and aerated.

The graphs given in the papers showed that the infrequently-dosed Filters C and D, which contained only small amounts of film all the year round and ample worms to keep them open and aerobic, gave consistently better results than the frequently-dosed Filters A and B. Filters A and B showed maximum purification efficiency at times of minimum film, maximum temperature, and maximum fly larvae population. Minimum purification in Filters A and B coincided with maximum film, and septicity in the surface layer of medium. During summer, when both sets of filters were open and aerobic, there was not much difference in their performance. It was evident that, for good performance, a filter must be open and aerobic.

It was generally accepted that the efficiency of a filter depended on intimate contact between the sewage and the film, and on the time of contact. Stanbridge had recently stated (*Wat. Sanit. Engr*, **5**, (5), January/February 1955, 213) that the efficiency of a filter depended on the amount of "active" film in the filter. The term "active" was important. During winter, scouring organisms left the upper layer of medium for the lower layers and unless other measures were taken to keep the surface open the filter became clogged, fungi developed, and anaerobic film accumulated. Anaerobic film was not active and was detrimental to the filter. Heavy, infrequent, doses of sewage effectively scoured the surface of a filter and kept it open and aerobic, even in winter. Filters C and D probably contained more active film than Filters A and B and only this active film should be taken into account when estimating the effect of film on filter performance. Estimations of the amounts of film, given in the papers, were complicated by the large amounts of anaerobic film in Filters A and B.

According to Butterfield and Wattie, activated sludge was practically identical with filter film. Yet, in activated sludge plants in which sewage was "in contact" with this film for several hours compared with a few minutes in a filter, purification efficiency was not great. Almost all improvements in activated sludge plants had been due to increased aeration. When there was a lack of air, activated sludge went out of condition while increased aeration restored it. Too much activated sludge (or "film") led to low purification efficiency because so much air was needed to keep the sludge aerobic. Even a river containing very little "film" would purify sewage, provided dissolved oxygen was always present, while recirculation with a nitrified effluent containing a reserve of oxygen would "open up" a ponded filter so that it once again became aerobic.

The common factor in all these processes was oxygen, and Mr. Raybould suggested that oxygen was more important than the amount of film. Oxygen kept the film active, and activity, or quality, in filter film was more important than quantity. Activated sludge was first obtained by aerating sewage ; in effect the "film" was already present but oxygen was needed to activate it. Research into methods for increasing the aeration of filters might yield useful results, and this was particularly true of enclosed filters since the performance of filters appeared to be better at higher temperatures.

Mr. Raybould asked the authors if the smaller amount of film in Filters C and D had had any effect on the concentration of suspended solids in the filter effluent and on the settlement of those solids. He also asked if they thought that, with infrequent dosing, Filters C and D could be run in series, with C always the primary and D always the secondary filter. He wondered if the high, infrequent, doses of sewage would keep the primary filter open so that it produced an improved effluent, each filter building up a flora and fauna best suited to the particular sewage it was treating instead of, as at present, each filter having the character of its feed altered every other day.

Mr. G. W. Bennett (Coventry) said the filters at Coventry had always ponded extensively during the winter months, and during 1951 a hand tractor was purchased for "forking" the medium. As stated by the authors, the small-scale plant at Finham had given interesting results. Of the filters dosed at 360 gal/cu.

yd./day, those with 12-min. and 26-min. dosing periods did not pond, the former giving the better results. Consequently, the City Engineer decided to extend the experiment to one of the works' filters, which were 120 ft. dia. and 6 ft. deep, the medium being ¾ in. to 1 in. granite. The filter was one of a block of eight and, for the most part, treated effluent from the bio-flocculation plant at a rate of approximately 200 gal./cu. yd./day.

An automatic brake was designed and constructed by the department consisting of a waterwheel attached to the distributor and driving, by means of a chain, a spiked drum which ran on the medium, the waterwheel being controlled by a governor. The distributor was virtually a 2-arm machine and the dosing period was from 12 to 15 minutes, the peripheral speed being 12.5 to 15.5 ft./min. A manufacturer had been approached and it was hoped to equip the block of eight filters with controls, and to compare the results with those obtained from a block of six filters treating the same sewage but without controls, each block having separate recorders and humus tanks. The brake had been in operation since August 1954 and so far the medium was in a remarkably clean condition. Except for a slight surface growth of algae, the filter had the appearance (and the medium when walked on, the "feel") of a newly sloughed filter. In the surrounding filters the medium was heavily coated with fungus and had been mechanically forked three times since the beginning of December to control ponding. All the glazed earthenware covers of the ventilators, which were approximately 1½ ft. from the filter periphery, were covered with a thick coating of fungus, but with the controlled filter the covers were quite clean. Finally, Mr. Bennett asked the authors if the findings were likely to influence the adoption of alternating double filtration at Minworth.

Dr. S. H. Jenkins (Birmingham) said that in 1946 the question of applying the results of the alternating double filtration experiments at Minworth was being considered. It was intended to use the process on large blocks of rectangular filters. At the time, he believed that better results would be obtained using revolving distributors giving a short dosing cycle. The difficulty of covering the 42 acres of filters at Minworth with revolving distributors made it necessary to obtain information on the effect of the periodicity of dosing and this led to the experiments reported by the authors.

Messrs. Tomlinson and Hall had shown that Minworth sewage gave a satisfactory effluent after filtration by alternating double filtration at an overall rate of 150 gal./cu. yd./day if the filter effluent was settled quiescently for 1 hour. However, when the flow was varied throughout the twenty-four hours, the effluent from the primary filter was also satisfactory when the rate of application was 75 gal./cu. yd./day, corresponding to a rate of 150 gal./cu. yd./day to the primary filter. Since the filters were kept clean when slowly revolving distributors were used, it seemed likely that such a filter would continue to give satisfactory results if maintained as a single filter at 150 gal./cu. yd./day with slowly revolving distributors and that there would be no need for alternating double filtration.

The results indicated that for every filter there was an optimum load that could be applied to obtain an effluent of given quality, and that a somewhat long dosing interval was an important factor so far as this optimum load was concerned as it controlled the amount of growth in the filter. However, even with a clean filter, overloading became evident when the rate of revolution of the distributors was once in 55 minutes. Dr. Jenkins asked if this was due to short-circuiting and if so, how important a factor was short-circuiting in the normal application of sewage to filters. In connection with the optimum loading of filters, he asked what was the cause of increased efficiency resulting from recirculation; he wondered if it was due either to an increased supply of dissolved oxygen to the surface and sub-surface layer of growth, to better distribution of the load throughout the filter, or to reduced surface growth caused by the weaker sewage. The authors' results also prompted the question whether best use was being made of filter capacity by using one-half of the filters for each stage of purification, when it appeared possible to apply so much heavier a load in the primary stage.

It was interesting to speculate on the reasons for the cleanliness of filters dosed with sewage from slowly revolving distributors. Sewage, and also filter growths, contained much non-living organic matter. Such organic matter, one could visualise, became flocculated and intimately associated with the living matter, which grew from the nutrients in the sewage. With the gentle application of sewage from rapidly revolving distributors there was no opportunity to separate growth from flocculation, other than by the natural action of scavenging organisms. With slowly revolving distributors, flocculation could occur and the flocs would be washed away from actual growths; these would have to be of such a type as to be capable of adhering to the medium in spite of being subjected to a heavy jet of liquid.

Mr. H. Myatt (Tipton) described two experiments in which the dosing cycle had been lengthened. In the first, sewage was applied to a fine-grade filter by a 4-arm distributor having fine jets close together and the results were disappointing. In the second, sewage was applied to a filter containing much coarser medium by a 2-arm distributor, one arm being fitted with large self-cleansing jets that were well apart while the other arm supplied sewage to a paddlewheel to give a friction drive. The speed of the distributor was controlled by reducing the amount of sewage passing to the paddle. In this case, the results were very gratifying and ponding was eliminated except on that portion of the filter traversed by the paddle, where a thick fungal surface growth developed. He could only assume that this was due to sewage dripping from the paddle on to the filter surface. Mr. Myatt concluded that the grading of the upper layer of medium and the size and spacing of the jets in the distributor arms were most important factors.

Mr. R. W. Lucas (John Thompson-Kennicott Ltd.) recalled a type of distributor jet which was put on the market some years ago. It was arranged to discharge vertically downwards and driving reaction was obtained by the jets impinging on to spray plates fixed underneath the distributor arms. In addition, the spray plates caused the jets to spread into a wide thin film. The jets were spaced so that adjacent sprays all touched, thus completely covering the surface of the medium, with no dry areas between the jets. It was hoped this would help the biological process but it did not prove satisfactory, the filters ponding so badly that liquor overflowed the walls. On removal of the spray plates, the ponding gradually disappeared.

Mr. C. Lumb (Halifax), in a written contribution, said that some work on almost identical lines to that described was reported by Mr. J. P. Barnes and himself in 1948, where it was shown that for ordinary conventional straight filtration, under Halifax conditions, superior results were obtained and the beds were maintained in a cleaner condition if the feed was applied in flushes at intervals. The optimum periodicity was tentatively put in the region of 4 to 9 minutes. It was suggested in that paper (*J. Inst. Sewage Purif.*, 1948, (1), 83) that if these findings could be confirmed elsewhere their application would result in worthwhile improvement of percolating filter operation at very small cost. Since that time he had discussed this matter privately with a number of members, who had confirmed that they had obtained similar improvement at their own works by increasing the periodicity of dosage in this way, but no published data were available. It was consequently gratifying to note the present authors had now confirmed that similar findings applied both to alternating double filtration at Birmingham (optimum periodicity evidently about 4 to 8 minutes) and to filtration at a fairly high rate at Coventry, where an optimum of about 12 minutes was suggested.

The authors suggested that the periodic dosing of filters from siphons might achieve the desired object. It seemed to Mr. Lumb, however, that a dosing siphon resulted in the distributor revolving fairly rapidly while in operation and, unless this distributor was specially designed, the feed would still be applied to the bed in relatively light sprinkles not producing the desired intensity of flushing on the surface necessary to keep the surface layer of the bed clean.

He felt the work carried out at Coventry would have been of greater value if a more normal dosage had been employed rather than the very high figure of 360 gal./cu. yd./day used. Members would no doubt be interested in the possibilities of increasing the periodicity of dosing with conventional 4-arm revolving distributors. Even by reversing one arm to act as a brake, it was rarely possible to reduce the speed of rotation to much above 4 minutes per revolution, and if the sparge holes were so close together that one arm virtually dosed the whole of the bed the periodicity was then only one quarter of this, *i.e.*, one minute, and still much below the optimum period.

Mr. Lumb said he had carried out experiments by equipping 4-arm distributors with large-bore film sprays fitted to the sparge arms in staggered positions so that any one arm wetted only one quarter of the bed surface and a complete revolution was needed to wet the whole bed. By having one arm reversed to act as a brake, the speed of rotation could be reduced to about 4 minutes per revolution, thus giving a periodicity of dosing marginally within the optimum range. This could consequently be achieved cheaply without recourse to relatively expensive electrical drives. Several years' experience with distributors so amended had confirmed that these definitely maintained filters in a cleaner condition than formerly, and records confirmed that only a fraction of the forking over in the winter months of that required in the past was currently necessary on such beds; these experiences were despite somewhat worse precipitation than formerly due to the adverse influence of synthetic detergents. The subject generally would appear to merit the close study of designers of filter distributors.

Mr. C. H. Hewitt (Birmingham) said that, from the historical point of view, it was interesting to recall that one of the four circular filters used in the experiments was originally fitted with a distributor which was propelled mechanically at a slow rate. Quoting from a paper presented by J. D. Watson in 1903, "the distributor is an entirely new invention of Mr. Scott Moncrieff. It consists of two girders supporting an open trough supplied with sewage from a central pipe round which the trough revolves as on a pivot. The outer end rests on and travels along a circular mono-railway, being driven by a 2 h.p. engine geared to travel the circle in 7 minutes." Mr. Watson continued "this is, so far as I know, the most perfect revolving distributor on the market but it is too costly to become popular." It was a coincidence that this particular rate of rotation was now being recommended, and it might be that the type of distributor which Mr. Watson regarded as an impossible ideal might soon be realised on the Minworth works.

Mr. J. P. Barnes (Walsall), in a written contribution, said that he took part in similar experiments at Halifax some years ago and it was encouraging to see the results of that work confirmed, even to the optimum period between applications having been found to be within similar limits. One would have imagined that with the shorter time of contact in double filtration, the intervals between doses would have to be shorter than in single filtration; Fig. 5, however, showed just how short a period of contact was required for the 5-day B.O.D. of a sewage to be reduced by upwards of 70%. A feature of the work at Halifax was the speed with which the effect became apparent when the period between applications of sewage was lengthened, a striking improvement taking place even when the time taken by a 4-arm distributor to rotate was increased from about 1 to 4 minutes, *i.e.*, increasing the intervals between doses from ¼ to 1 minute. Further confirmation was given at Walsall, where 2-arm paddle-driven machines rotating at about 1 revolution in 6-7 minutes produced effluents equal in quality to those from 2-arm machines the speed of which was about 6 times greater though 15% less sewage per cu. yd. of medium was being applied to filters fed by the faster machines.

In the experiments at Coventry the only improvement brought about by longer periods between doses appeared to be in the condition of the beds, but this might have been very significant if the work had continued. Perhaps more positive results would have been achieved if a more usual rate than 360 gal./cu. yd./day had been applied; it was noticeable, in any case, that the optimum period between doses was not used in any of the filters in the experiment.

Mr. Barnes wondered if it was correct to suppose that a dosing siphon produced the same effect as slowing down a distributor. With a siphon, virtually the whole surface of a filter was being continuously lightly sprayed for an appreciable time and this was then followed by the rest period whilst the siphon chamber was refilling; this was not the same as applying a heavy flush of sewage followed by a rest period, which was what happened with a slow-moving distributor. His experience had been that with an installation of filters dosed from siphons, an improvement followed the reversal of one arm of each 4-arm distributor.

The authors had pointed out the difficulty of making circular distributors revolve more slowly. Whilst the speed of rotation might be adjusted within limits on a paddle-driven machine by altering the size of the driving wheel, it appeared that means were not yet available for reducing the speed of reaction-jet machines without their being adversely affected by wind.

Mr. V. M. Brown (Derby) asked Mr. Hawkes if he had made any egg-counts for *Anisopus* and *Psychoda* in the filters. It was felt that these fragile-bodied insects would be killed by the jets and so prevented from laying, thereby accounting for the low numbers present rather than that this was caused by the inadequacy of film on the filter medium. He also asked whether "starvation" was the correct term to use when accounting for the limited film development. Starvation usually resulted from one of two factors: either non-availability of food, or incapacity to utilise and assimilate food. As neither of these were applicable in this case, it would appear that the limitation was caused chiefly by the scouring effect of the jets and not by starvation.

REPLY TO DISCUSSION

In reply to Mr. Roberts, MR. TOMLINSON said it seemed likely that the optimum period of dosing would be different at different rates of flow. Since lengthening the period would tend to cause a decrease in the accumulation of film, it was reasonable to suppose that within certain limits the optimum period would increase as the rate increased.

Mr. Raybould had asked about the relative quantities and settlement of suspended solids discharged from the two pairs of filters. The concentration of solid matter discharged from the filters had not been determined. From September 1947 to May 1954 the average concentration of suspended matter in the final humus tank effluent from Filters A and B and Filters C and D were 37.0 and 38.7 p.p.m. In both cases 37% of the solids remaining after humus-tank treatment settled after a further hour's quiescent settlement in the laboratory. It was probable that Filters C and D could have been operated successfully in series without alternation but it was impossible to predict the effect of such a change.

Mr. Tomlinson said he had been very interested to see the beneficial effect of the automatic braking mechanism on the condition of a filter when he visited the Finham sewage works at the end of January at the invitation of Mr. Bennett; he felt sure there would be a demand for such a mechanism if it could be manufactured at a reasonable price.

With regard to Dr. Jenkins' remarks on short-circuiting of sewage in a filter, the shape of the "time of contact" curve showed that different fractions of every dose of sewage applied took different times to pass through the filter. At high instantaneous rates of application some of the sewage appeared at the bottom of the filter very shortly after being applied. A compensating factor might be the improved lateral distribution resulting from an increase in the instantaneous rate of application. As Dr. Jenkins had suggested, the increase in efficiency of circular filters which usually resulted from recirculation might be due to a number of factors such as oxygen supply, control of surface growths, and improved vertical and lateral distribution.

MR. HAWKES, replying to Mr. Roberts, said that if (and it was a big *if*) conditions similar to those in Filters C and D could be established in the large-scale filters at Minworth, the control of flies by chemicals would not be necessary.

He agreed with Mr. Raybould that the "activity" of the film and aeration were important factors; in his experience, however, filters containing a small amount of film were quite efficient although a certain amount of fungal growth might be beneficial in increasing the detention period at high flows. The nature of filter film varied considerably; some was bacterial and similar to activated sludge while in other cases, as at Minworth, the film was composed mostly of fungal hyphae during the winter months.

Concerning Mr. Lucas's observations on the effect of removing the splash plates from the distributor arms, it would appear that although splash plates ensured a more even distribution of sewage, the reduced scouring action could result in surface growths with resultant ponding. In the absence of splash plates, however, the spacing of the jets became an important factor. Some travelling distributors for rectangular beds had jets spaced over 2 ft. apart on the normal flow arm; under such conditions much of the filter capacity was not being used as the lateral spread, even in filters having a considerable amount of film, would not result in even distribution within the filter. An investigation into the effect of splash plates on alternating double filters was at present being carried out at Minworth.

Mr. Barnes had remarked upon the speed with which the effect on the Halifax filters became apparent when the periodicity was changed. It was worth recording that after Mr. Tomlinson's departure it was necessary, because of delay in obtaining replacements for the gear drive, to operate Filter C by self-propulsion for some time. Within a matter of weeks the thin algal film had been replaced by a thicker fungal film which increased rapidly and after two months resulted in some surface ponding. The gear drive had now been replaced and the filter was regaining its original condition.

In reply to Mr. Brown, egg counts of *Anisopus* had been made; these were greater in Filter A than in Filter C but this was probably the result of the higher *Anisopus* population in Filter A and not the cause of it. In other filters at Minworth, detailed studies had shown that *Anisopus* laid its egg masses in the medium between the jets, the larvae migrating to graze upon the film below the jet line and later returning to the drier interjet zone to pupate. Mr. Hawkes therefore considered that, although the adult flies could exist in Filters C and D, the young larvae were hardly able to do so and a large population was therefore never established.

Dr. Jenkins, Mr. Brown, and other contributors had speculated on the reasons for the reduction in film due to slowing down of the distributors. Dr. Jenkins had differentiated between actual growths on the filter medium and the flocculated non-living organic matter. The latter was undoubtedly more likely to be washed through the filter by the flush from a slowly revolving distributor. This alone, however, did not account for the difference in film accumulation, which was due mostly to the luxuriant fungal growth in Filters A and B. Mechanical scouring by the jets from the slowly revolving distributors, as suggested by Mr. Brown, would probably prevent the luxuriant growth on the surface of the filter but within the filter this scouring action would be much reduced and other factors must therefore be involved in the reduction of fungal growths. Filter fungi, especially *Sepedonium*, which was dominant in the film of Filter A, appear to thrive best when constantly bathed in nutrient organic matter. At Minworth the fungal growths were most luxuriant on the filters served by spray jets, where there was a constant steady supply of nutrient matter. In this connection, the more frequent dosing by the more rapidly revolving distributors should favour fungal growth. Furthermore, this effect was cumulative in that once a critical amount of film had accumulated this impeded the sewage flow, thus encouraging more luxuriant growths to develop and thereby aggravating the situation. This critical amount of film was never reached in Filters C and D because of the scouring action of the jets on the surface and the long periods between feeds, and this, together with the fact that a constant food supply was not available, might be termed the "starvation effect." These filters were thus maintained in a clean condition. In Filters A and B, however, the reduced surface scouring action and the more frequent feeds resulted in the film developing until the critical point was reached at which the flow was impeded and luxuriant fungal growths developed each winter.

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Comparison of double infiltration and alternating double filtration of an industrial sewage using beds having controlled frequency of dosing.

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H. A. HAWKES AND S. H. JENKINS

COMPARISON OF DOUBLE FILTRATION AND ALTERNATING DOUBLE FILTRATION OF AN INDUSTRIAL SEWAGE USING BEDS HAVING CONTROLLED FREQUENCY OF DOSING

With a note on the justifiability of using zero constant equation to relate effluent and feed by (Mrs) J. M. STOKES and A. B. NEALE

College of Advanced Technology, Birmingham, England, and
Birmingham Rame and Rea District Drainage Board, Birmingham, England

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INTRODUCTION

Conversion Table

1 gall/cu.yd./24 hrs = g.y.d. = 0.000248$m^3/m^3/h$
1 lb.B.O.D./cu.yd. = 593 g/m^3
1 lb./cu.yd./day = 0.593 $Kg/m^3/day$
1 cu.yd. = 0.764 m^3

The double filtration of weak domestic sewages through two beds in series with settlement between the two stages is successfully practised on many works especially where the topography of the site permits the sewage to gravitate through the works. At Cheltenham, PEACH (1957) compared alternating double filtration, double filtration without alternation, and recirculation. He found that double filtration without alternation gave the best results.

At Huddersfield, after intensive investigations (GOLDTHORPE and NIXON, 1942) double filtration was adopted for the treatment of a highly industrial strong sewage. The use of double filtration for treating strong industrial sewages appears to have been limited by the winter accumulation of fungal growths in the primary bed. At Reading, BARRACLOUGH (1954) experienced difficulty with the choking of the primary beds of a high rate double filtration plant. TIDSWELL (1960), however, found double filtration to be slightly superior to alternating double filtration and much superior to recirculation in treating a sewage containing a high proportion of brewery waste at Buton-on-Trent.

At Minworth, a series of investigations had been carried out by the Water Pollution Research Laboratory Staff comparing different methods of filtration of the Birmingham sewage. The highly industrial sewage, apart from being less amenable to biological oxidation, also created difficulties by encouraging luxuriant growths of fungus in the beds, especially during the winter months. These growths choked the beds, impaired their efficiency, and also provided ample food to support a large fly population which gave rise to nuisances the following spring. The prevention of such growths was considered necessary for successful operation of the beds.

The results of these earlier investigations (Mills, 1945; Tomlinson and Hall, 1951) showed that whereas in the warmer months recirculation, double filtration and alternating double filtration gave equally good results, during the winter the accumulation of film in the recirculation bed and in the primary bed of the double filtration pair impaired their efficiency. As a result of these investigations the existing 42 acres of beds at Minworth Works are being reconstructed to operate on

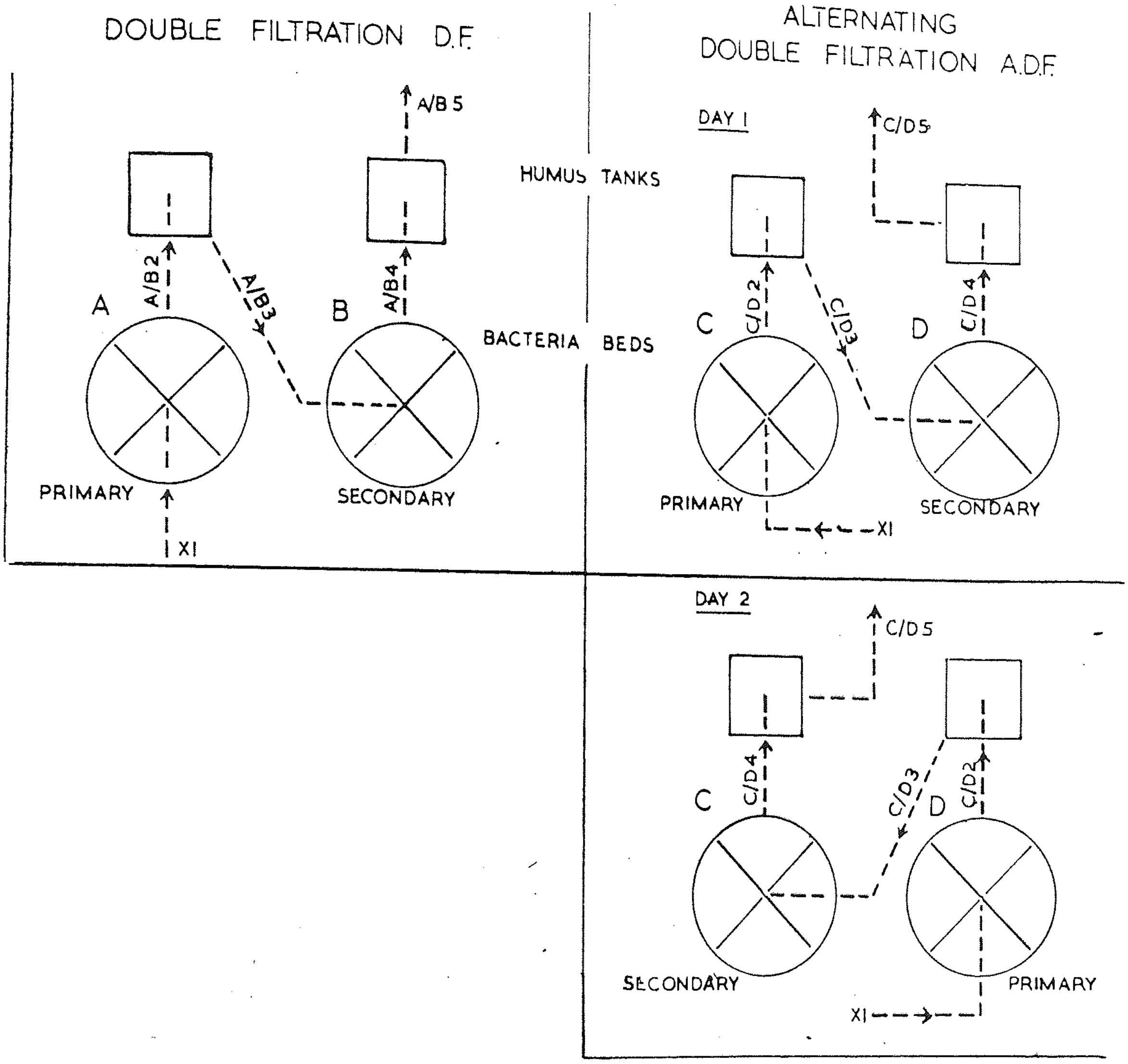

Fig. 1. Flow diagram comparing the operation of two beds (A and B) as Double Filters and the other two (C and D) as Alternating Double Filters

alternating double filtration, with the possibility of operation by double filtration, partial recirculation or partial recirculation combined with alternations or double filtration. The reconstructed beds are being dosed from distributors capable of travelling at four different speeds.

Continued investigations on alternating double filtration showed that the accumulation of film could be further controlled and the efficiency of the process increased by reducing the frequency at which successive doses of the settled sewage were applied to the bed. Thus by mechanically driving the distributor arms so that they revolved once every 30 minutes, better bed conditions and a better effluent were obtained than from the beds on which the jet driven distributor arms rotated in 1–5 minutes (Tomlinson and Hall, 1955), (Hawkes, 1955). Subsequent investigations at Coventry (Tomlinson and Hall, 1955) and at Ewell (Stanbridge 1958) confirmed that film accumulation could be controlled by low frequency dozing, a phenomenon first reported by Lumb and Barnes (1948) from their experience at Halifax.

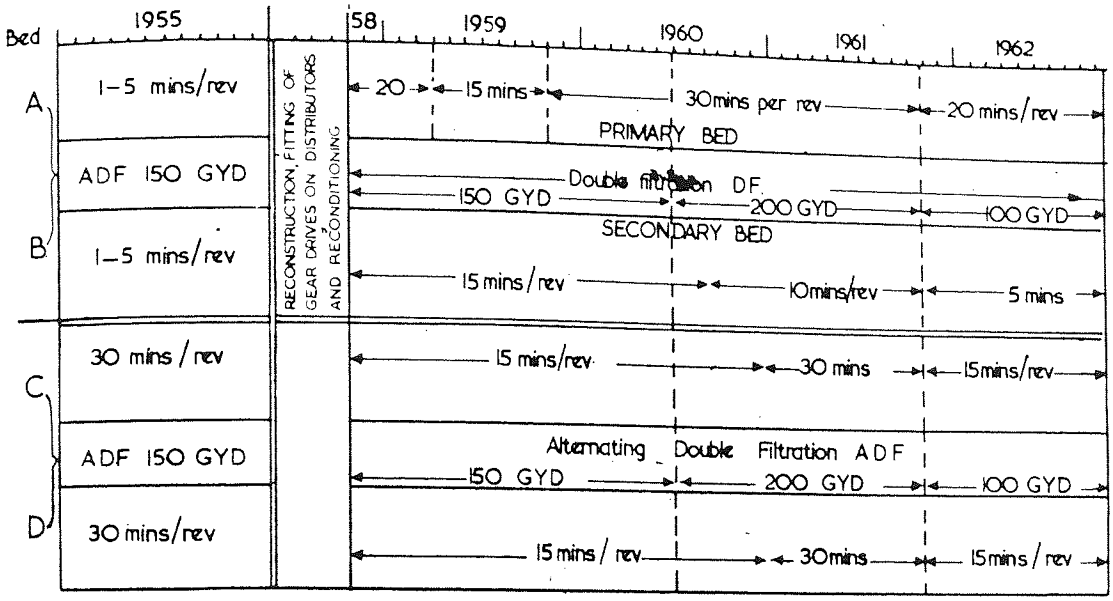

Table 1. Timetable of operating conditions of the four beds before and throughout the period of the investigations

Ecological observations on the first 8 acre block of beds that were converted to operate on alternating double filtration (Hawkes, 1957) suggested that – "two stage filtration with the secondary filter acting as a nitrifying filter would produce a more highly nitrified effluent than alternating double filtration or recirculation". With the establishment of the growth controlling effects of low frequency dosing it was considered worth while re-assessing the efficiency of double filtration using low frequency dosing to control the accumulation of film in the primary bed: The present work is an account of investigations carried out on the four 120 ft. diameter filters referred to above. In this work the ecology and efficiency of a pair of beds operating as double filters are compared with a pair of similar beds operating as alternating double filters. The comparisons were made at three dosage rates during a period of some 3½ years.

METHODS

The beds used were the four experimental beds which had been used in the previous investigations mentioned above. They were each approximately 120 ft. in diameter and 6–7 ft. deep containing about 2,500 cu.yds. of medium graded approximately 1-2½ in. One bed which had previously contained much smaller media had this replaced by media similar to the other beds. All the beds were served by 4-armed rotating distributors which were power driven by electric motors. Two beds which had been fitted with power drives for earlier investigations were chain driven and could be rotated once every 8, 15, 30, 42 or 55 minutes by selecting the appropriate combination of drive wheels. The other pair of beds which in past tests had distributors driven by jet reaction were also fitted with power drives for the purpose of the investigation. These were driven through two variable speed gears enabling the distributors to be rotated at numerous speeds between 1 rev. in 1 minute to 1 rev. in 60 minutes.

Throughout the investigations two beds (A. and B.) were operated as double filters, A being the primary and B the secondary; the other two (C. and D.) were operated as alternating double filters, each being primary and secondary on alternate days (Fig. 1.).

Initially the double filtration beds (A. and B.) were operated at overall rate of 150 g.y.d. and in order to follow the practice that has sometimes been adopted of having one primary bed and two secondary beds the rate on the primary bed was 450 g.y.d. and on the secondary 225 g.y.d. Under these conditions there was, in spite of low frequency dosing, a rapid deterioration in the condition of the primary bed (A.) and the test was therefore discontinued. After a short period of reconditioning the test was recommenced, applying the same flow to the primary and secondary beds, 300 g.y.d., as alternating filters, giving an overall steady rate of 150 g.y.d. for both double filtration and alternating double filtration. This rate was maintained from October, 1958 until June 1960, when the rate to both units was increased to 200 g.y.d. until October, 1961. From then until the end of the observations in September 1962 both units operated at only 100 g.y.d. The timetable showing the operational details of the four beds, including speeds of revolution are summarised in table 1.

The relative efficiencies of the two processes were assessed by analysis of samples taken over periods of 24 hours once each week. The samples taken, and the symbols used to describe them are as follows:

X1: Feed of settled sewage—common to both units.

Double Filtration Unit

A/B2: Primary bed effluent (A-Bed)
A/B3: Primary bed effluent after settlement in primary humus tanks.
A/B4: Secondary bed effluent (B-Bed)
A/B5: Secondary bed effluent after settlement in final humus tanks.

Alternating Double Filtration Unit

C/D2: Primary stage bed effluent
C/D3: Primary stage effluent after settlement in primary humus tank.
C/D4: Secondary stage bed effluent
C/D5: Secondary stage effluent after settlement in final humus tanks.

The suffixes (Sh) (S) (F) indicate that the analysis was done on the sample shaken, after 1 hour quiescent settlement or paper filtered respectively. All bed effluents A/B2, A/B4, C/D2 and C/D4 were settled for 1 hour to remove the humus solids.

On each sampling period the temperature of the feed and the four bed effluents was recorded and these were taken as indicating any differences and changes in bed temperature.

The ecological condition of the bed was assessed by removing samples of the bed medium contained in perforated canisters approximately 0.1 cu.ft. in capacity, which had previously been placed in the bed. The canisters were positioned in pairs, one of each pair being used to assess the film and the other the grazing fauna. The weight of film was found by washing the medium twice, 2 litres of water being used for each wash, and determining the volatile solid content in an aliquot of the resultant 4 litres. A correction was made for the grazing fauna present on the basis of the numbers assessed in the corresponding fauna sample. The macro fauna were removed from the other sample by washing the medium on a grid supported on a trough. The wash water was strained through a fine-mesh sieve to retain the macro-fauna which were then counted on a sectored illuminated counting chamber.

Each month 6 duplicate samples were removed from each of the four beds, at two levels, one in the upper 6 in. and the other at a depth of 6–12 in. The canisters were so positioned that the samples removed each month represented different sectors of the bed. During the course of the investigations perforated shafts, designed to hold columns of the perforated canisters, were inserted in three of the beds—the primary and secondary of the double filtration unit and one of the pair of alternating double filters. This enabled the ecological condition throughout the depth of the beds to be investigated. The medium was left in the shafts for a period of 1 year to become stabilized and it was therefore only possible to obtain depth samples during the latter period of the investigations, one observation being made at the end of the period of dosing at 200 g.y.d. and three at different seasons during the last year when the dosing rate was 100 g.y.d.

RESULTS

Analytical

In comparing the efficiencies of the two processes a distinction is made between the oxidation of carbonaceous matter and the oxidation of nitrogenous matter. The former was measured by the Permanganate Value (P. V.) test in 4 hours at 27°C using N/80 permanganate, and the 5 day Biochemical Oxygen Demand test. The amount of oxidised nitrogen (Ox. N.) i.e. nitrous and nitric N. was taken as indicative of the degree of nitrification.

1. Comparison of Carbonaceous Oxidation in the Two Processes

Statistical comparisons were made between the average P. V. results at different stages of oxidation in the two processes. These comparisons for the three different rates of treatment, 100, 150 and 200 g.y.d., are given in table 2a, b and c respectively. The statistical confidence limits given are those which are expected to include the real average with 95% certainty. The differences between the Permanganate Value at successive stages in each process are also given. In the final column are given the differences between the corresponding means for the two processes, together with the 95% confidence limits on these differences. If the confidence range includes zero, the difference is not significant at the 5% level.

Similar comparisons were made between the corresponding B.O.D. results and these are given in tables 3a, b and c.

The results presented in tables 2 and 3 show that:

(i) The average P.V. and B.O.D. of the final effluent from the double filtration (A/B5) are virtually the same as those from the alternating double filtration (C/D5) at all three rates of treatment. None of the overall differences are significant at the 5% level.

(ii) More oxidisable matter is removed in the primary stage of A.D.F. than in the primary stage of D.F., as shown in columns giving the successive differences between the different stages.

In the secondary stage however, the reverse is true, there being more oxidisable matter removed in the secondary stage of D.F. than in that of A.D.F.

Tables 4a, b and c give the relationships between the average Permanganate Values at different stages both of double filtration and alternating double filtration at 100, 150 and 200 g.y.d. respectively.

In column III are given the correlation coefficients (r) for each set of paired results. The correlation coefficient has a maximum value of unity which is only attained if all data lie exactly on a straight line.

A value of zero would indicate complete lack of correlation. Intermediate values represent varying degrees of correlation 0.5 or less being generally considered low, 0.8 or more high.

The significance levels of the correlation coefficients are given in column IV. A calculated value is said to be significant at the 5% level if it would not occur in more than 5% of trials when correlation was in fact absent. A significant value implies that it is valid to fit a linear relationship to the data.

The calculated unconstrained regression lines (L) and the associated residual standard deviation (s_0) are given in columns V and VI. The latter statistic is a measure of the spread of the data about the line in the direction of the effluent axis. Approximately 95% of the data will lie within a range of $\pm 2s_0$ from this line.

The regression lines 'L' fitting the data and passing through the origin, and their residual standard deviation (s_0') are given in columns VII and VIII.

In the final column IX is given the significance of a comparison between s_0 and s_0'—strictly speaking of the ratio between a measure of spread allied to s'_0 and the corresponding measure allied to s_0. A significantly high ratio indicates that the unconstrained line fits the data better than the line through the origin.

The corresponding statistical treatment of the B.O.D. results are given in tables 5a, b and c.

The results given in tables 4 and 5 show that, with one exception (XI and A/B2 table 4a) there exists a significant correlation between all sets of data. In the exceptional case the omission of two points leaves 29 points which exhibit significant correlation, as

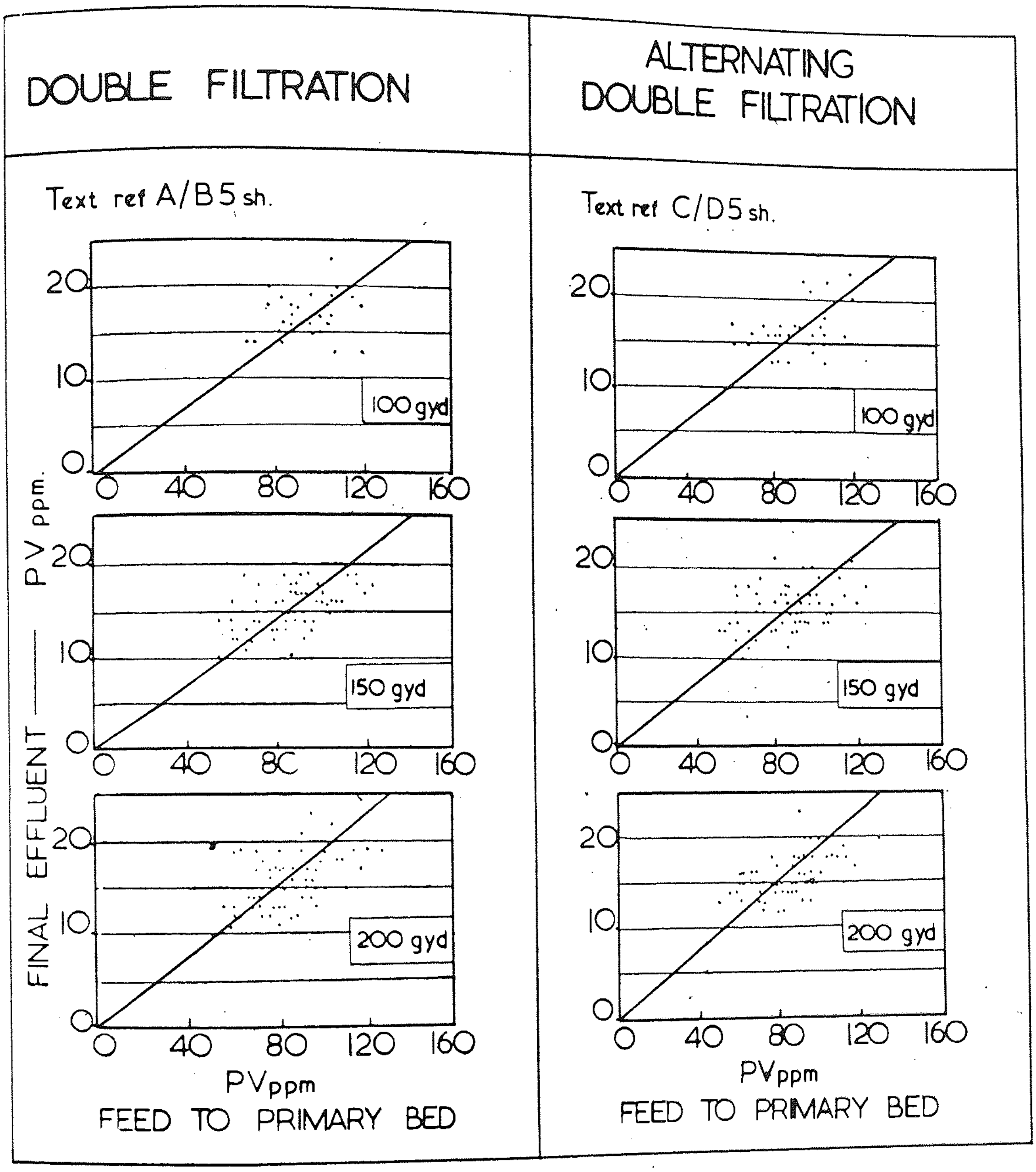

Fig. 2. Regression lines comparing the relationships between the Permanganate Value of the primary feeds and final effluents of Double Filtration and Alternating Double Filtration at different rates of dosage

discussed in the statistical appendix. The calculation of a straight line to fit all other sets of data is justified by the significance of the correlation coefficients.

For comparison of filtration efficiency, the lines through the origin given in column VII have veen used. The validity for doing so is discussed in an appendix to this paper by Mrs. J. M. Stokes and Mr. A. B. Neale of the Birmingham Corporation Central Statistical Office.

Some of the regression lines are shown graphically in figures 2 and 3. In figure 2 the relationship between the primary feed (XI) and the two final effluents (A/B5) and C/D5) is shown. The relationships between feeds and bed effluents in the intermediate primary and secondary stages are shown in figure 3.

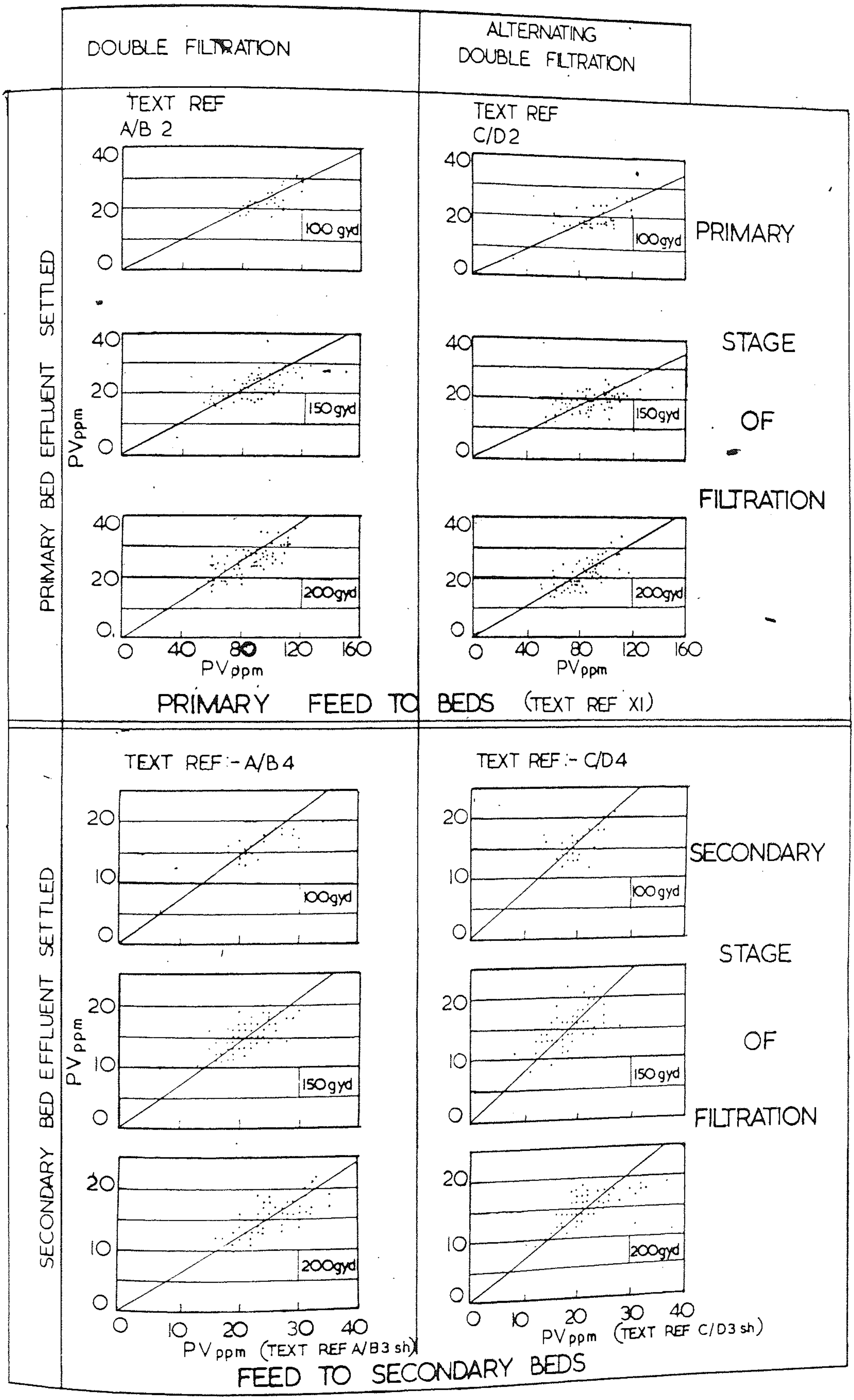

Fig. 3. Regression lines comparing the relationships between the Permanganate Values of feeds and effluents in the primary and secondary stages of Double Filtration and Alternating Double Filtration at different rates of dosage.

Comparison of the regression lines confirm the previous conclusions. The relationship between the primary feed and final effluent is very similar for double filtration and alternating double filtration. Again the differences between the two processes in both primary and secondary stages are evident.

Comparing the regression lines at different rates of treatment, it is seen that the regressions for the overall processes (A/B5 and C/D5 on XI) are similar at 100 g.y.d. and at 150 g.y.d. At 200 g.y.d. however a different relationship exists. Comparing the intermediate stages it is seen that in the primary stage in both processes the percentage efficiency decreases with increasing rate of treatment. In the secondary stage it increases with increasing rates of treatment. This however can be accounted for by the fact that the efficiency is related to the strength of the secondary feed; this increases with decreasing efficiency at high rates of treatment and thus increase the efficiency of the secondary stage.

The percentage removal of oxidisable matter at different stages of double filtration and alternating double filtration at different rates of treatment can be summarized:

Percentage Removal P.V.

Rate of Treatment g.y.d.	Primary Stage		Secondary Stage	
	D.F.	A.D.F.	D.F.	A.D.F.
100	74	79	29	22
150	74	78	30	20
200	69	74	39	32

Percentage Removal B.O.D.

Rate of Treatment	Primary Stage		Stage Secondary	
	D.F.	A.D.F.	D.F.	A.D.F.
100	81	86	43	37
150	83	86	46	29
200	79	83	41	37

To investigate the possibility of relative seasonal differences in the overall efficiency of the two processes, the P.V. and B.O.D. averages of the two final effluents during successive winter and summer periods were examined statistically. The results given in tables 6 and 7 show no relative seasonal differences. Again none of the overall differences between the two processes was significant at the 5% level.

2. Comparison of Nitrification in the two processes

To assess the relative efficiencies of the two processes in oxidising nitrogeneous matter, the average oxidised nitrogen (Ox.N) of the primary feed (XI), the primary stage effluents (A/B3 and C/D3) and the final effluents (A/B5 and C/D5) were compared statistically in a similar way to the P.V. and B.O.D. results. The results are given in table 8. The final column gives the differences in mean levels between the two processes at corresponding stages and the associated 95% confidence limits.

The results presented in table 8 show that:

(i) At all rates of treatment the Ox.N. concentration in the primary stage effluent from the alternating double filtration plant (C/D3) is significantly greater than the corresponding effluent from double filtration (A/B3).

(ii) The Ox.N. in the final effluent of the double filtration (A/B5) however is significantly greater than that in the final effluent of the alternating double filtration (C/D5). This is true at all three rates of treatment.

(iii) The successive differences in Ox.N. between the different stages of filtration differ appreciably in the two processes. Whereas in alternating double filtration the successive increments in Ox.N. at the primary and secondary stages are of the same order, in double filtration the increase in the secondary stage is more than double that in the primary stage.

(iv) The difference in the Ox.N. in the two final effluents was more marked at 200 g.y.d. than at 150 g.y.d. suggesting that the difference in nitrification was greater at higher loadings. The difference at 100 g.y.d. however was greater than at 150 g.y.d. This could be explained by the sequence of the tests, the period at 100 g.y.d. following the 200 g.y.d. (Table 1) and the resultant conditions of the different beds, as discussed in the next section.

As with the P.V. and B.O.D. results the possibility of relative season differences in nitrification in the two processes was investigated. The differences between the Ox.N. in the two final effluents for successive winter and summer periods are given in table 9.

The results show no seasonal differences in the relative Ox.N. levels in the two effluents.

The results given in table 9 also show that there was no difference in nitrification in the winter and summer periods in either unit. It thus appears that nitrification in bacteria beds is not affected by changes in temperature over the range existing in the beds, i.e. between approx. 10°C. and 20°C.

The reduced nitrification in bacteria beds in the winter when it does occur is probably due to the increased film accumulation.

BIOLOGICAL

The efficiency of bacteria beds is related to their biological condition. For continued efficient operation it is necessary to maintain a balanced community of organisms and to prevent the excessive accumulation of solids within the bed. The biological conditions of the two pairs of beds throughout the trials as reflected by the degree of film accumulation and the numbers of macro invertebrate grazers, including Enchytraeid worms and dipterous larvae and pupae, were kept under observation.

Conditions in the uppermost foot of the beds

Figure 4 shows the comparative degrees of film accumulation in the upper foot of the four beds throughout the trials. For comparison, the film accumulation in the four beds for a period of one year before the trials and before the distributors on beds A and B had been modified to rotate more slowly by the fitting of gear drives as were previously fitted to beds C and D. It is seen that there was a marked reduction in the amount of film in Bed A following the reduction in the speed of rotation, in spite of the increased organic loading whilst operating as the primary bed of the double filtration unit. Throughout the period of the trials there was no excessive accumulation of film or ponding in the surface layers of the primary bed. The prevention of the excessive accumulation of film in the primary bed, especially during the winter periods, was considered to be an essential feature contributing to the success of double filtration in these trials. There was no significant difference in the amount of film during the periods of different loadings.

The amount of film in the upper foot of the secondary bed (B) of the double filtration unit was even less. This was due to the reduced organic loading. It was found possible to increase the speed of rotation of the distributor to five minutes per revolution—i.e. to increase the frequency of dosing, without causing the film to increase. This suggests that the nutrient concentration of the feed was itself a limiting factor. There was a slight increase in film during the period of highest loading (200 g.y.d.). This was probably

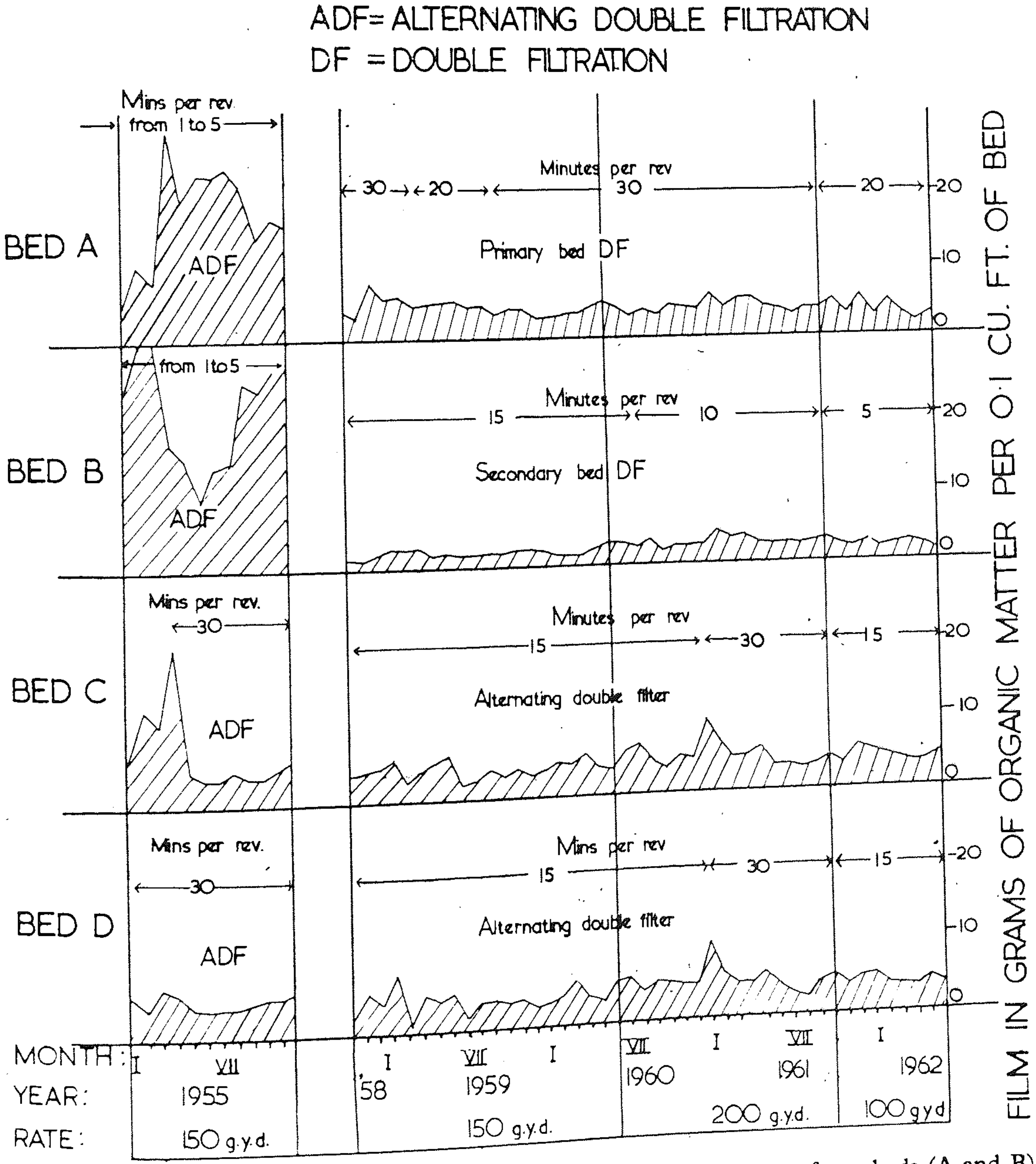

Fig. 4. Comparison of the degrees of film accumulation in the upper foot of two beds (A and B) operating as double filters and in beds C and D operating as alternating double filters, in relation to loading and frequency of dosing as determined by the speed of rotation of the distributors. For comparison the film accumulations in the four beds for a period (1955) before beds A and B were fitted with gear driven distributors are included

caused by the increased nutrient concentration in the feed due to the inferior primary bed effluent under conditions of increased loading, rather than by the higher volumetric load on the secondary bed.

The two A.D.F. beds (C and D) had previously been operated with gear-driven slowly revolving distributors. By doing so it had been found that excessive accumulation of film was prevented (Hawkes, 1955) and the efficiency was improved (Tomlinson & Hall, 1955). The increased film present in bed C early in 1955 coincided with a period when the distribution on that bed revolved rapidly being propelled by jet-reaction during a period of breakdown of the driving mechanism. This demonstrates the importance of frequency of dosing in controlling the accumulation of film. It is seen that throughout the trials there was no excessive accumulation of film and both beds had a similar amount of film present, this amount being similar to that in the primary bed (A) of the double filtration unit. It should be noted that for most of the time the distributors on the A.D.F. beds (C and D) were rotated more rapidly than that on the primary bed (A).

It was considered that throughout the trials, at all three rates of application, the amount of film in the upper foot of all four beds was maintained at a satisfactory level by controlling the frequency of dosing, i.e. regulating the rate of rotation of the distributors.

The nature of the film differed considerably on the different beds. On the primary bed (A) of the double filtration unit a bacterial fungal film was present. For most of the year this remained in a healthy aerobic condition, but at the height of summer although not excessive in amount, it tended to turn black and septic. This suggested that under conditions of daily heavy organic loading and high temperatures, anaerobic conditions existed in the film. This condition was observed in successive summers.

At all times the surface of the secondary bed (B) was covered with a green algal growth including *Ulothrix sp.* and unicellular chlorcoccales. Below the surface a thin bacterial slime was present which at no time turned septic. Beds C and D of the alternating double filtration unit were similar and for most of the year supported a thin algal growth on the surface with bacterial slime within the bed, which appeared to remain in a healthy aerobic condition. Beautiful but troublesome growths of the liverwort—*Marchantia* occurred each summer on the A.D.F. beds. These died back each winter, but were slow to decay. These growths occurred between the jets towards the centre of the beds where the jets were more widely spaced and were not present in the sampling areas.

Figure 5 shows the comparative populations of fly larvae and pupae—dominated by *Anisopus fenestralis* and *Psychoda alternata*—and Enchytraeid worms. Comparing bed A before the fitting of the gear drives—1955—with the subsequent period when distributor arms were rotated slowly by gear drives, it is seen that there was a marked reduction in the fly population and an increase in the Enchytraeid worm population. The populations and seasonal incidence of flies in the primary bed (A) of the double filtration unit and both A.D.F. beds (C and D) were all very similar. In all three beds there was a peak in the fly population in the spring of each year.

In the secondary bed (B) of the double filtration unit very few fly larvae or pupae existed. This was presumably due to the limited film available as food to support a fly population in competition with the Enchytraeids. One insect which was fairly common in this bed (B) and which was not found in the other beds in any number, was *Tomocerus minor*—Collembola.

The Enchytraeid worms were more abundant in the two A.D.F. beds (C and D) than in the double filtration beds (A and B). In the secondary bed (B) of the double filtration pair they were relatively rare throughout the first period of the trials at a dosage rate of 150 g.y.d. This was probably due to the shortage of food. During the second period, at 200 g.y.d., they increased appreciably, presumably associated with the increased

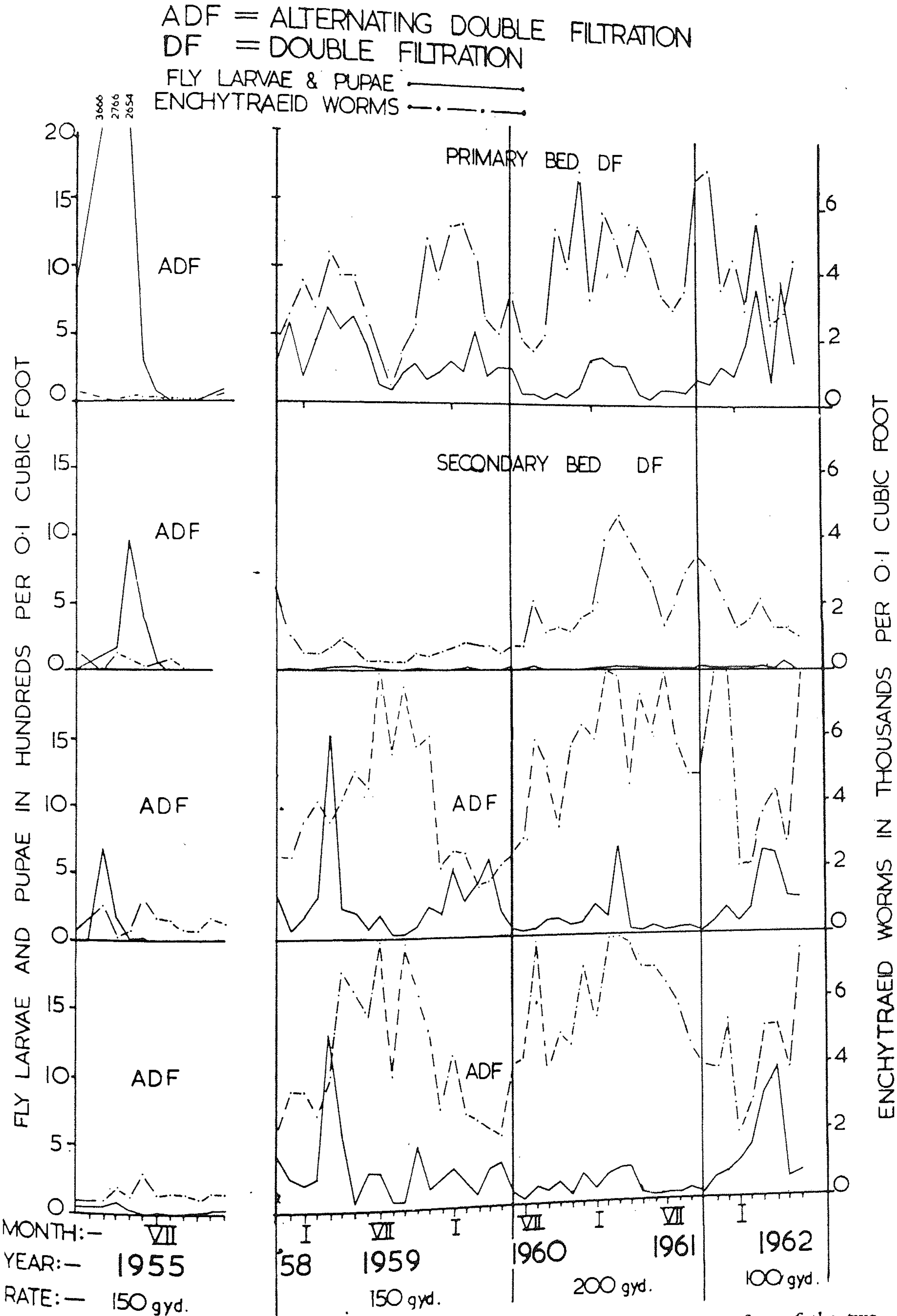

Fig. 5. Comparison of the macro-invertebrate grazing population in the upper foot of the two double filters (A and B) and the two alternating double filters (C and D). For comparison the corresponding populations in 1955, before beds A and B were fitted with gear drives, are included

amount of film during this period, as previously observed. There was a reduction in the population in the final period at 100 g.y.d.

Although the populations of Enchytraeids fluctuated erratically the general incidence in the primary bed (A) of the double filtration unit was markedly different from that in the two A.D.F. beds. In the latter there was generally a reduction in the worm population in the early part of the year associated with the increases in the fly populations. This could be accounted for by interspecific competition. In bed A however the lowest populations occurred in the summer, i.e. when the worm populations in the A.D.F. beds were at a maximum. This summer reduction in the worm population in A bed was associated with, and probably caused by, the anaerobic conditions of the film, previously mentioned. These adverse conditions may have prevented the summer increase in worms in bed A and thereby have been the cause of the overall smaller population of worms. During the winter more worms were usually present in bed A than in either of the A.D.F. beds (C and D).

These biological results show that although excessive accumulation of film was prevented in the surface layer of all beds, more stable ecological conditions existed in the two A.D.F. beds (C and D) than in the primary bed (A) of the double filtration unit. The populations of heterotrophic organisms, both micro-organisms and macro-invertebrate grazers in the secondary bed (B) of the double filtration unit were limited by the low organic content of the secondary feed. This resulted in an ecologically balanced bed with reserve capacity for biological oxidation.

Conditions throughout the depth of the beds

As previously explained it was only possible to take samples throughout the depth of the beds in the last year of the trials. The results of samples taken on four occasions are given as histograms in figure 6. The relative widths of the histograms at different heights indicates the amounts of film or numbers of organisms per unit volume of bed at different depths.

The first samples were taken at the end of the period of highest loading (200 g.y.d.) and the results are given in the uppermost row of histograms. These show that there was no excessive accumulation of film in the upper layers of both the double filtration beds (A and B) nor in the one A.D.F. bed sampled (C) thus confirming the results from the monthly surface samples.

Although similar conditions were present throughout the depth of the A.D.F. bed (C) and in the secondary bed (B) of the double filtration pair, this was not true of the primary bed (A). In this bed, what was considered to be an excessive accumulation of solids occurred in the lower half of the bed. Few fly larvae (*Anisopus fenestralis*) were present in any of the three beds, hardly any being found throughout the depth of the secondary bed B of the double filtration unit. In beds A and C they were distributed throughout the depth of the beds being somewhat more frequent at a depth of 2 feet. This scarcity of fly larvae was associated with the time of sampling—October—when the fly population was normally low.

Enchytraeid worms were present throughout the depths of the primary bed A of the double filtration unit and the A.D.F. bed C. In the latter (C) they were more abundant in the upper half of the bed, whereas in the primary bed (A) they were more evenly distributed. In the secondary bed (B) of the D.F. unit they were less frequent, being most numerous between 1 foot and 2 foot and decreasing in numbers below this.

The histograms in the other three lower rows of figure 6 show the conditions in January, March and June during the final period when the beds were operating on reduced loading of 100 g.y.d. In comparing the results for these three occasions and with the results at 200 g.y.d., discussed above, not only must the different seasons be considered but the possibility that they represent different phases in the changes in conditions following the reduction in rate of application from 200 g.y.d. to 100 g.y.d. Also, besides this change in rate of application, the speed of rotation of the distributors was altered at the same time, as indicated in figure 6.

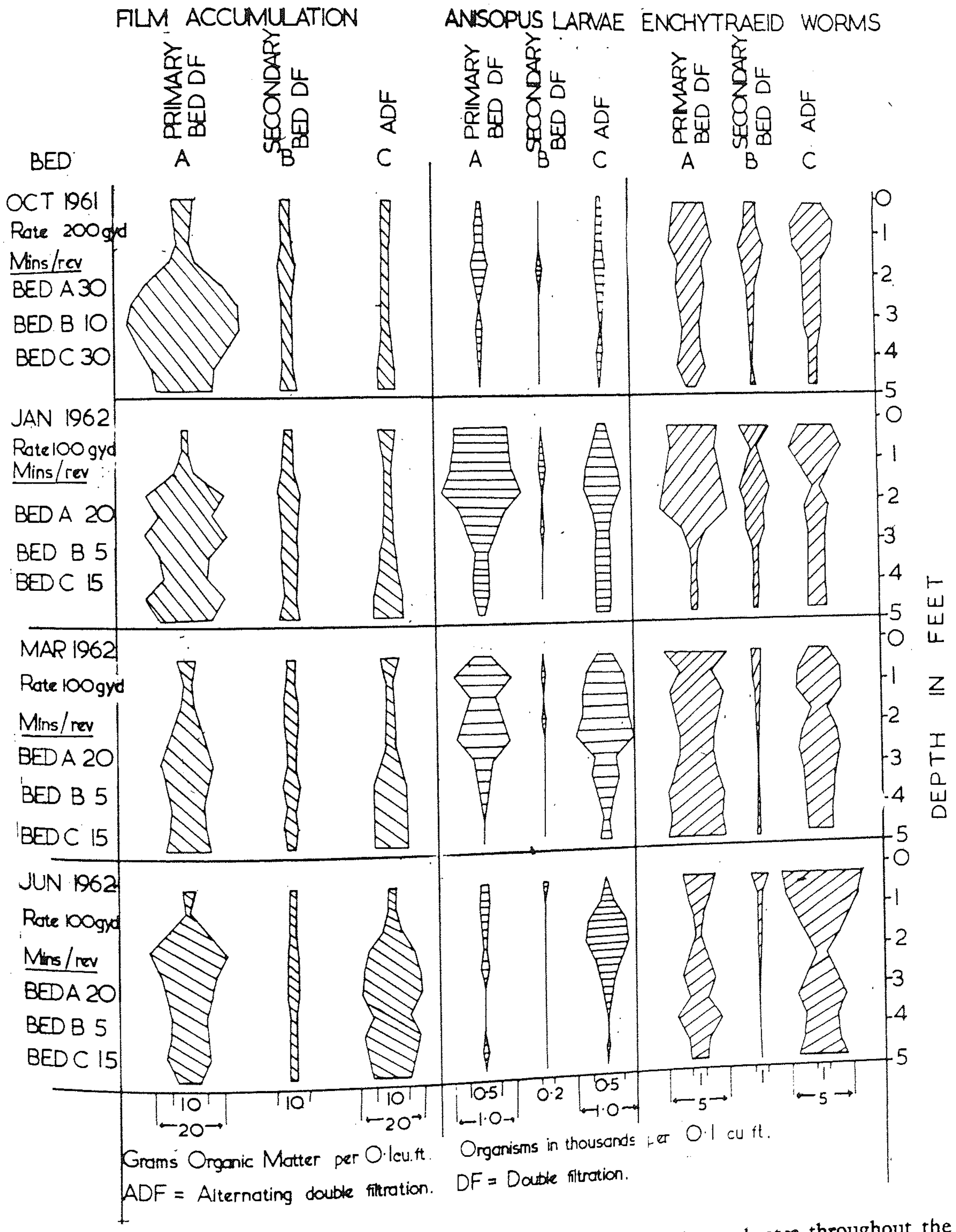

Fig. 6. Comparison of the vertical distribution of film and macro-invertebrates throughout the depths of the two double filters (A and B) and one alternating double filter (C)

In bed A, the primary bed of the D.F. pair, there was a decrease in the excessive amount of film which had accumulated in the lower half of the bed during the period of high loading (200 g.y.d.). The change in load made little difference to the amount or distribution of the film in bed B, the secondary bed of the D.F. pair. In bed C, the one A.D.F. bed sampled through the depth, there was a progressive increase in film from the bottom upwards on the three occasions that samples were examined. On the last occasion the amount and distribution of the film in the A.D.F. bed was similar to that in the primary bed (A) of the D.F. unit. This increase in film below the 1 foot level under conditions of reduced loading could only be accounted for by the speeding up of the distributors from 1 rev. in 30 minutes to 1 rev. in 15 minutes. The results show the importance of the frequency of dosing on controlling film accumulation.

The marked changes in the grazing fauna populations is probably due to natural seasonal changes. *Anisopus fenestralis* larvae were most abundant in January and March in beds A and in these beds were most abundant in the upper half. They were practically absent from the secondary bed B on all occasions. The difference in the seasonable incidence of Enchytraeid worms in the surface layers of the primary bed (A) of the D.F. pair and in the A.D.F. beds was confirmed by results throughout the depths of the beds. Whereas in the A.D.F. bed (C) was an increase in the worm population in the summer (June), there was a marked decrease in the primary bed (A) of the D.F. pair at this time.

These results from samples through the depths of the beds revealed that the conditions in the surface layers were not necessarily indicative of conditions within the beds. They did however confirm the results from the more frequent surface samples in showing that the A.D.F. beds (C and D) were in better condition that the primary bed (A) of the D.F. unit. Only the depth samples showed the full effect of the frequency of dosing and the accumulation of film.

Comparison of the Humus Solids discharged from the Beds

The humus solids discharged from each of the four beds was assessed by sampling the bed effluents at two hourly intervals daily and determining the suspended solid concentration in the bulked weekly samples. The average results for the three periods at different rates of application are shown as histograms in figure 7. These show the comparative concentration of solids in the effluents, i.e. the amounts of humus discharged per unit volume of sewage treated. To compare the relative amounts of solids discharged at the different rates of treatment the relative volumes have to be taken into account. For example the figures at 200 g.y.d. would need to be doubled for comparison with the figures at 100 g.y.d., and those at 150 g.y.d. multiplied by 1.5. Figure 7 shows that the solids discharged per unit volume of sewage treated varies at different rates of treatment. Thus at 200 g.y.d. the humus solids produced for each unit volume of sewage treated was appreciably greater in both D.F. and A.D.F. than at 150 g.y.d. This could be accounted for by the reduced endogenous respiration (autolysis) of the film with the increased organic food available at the higher rate of application. At 100 g.y.d. the concentration of solids, but not the total solid discharge, slightly exceeded that at 150 g.y.d.; this could not be explained.

The amount of humus solids produced by the two D.F. beds (A and B) jointly was of the same order as that produced by the two A.D.F. beds (C and D) at all three rates of treatment. But whereas in the A.D.F. beds equal amounts were produced by each bed, the primary bed (A) of the D.F. pair produced far more than the secondary bed (B).

Comparison of Bed Temperatures

TIDSWELL (1960) compared double filtration and alternating double filtration of a sewage containing a high proportion of brewery waste. In accounting for the differences in efficiences he considered that the higher temperature of the primary bed of the double filtration unit (by 4°C) was a significant factor.

Although no record of bed temperatures was possible the temperatures of the effluents were taken as indicating relative differences between the temperatures of the beds. The monthly average temperatures are given in table 10. Some of the differences between the effluent temperatures in any one month may be accounted for by the fact that whereas the figures for the two D.F. beds (A and B) represent the average of all the sampling occasions in the month, the separate figures for primary and secondary stages of beds C and D each represent the averages of different occasions as obviously both beds could not be primary or secondary on the same day. In spite of this the results show that there was no marked difference in temperatures between the two units. The difference was never greater than 2°C and was usually less than 1°C. It was therefore concluded that temperature was not an important factor in accounting for the difference in efficiency in the two processes.

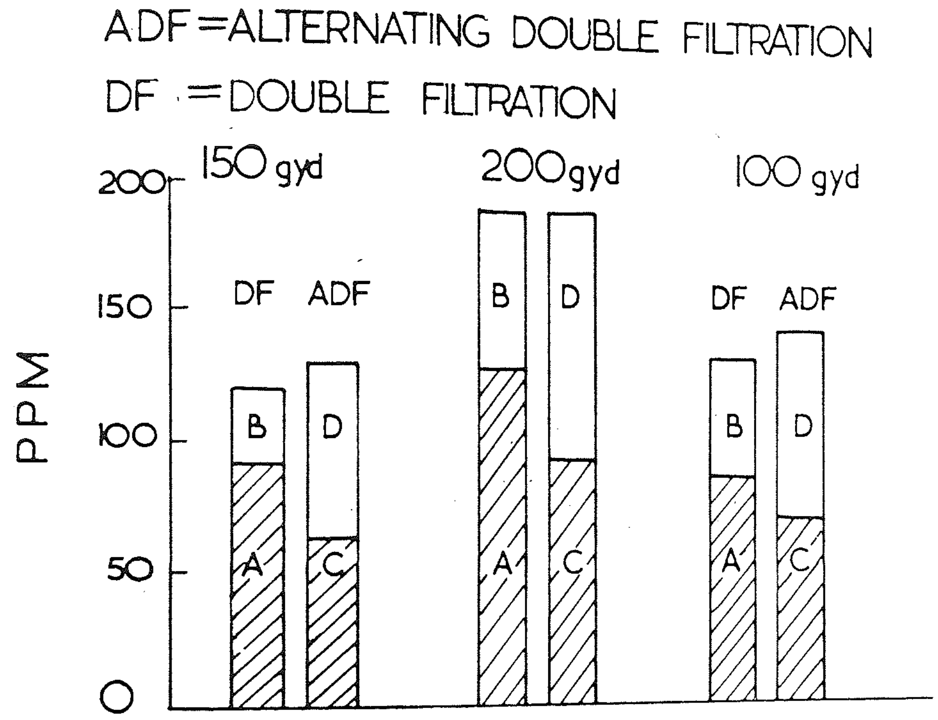

Fig. 7. Comparison of the amounts of humus solids discharged per unit volumes of sewage treated from a pair of double filters (A and B) and a pair of alternating double filters (C and D) at different volumetric loadings

DISCUSSION

Statistical treatment of the analytical data showed that there was no significant difference in the removal of oxidisable organic matter by double filtration and by alternating double filtration. However, the proportion removed in the corresponding two stages differed. A somewhat higher proportion of the organic load was removed in the primary stage of A.D.F. than in the corresponding stage of D.F. In the secondary stage a higher proportion was removed by D.F. The primary stage of A.D.F. may therefore be said to be more efficient (5%) than the primary bed of D.F. This is in agreement with the different observed ecological conditions of the beds involved (A, C and D). Although somewhat less efficient the primary bed (A) of D.F. did appreciably more work in removing organic matter, since it performed this role every day, in contrast to every other day by the A.D.F. beds. Considering this the reduction in efficiency was remarkably small.

Although statistically the efficiency of the secondary bed of D.F. was greater than the corresponding stage of A.D.F. in removing oxidisable organic matter, a comparison is not valid since unlike the primary stage, the beds received a feed of different organic content as a result of the different efficiencies in the primary stage. More work in removing organic matter was done by the A.D.F. beds (C and D) than by the secondary bed (B) of D.F., since on alternate days they received primary feed.

For efficient operation of bacteria beds it is necessary to maintain an ecologically balanced community and prevent the excessive accumulation of film. In the A.D.F. beds these conditions were achieved by the nutritional control of the film both by applying secondary feed of low organic content on alternate days and by intermittent dosing. In the primary bed (A) of D.F. only one of these factors, controlled frequency of dosing, operated. The success of D.F. depended upon the control of film in the primary bed. Throughout the 3½ years of the trials, the film in the upper layers of the primary bed was successfully limited by controlled frequency of dosing. The limited results available from the depth of the bed however, showed that at least at the highest rate of application (200 g.y.d. overall i.e. 400 g.y.d. on the primary bed) there was considerable accumulation of solids in the middle layers of the bed. This did not seriously affect the efficiency of the bed and it was considered that controlled frequency of dosing was successful in preventing the accumulation of film to such an extent that the efficiency of the bed was not seriously impaired.

It was thought possible that the hydraulic conditions imposed by controlled frequency dosing would decrease the retention time of the liquor within the beds. Times of contact in three different depths (2 ft, 4 ft. and 6 ft.) were determined in one bed (B) at three different rates of rotation of the distribution arms, (approximately 3 minutes, 10 minutes and 20 minutes per rev.) using a solution of a lithium salt. The determination was carried out at the highest rate of dosage (200 g.y.d. overall i.e. 400 g.y.d. on the one bed). The results given in table 11 show that the overall retention time of the liquor in the bed was slightly increased by increasing the period between doses within the range tested. This was also true of the upper 2 ft. and 4 ft. of the bed except for the 2 ft. depth at the slowest speed of rotation.

Nitrification as represented by the amount of Ox.N. in the effluent was greater by D.F. than by A.D.F. Again there was a difference in the relative degree of nitrification in the two stages. In A.D.F. approximately the same degree of nitrification was achieved in the primary and secondary stages but in D.F. appreciably more occurred in the secondary bed. This can be related to the different conditions of the beds. Previous work (Hawkes, 1957) showed that nitrification was impaired by increasing amounts of accumulated film in the bed. The results of the present investigation confirm this. Most nitrification occurred in the bed with the least film, i.e. the secondary bed (B) of D.F. and least in the primary bed (A) of D.F. in which the film accumulation was greatest. In the two A.D.F. stages in beds having similar degrees of film accumulation the degree of nitrification was similar.

The chief differences between the two processes are in the role of the beds in each pair. In A.D.F. the role of both is the same and is multipurpose, carrying out the oxidation

TABLES 2a, b, c. *Mean P.V. levels in ppm. for double filtration and alternating double filtration at 100, 150 and 200 g.y.d.*

Stage		Double filtration (D.F.		Alternating double filtration (A.D.F.)		Average (D.F.) – Average (A.D.F.) with 95% confidence limits
D.F.	A.D.F.	Average level with 95% confidence limits	Successive difference	Average level with 95% confidence limits	Successive difference	
			Tab. 2a. 100 g.y.d.			
X1	X1	92.80 ± 5.34	—	92.80 ± 5.34	—	0
A/B2	C/D2	24.13 ± 1.88	68.67	19.80 ± 1.04	73.00	4.33 ± 2.14
A/B3s	C/D3s	20.68 ± 1.42	3.45	17.43 ± 1.10	2.37	3.25 ± 1.80
A/B3sh	C/D3sh	23.58 ± 1.66	— 2.90	20.26 ± 1.30	— 2.83	3.32 ± 2.12
A/B4	C/D4	16.50 ± 1.04	7.08	15.59 ± 0.76	4.67	0.91 ± 1.30
A/B5s	C/D5s	14.86 ± 0.94	1.64	14.44 ± 0.84	1.15	0.42 ± 1.26
A/B5sh	C/D5sh	16.90 ± 0.92	— 2.04	16.59 ± 1.00	— 2.15	0.31 ± 1.36
All Stages			75.90		76.21	0.31 ± 1.36
			Tab. 2b. 150 g.y.d.			
X1	X1	86.83 ± 4.40	—	86.83 ± 4.40	—	0
A/B2	C/D2	22.42 ± 1.14	64.41	18.96 ± 0.76	67.87	3.46 ± 1.36
A/B3s	C/D3s	18.65 ± 0.92	3.77	16.49 ± 0.80	2.47	2.16 ± 1.22
A/B3sh	C/D3sh	21.31 ± 0.88	— 2.66	18.74 ± 0.80	— 2.25	2.57 ± 1.18
A/B4	C/D4	14.99 ± 0.58	6.32	15.04 ± 0.62	3.70	— 0.05 ± 0.84
A/B5s	C/D5s	13.31 ± 0.56	1.68	13.34 ± 0.54	1.70	— 0.03 ± 0.78
A/B5sh	C/D5sh	15.46 ± 0.58	— 2.15	15.57 ± 0.58	— 2.23	— 0.11 ± 0.82
All Stages			71.37		74.26	— 0.11 ± 0.82
			Tab. 2c. 200 g.y.d.			
X1	X1	82.90 ± 3.76	—	82.90 ± 3.76	—	0
A/B2	C/D2	25.73 ± 1.34	57.17	21.54 ± 1.22	61.36	4.19 ± 1.80
A/B3s	C/D3s	22.19 ± 1.14	3.54	19.19 ± 1.10	2.35	3.00 ± 1.58
A/B3sh	C/D3sh	25.51 ± 1.22	— 3.32	22.33 ± 1.22	— 3.14	3.18 ± 1.74
A/B4	C/D4	15.51 ± 0.64	10.00	15.21 ± 0.56	7.12	0.30 ± 0.84
A/B5s	C/D5s	13.17 ± 0.62	2.34	13.38 ± 0.60	1.83	— 0.21 ± 0.86
A/B5sh	C/D5sh	15.83 ± 0.66	— 2.66	15.88 ± 0.64	— 2.50	— 0.05 ± 0.92
All Stages			67.07		67.02	— 0.05 ± 0.92

TABLES 3a, b, c. *Mean B.O.D. levels (ppm) for double filtration and alternating double filtration at 100, 150 and 200 g.y.d.*

Stage		Double filtration (D.F.)		Alternating double filtration (A.D.F.)		Average (D.F.) – Average (A.D.F.) with 95% confidence limits
D.F.	A.D.F.	Average level with 95% confidence limits	Successive difference	Average level with 95% confidence limits	Successive difference	
Tab. 3a. 100 g.y.d.						
X1	X1	190.65 ± 19.80	—	190.65 ± 19.90	—	0
A/B2	C/D2	36.63 ± 4.10	154.02	27.03 ± 2.80	163.62	9.60 ± 4.96
A/B3s	C/D3s	21.17 ± 2.80	15.46	18.97 ± 3.08	8.06	2.20 ± 4.16
A/B3sh	C/D3sh	30.67 ± 3.28	— 9.50	31.68 ± 3.50	—12.71	— 1.01 ± 4.80
A/B4	C/D4	17.79 ± 2.52	12.88	20.06 ± 2.70	11.62	— 2.27 ± 3.70
A/B5s	C/D5s	12.76 ± 2.28	5.03	13.03 ± 1.50	7.03	— 0.27 ± 2.72
A/B5sh	C/D5sh	22.03 ± 3.64	— 9.27	24.27 ± 3.16	—11.24	— 2.24 ± 4.82
All Stages			168.62		166.38	— 2.24 ± 4.82
Tab. 3b. 150 g.y.d.						
X1	X1	213.59 ± 13.24	—	213.59 ± 13.24	—	0
A/B2	C/D2	37.00 ± 2.66	176.59	29.70 ± 1.68	183.89	7.30 ± 3.14
A/B3s	C/D3s	24.94 ± 2.20	12.06	20.54 ± 1.58	9.16	4.40 ± 2.72
A/B3sh	C/D3sh	34.01 ± 2.74	— 9.07	30.00 ± 1.96	— 9.46	4.01 ± 3.36
A/B4	C/D4	18.28 ± 1.28	15.73	21.26 ± 1.92	8.74	— 2.98 ± 2.32
A/B5s	C/D5s	12.79 ± 1.00	5.49	13.90 ± 1.08	7.36	— 1.11 ± 1.48
A/B5sh	C/D5sh	18.76 ± 1.62	— 5.97	20.87 ± 1.60	— 6.97	— 2.11 ± 2.28
All Stages			194.83		192.72	— 2.11 ± 2.28
Tab. 3c. 200 g.y.d.						
X1	X1	197.20 ± 12.20	—	197.20 ± 12.20	—	0
A/B2	C/D2	40.39 ± 2.58	156.80	34.06 ± 2.98	163.10	6.33 ± 3.94
A/B3s	C/D3s	28.04 ± 2.34	12.35	23.60 ± 2.66	10.46	4.44 ± 3.54
A/B3sh	C/D3sh	39.62 ± 2.76	—11.58	37.87 ± 2.84	—14.27	1.75 ± 3.96
A/B4	C/D4	23.41 ± 2.50	16.21	23.91 ± 2.04	13.96	— 0.50 ± 3.80
A/B5s	C/D5s	13.60 ± 1.50	9.81	12.95 ± 1.36	10.96	0.65 ± 2.02
A/B5sh	C/D5sh	26.25 ± 2.84	—12.65	27.59 ± 2.18	—14.64	— 1.34 ± 3.58
All Stages			170.90		169.60	— 1.34 ± 3.58

TABLES 4a, b, c. *Relationship between P.V. readings at different stages of the double filtration and alternating double filtration trials. 100, 150 and 200 g.y.d.*

Stages compared (X)	(Y)	Number of Observations	Correlation coefficient (r)	Significance of (r)	Unconstrained line (L)	Residual standard deviation about L (s_0)	Line through origin (L')	Residual standard deviation about L' (s_0')	Significance of comparison between s_0 and s_0'
Tab. 4a. 100 g.y.d.									
	(A/B2*	31	0.19	—	—	—	—	—	—
	(C/D2	35	0.40	1%	Y = 0.0775 X + 12.61	2.9	Y = 0.213 X	3.4	—
	(A/B3s	31	0.37	5%	Y = 0.0952 X + 11.76	3.8	Y = 0.221 X	4.2	—
	(C/D3s	35	0.57	0.1%	Y = 0.1163 X + 6.64	2.7	Y = 0.188 X	3.0	—
X1 and									
X1 and	(A/B3sh	31	0.41	1%	Y = 0.1212 X + 12.23	4.3	Y = 0.252 X	4.8	—
X1 and	(C/D3sh	35	0.60	0.1%	Y = 0.1460 X + 6.71	3.1	Y = 0.218 X	3.3	—
	(A/B5sh	29	0.32	5%	Y = 0.0546 X + 11.71	2.4	Y = 0.178 X	3.1	—
	(C/D5sh	34	0.41	1%	Y = 0.0740 X + 9.73	2.7	Y = 0.179 X	3.2	—
A/B3sh and A/B4		30	0.75	0.1%	Y = 0.5034 X + 4.81	2.0	Y = 0.710 X	2.1	—
C/D3sh and C/D4		34	0.71	0.1%	Y = 0.4169 X + 7.21	1.6	Y)= 0.776 X	2.1	—
A/B3sh and A/B5s		29	0.45	1%	Y = 0.2598 X + 8.81	2.3	Y = 0.639 X	2.8	—
C/D3sh and C/D5s		34	0.72	0.1%	Y = 0.4645 X + 5.11	1.7	Y = 0.719 X	2.0	—
A/B3sh and A/B5sh		29	0.55	1%	Y = 0.3142 X + 9.59	2.1	Y = 0.726 X	2.8	—
C/D3sh and C/D5sh		34	0.55	0.1%	Y = 0.5040 X + 6.46	2.3	Y = 0.826 X	2.6	—
* Omitting two freak points (see Figure 1) the results are:									
X1	A/B2	29	0.79	0.1%	Y = 0.2081 X + 3.33	2.4	Y = 0.243 X	2.4	—
Tab. 4b. 150 g.y.d.									
X1 and	(A/B2	71	0.60	0.1%	Y = 0.1548 X + 8.98	3.9	Y = 0.258 X	4.3	—
	(C/D2	71	0.62	0.1%	Y = 0.1069 X + 9.68	2.5	Y = 0.218 X	3.3	5%

X1 and (A/B3s	71	0.31	1%	Y = 0.0658 X + 12.94	3.7	Y = 0.215 X	4.7	—
X1 and (C/D3s	70	0.64	0.1%	Y = 0.1154 X + 6.51	2.6	Y = 0.191 X	2.9	—
X1 and (A/B3sh	71	0.60	0.1%	Y = 0.1196 X + 10.93	3.0	Y = 0.245 X	3.9	5%
X1 and (C/D3sh	70	0.64	0.1%	Y = 0.1155 X + 8.75	2.6	Y = 0.217 X	3.3	—
X1 and (A/B5sh	70	0.33	1%	Y = 0.0438 X + 11.64	2.3	Y = 0.177 X	2.6	—
X1 and (C/D5sh	71	0.46	0.1%	Y = 0.0600 X + 10.37	2.1	Y = 0.179 X	3.1	1%
A/B3sh and A/B4	70	0.66	0.1%	Y = 0.4322 X + 5.77	1.8	Y = 0.702 X	2.1	—
C/D3sh and C/D4	70	0.60	0.1%	Y = 0.4654 X + 6.32	2.1	Y = 0.803 X	3.4	—
A/B3sh and A/B5s	70	0.70	0.1%	Y = 0.4444 X + 3.83	1.7	Y = 0.624 X	1.8	—
C/D3sh and C/D5s	70	0.54	0.1%	Y = 0.3643 X + 6.51	1.9	Y = 0.712 X	2.2	—
A/B3sh and A/B5sh	70	0.65	0.1%	Y = 0.4207 X + 6.48	1.8	Y = 0.724 X	2.2	—
C/D3sh and C/D5sh	70	0.49	0.1%	Y = 0.3580 X + 8.86	2.1	Y = 0.831 X	2.7	—

Tab. 4c. 200 g.y.d.

X1 and (A/B2	73	0.65	0.1%	Y = 0.2306 X + 6.61	4.4	Y = 0.310 X	4.6	—
X1 and (C/D2	72	0.72	0.1%	Y = 0.2289 X + 2.53	3.6	Y = 0.259 X	3.7	—
X1 and (A/B3s	72	0.69	0.1%	Y = 0.2081 X + 4.97	3.5	Y = 0.268 X	3.7	—
X1 and (C/D3s	73	0.63	0.1%	Y = 0.1833 X + 3.99	3.7	Y = 0.231 X	3.7	—
X1 and (A/B3sh	72	0.68	0.1%	Y = 0.2191 X + 7.38	3.9	Y = 0.308 X	4.1	—
X1 and (C/D3sh	73	0.56	0.1%	Y = 0.1815 X + 7.28	4.4	Y = 0.269 X	4.6	—
X1 and (A/B5sh	72	0.47	0.1%	Y = 0.0815 X + 9.07	2.5	Y = 0.191 X	3.1	—
X1 and (C/D5sh	72	0.36	1%	Y = 0.0603 X + 10.88	2.5	Y = 0.191 X	3.3	—
A/B3sh and A/B4	71	0.67	0.1%	Y = 0.3414 X + 6.77	2.0	Y = 0.606 X	2.5	—
C/D3sh and C/D4	72	0.54	0.1%	Y = 0.2438 X + 9.78	2.0	Y = 0.682 X	3.1	—
A/B3sh and A/B5s	71	0.73	0.1%	Y = 0.3682 X + 3.81	1.8	Y = 0.518 X	2.0	5%
C/D3sh and C/D5s	72	0.65	0.1%	Y = 0.3163 X + 6.33	2.0	Y = 0.600 X	2.5	1%
A/B3sh and A/B5sh	71	0.68	0.1%	Y = 0.3702 X + 6.42	2.1	Y = 0.623 X	2.5	—
C/D3sh and C/D5sh	72	0.63	0.1%	Y = 0.3221 X + 8.70	2.1	Y = 0.712 X	2.9	1%

TABLES 5a, b, c. *Relationships between B.O.D. readings at different stages of the double filtration and alternating double filtration trials. 100, 150 and 200 g.y.d.*

Stages compared (X) (Y)	Number of Observations	Correlation coefficient (r)	Significance of r	Unconstrained Line (L)	Residual standard deviation about L (^{s}o)	Line through origin (L')	Residual standard deviation about L' (^{s}o')	Significance of comparison between ^{s}o and ^{s}o'
Tab. 5a. 100 g.y.d.								
X1 and (A/B2	30	0.41	5%	Y = 0.0839 X + 20.10	10.4	Y = 0.186 X	12.0	—
(C/D2	33	0.31	5%	Y = 0.0417 X + 19.06	7.8	Y = 0.142 X	9.8	—
(A/B3s	30	0.52	1%	Y = 0.0730 X + 6.79	6.7	Y = 0.107 X	7.0	—
(C/D3s	34	0.51	1%	Y = 0.0782 X + 4.07	7.8	Y = 0.100 X	7.9	—
(A/B3sh	30	0.59	0.1%	Y = 0.0961 X + 13.39	7.4	Y = 0.156 X	8.2	1%
(C/D3sh	34	0.56	0.1%	Y = 0.0978 X + 13.04	8.6	Y = 0.166 X	9.6	—
(A/B5sh	29	0.33	5%	Y = 0.0551 X + 11.13	9.4	Y = 0.11 X	9.8	—
(C/D5sh	33	0.39	5%	Y = 0.0597 X + 12.89	8.5	Y = 0.127 X	9.5	—
A/B3sh and A/B4	28	0.93	0.1%	Y = 0.5611 X + 0.42	2.6	Y = 0.574 X	4.2	—
C/D3sh and C/D4	33	0.50	1%	Y = 0.3764 X + 18.06	6.8	Y = 0.629 X	7.3	—
A/B3sh and A/B5s	29	0.71	0.1%	Y = 0.4805 X — 2.07	4.4	Y = 0.413 X	4.4	—
C/D3sh and C/D5s	33	0.53	1%	Y = 0.2213 X + 5.78	3.7	Y = 0.409 X	3.9	—
A/B3sh and A/B5sh	29	0.78	01.%	Y = 0.8440 X — 4.02	6.3	Y = 0.714 X	6.4	—
C/D3sh and C/D5sh	33	0.56	0.1%	Y = 0.4906 X + 8.63	7.7	Y = 0.761 X	8.2	—
Tab. 5b. 150 g.y.d.								
X1 and (A/B2	69	0.67	0.1%	Y = 0.1354 X + 8.08	8.2	Y = 0.173 X	8.5	—
(C/D2	69	0.42	0.1%	Y = 0.0539 X + 18.19	6.4	Y = 0.139 X	8.0	—
(A/B3s	69	0.67	0.1%	Y = 0.1114 X + 1.15	6.8	Y = 0.117 X	6.9	—
(C/D3s	69	0.50	0.1%	Y = 0.0597 X + 7.79	5.8	Y = 0.096 X	6.2	—

X1 and (A/B3sh	69	0.36	1%	Y = 0.0693 X + 19.21	10.8	Y = 0.159 X	11.9	—
X1 and (C/D3sh	69	0.36	1%	Y = 0.0531 X + 18.66	7.7	Y = 0.140 X	9.1	—
X1 and (A/B5sh	68	0.34	1%	Y = 0.0437 X + 9.53	6.4	Y = 0.089 X	6.8	—
X1 and (C/D5sh	68	0.25	5%	Y = 0.0302 X + 14.38	6.5	Y = 0.097 X	7.5	—
A/B3sh and A/B4	68	0.55	0.1%	Y = 0.2567 X + 9.58	4.4	Y = 0.539 X	5.5	—
C/D3sh and C/D4	69	0.27	5%	Y = 0.2679 X + 13.22	7.7	Y = 0.709 X	8.6	—
A/B3sh and A/B5s	68	0.53	0.1%	Y = 0.1906 X + 6.33	3.5	Y = 0.377 X	5.2	1%
C/D3sh and C/D5s	68	0.47	0.1%	Y = 0.2652 X + 5.87	4.0	Y = 0.459 X	4.3	—
A/B3sh and A/B5sh	68	0.69	0.1%	Y = 0.4083 X + 4.92	4.9	Y = 0.554 X	5.1	—
C/D3sh and C/D5sh	68	0.50	0.1%	Y = 0.4227 X + 1.07	5.8	Y = 0.689 X	6.2	—
Tab. 5c. 200 g.y.d.								
X1 and (A/B2	69	0.59	0.1%	Y = 0.1241 X + 15.92	8.7	Y = 0.205 X	9.8	—
X1 and (C/D2	68	0.50	0.1%	Y = 0.1215 X + 10.07	10.7	Y = 0.173 X	11.0	—
X1 and (A/B3s	69	0.55	0.1%	Y = 0.1064 X + 7.06	8.2	Y = 0.142 X	8.3	—
X1 and (C/D3s	68	0.47	0.1%	Y = 0.1007 X + 3.72	9.8	Y = 0.120 X	9.8	—
X1 and (A/B3sh	69	0.44	0.1%	Y = 0.1000 X + 20.48	10.4	Y = 0.201 X	11.6	—
X1 and (C/D3sh	67	0.44	0.1%	Y = 0.1003 X + 18.04	10.5	Y = 0.192 X	11.5	—
X1 and (A/B5sh	68	0.30	1%	Y = 0.0694 X + 8.09	11.2	Y = 0.133 X	11.7	—
X1 and (C/D5sh	66	0.37	1%	Y = 0.0594 X + 15.80	8.4	Y = 0.139 X	9.4	—
A/B3sh and A/B4	68	0.45	0.1%	Y = 0.4053 X + 7.35	9.3	Y = 0.591 X	9.5	—
C/D3sh and C/D4	66	0.61	0.1%	Y = 0.4336 X + 7.43	6.6	Y = 0.629 X	7.0	—
A/B3sh and A/B5s	68	0.53	0.1%	Y = 0.2845 X + 2.33	5.3	Y = 0.343 X	5.3	—
C/D3sh and C/D5s	66	0.59	0.1%	Y = 0.2798 X + 2.32	4.5	Y = 0.341 X	4.5	—
A/B3sh and A/B5sh	68	0.30	1%	Y = 0.2017 X + 14.29	11.2	Y = 0.662 X	12.0	—
C/D3sh and C/D5sh	66	0.47	0.1%	Y = 0.3554 X + 14.08	7.9	Y = 0.726 X	9.1	—

TAB. 6. *Comparison of mean P.V. (with 95% Confidence Limits) of final stage effluents from double filtration (A/B) and alternating double filtration (C/D) during successive Winter and Summer periods –*

P.V.ppm	58–59 Nov-March	59 April-Sept	59–60 Oct-March	60 June-Sept	60–61 Oct-March	61 April-Sept	61–62 Nov-March	62 March-Sept
A/B4(F)	13.2 ± 1.04	11.1 ± 0.5	12.5 ± 0.84	13.0 ± 1.08	13.4 ± 0.76	12.9 ± 0.97	13.8 ± 1.12	12.2 ± 0.99
C/D4(F)	13.3 ± 1.17	11.9 ± 0.52	12.2 ± 0.91	13.1 ± 1.05	12.8 ± 0.73	12.4 ± 0.8	12.8 ± 0.8	11.4 ± 0.82
Difference	—0.1 ± 1.56	—0.8 ± 0.72	0.3 ± 1.24	—0.1 ± 1.51	0.6 ± 1.05	0.5 ± 1.26	1.0 ± 1.38	0.8 ± 1.28
A/B5(S)	14.1 ± 1.24	12.6 ± 0.63	13.5 ± 0.96	13.7 ± 1.34	13.2 ± 1.02	13. ± 0.9	14.3 ± 1.25	13.4 ± 1.0
C/D5(S)	14.4 ± 1.0	12.7 ± 0.66	13.3 ± 0.9	13.4 ± 1.1	13.3 ± 0.92	13.5 ± 1.1	15.2 ± 1.17	12.9 ± 0.8
Difference	—0.3 ± 1.59	—0.1 ± 0.91	0.2 ± 1.32	0.3 ± 1.73	—0.1 ± 1.37	—0.5 ± 1.43	—0.9 ± 1.73	0.5 ± 1.28
A/B5(SH)	16.7 ± 1.52	15 ± 0.72	15.2 ± 0.96	16.5 ± 1.23	15.6 ± 0.93	15.8 ± 1.15	16.4 ± 1.12	15.5 ± 1.1
C/D5(SH)	16.1 ± 1.19	15.3 ± 0.72	15.6 ± 1.07	15.7 ± 1.18	15.7 ± 0.78	16.0 ± 0.83	17.4 ± 1.36	15.7 ± 1.1
Difference	0.6 ± 1.93	—0.3 ± 1.02	—0.4 ± 1.43	0.8 ± 1.7	—0.1 ± 1.21	—0.2 ± 1.42	—1.0 ± 1.76	—0.2 ± 1.55

TAB. 7. *Comparison of mean B.O.D. values (with 95% Confidence Limits) from double filtration (A/B) and alternating double filtration (C/D) during successive Winter and Summer periods –*

B.O.D.	58–59 Nov-March	59 April-Sept	59–60 Oct-March	60 June-Sept	60–61 Oct-March	61–61 April-Sept	61–62 Nov-March	62 March-Sept
A/B4 (F)	9.8 ± 1.96	8.3 ± 1.12	8.5 ± 1.1	7.2 ± 1.7	10 ± 1.96	9.6 ± 1.62	9.7 ± 2.06	9.6 ± 1.0
C/D4 (F)	9.3 ± 1.91	9.1 ± 1.1	8.4 ± 1.17	9.7 ± 2.34	10.9 ± 1.96	8.4 ± 1.26	8.7 ± 1.86	9.5 ± 1.7
Difference	0.5 ± 2.73	—0.8 ± 1.58	0.1 ± 1.6	—2.5 ± 2.86	—0.9 ± 2.76	1.2 ± 2.03	2.2 ± 2.78	0.1 ± 2.56
A/B5 (S)	13.3 ± 2.34	11.9 ± 1.36	13.4 ± 1.5	11.5 ± 2.8	14.2 ± 2.56	13.9 ± 2.18	13.6 ± 2.86	11.8 ± 2.3
C/D5 (S)	15.6 ± 1.94	14.9 ± 1.9	12.3 ± 1.29	12.4 ± 2.64	13.3 ± 2.82	12.9 ± 1.5	13.1 ± 1.83	12.4 ± 1.67
Difference	—2.3 ± 3.04	—3.0 ± 2.34	1.1 ± 1.98	—0.9 ± 3.8	0.9 ± 3.8	1.0 ± 2.65	0.5 ± 3.4	—0.6 ± 2.84
A/B5 (SH)	19.0 ± 3.5	19.1 ± 2.8	17.5 ± 1.72	26.0 ± 5.8	26.1 ± 4.16	28.5 ± 4.9	20.9 ± 3.28	20.6 ± 4.4
C/D5 (SH)	22.4 ± 2.8	22.8 ± 2.44	16.9 ± 1.8	25.0 ± 4.8	25.9 ± 3.05	30.7 ± 3.7	24.6 ± 2.8	22.1 ± 4.12
Difference	—3.4 ± 4.48	—3.7 ± 3.72	0.6 ± 2.5	1.0 ± 7.5	0.2 ± 5.17	—2.2 ± 6.14	—3.7 ± 4.3	—1.5 ± 6.04

TAB. 8. *Mean Ox. N. levels ppm for double filtration and alternating double filtration*

Feed Rate (g.y.d.)	Stage		Double filtration (D.F.)		Alternating double filtration (A.D.F.)		Mean (D.F.) less Mean (A.D.F.) with 95% confidence limits
	D.F.	A.D.F.	Mean Ox.N (p.p.m.) with 95% confidence limits	Successive difference	Mean Ox. N. (p.p.m.) with 95% confidence limits	Successive difference	
100	X1	X1	1.87 ± 0.56		1.87 ± 0.56		0
	A/B3	C/D3	8.64 ± 0.72	6.77	11.19 ± 0.84	9.32	—2.55 ± 1.10
	A/B5	C/D5	23.02 ± 1.00	14.38	17.49 ± 0.74	6.30	5.53 ± 1.24
	All stages			21.15		15.62	5.53 ± 1.24
150	X1	X1	2.53 ± 0.42		2.53 ± 0.42		0
	A/B3	C/D3	8.53 ± 0.56	6.00	11.60 ± 1.14	9.07	—3.07 ± 1.26
	A/B5	C/D5	20.74 ± 0.76	12.21	18.96 ± 0.72	7.36	1.78 ± 1.06
	All stages			18.21		16.43	1.78 ± 1.06
200	X1	X1	1.77 ± 0.40		1.77 ± 0.40		0
	A/B3	C/D3	5.92 ± 0.70	4.15	7.83 ± 0.64	6.06	—1.91 ± 0.94
	A/B5	C/D5	20.55 ± 0.54	14.63	14.51 ± 0.76	6.68	6.04 ± 0.94
	All Stages			18.78		12.74	6.04 ± 0.94

TAB. 9. Comparison of the mean Ox. N. concentration (with 95% Confidence Limits) of the final effluents from double filtration (A/B5) and alternating double filtration (C/D5) during successive Winter and Summer periods.

p.p.m.	58–59 Nov-March	59 April-Sept	59–60 Oct-March	60 June-Sept	60–61 Oct-March	61 April-Sept	61–62 Nov-March	62 March-Sept
A/B5	22.0 ± 1.42	21.1 ± 1.1	19.6 ± 1.13	19.2 ± 1.28	21.4 ± 0.78	20.7 ± 0.78	22.2 ± 1.1	23.3 ± 0.9
C/D5	18.5 ± 1.0	19.7 ± 1.35	18.5 ± 1.18	12.3 ± 1.58	15.7 ± 1.22	14.6 ± 1.09	17.2 ± 1.26	17.1 ± 0.83
Difference	3.5 ± 1.73	1.4 ± 1.73	1.1 ± 1.62	6.9 ± 2.03	5.7 ± 1.45	6.1 ± 1.34	5.0 ± 1.66	6.2 ± 1.21

TAB. 10. *Comparison of the monthly average temperatures (C) of the different beds.*

Year			1958		1959												1960				
Month			11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5
Process	Sewage		15	12.5	10.5	12.7	13.5	14	17	20	20.5	20.6	20.5	17.5	15.5	13.5	11.7	12.5	12	—	16.7
D.F.	Bed A (Primary)		15	13	10,5	13.2	13.5	14	17	20	20.5	20.5	20	18	15	12.5	11.5	12	12.5	—	16.7
	Bed B (Secondary)		15	12.5	10	11.7	12.5	13.5	16.6	20	20	20	19.5	17.2	13.7	11.5	11	10.7	13.5	—	16
A.D.F.	Bed C	Primary	15.5	13	10.5	12.7	13.7	13.7	15.2	19	20	21	19.7	19	14.5	13	10.5	12	11.5	—	16.2
		Secondary	14	12	9	11	12.5	13.7	18.5	21	21	20	19.2	16.5	14	12.5	11.5	11	12	—	—
	Bed D	Primary	15	12	10	11.7	13.5	13.7	18.5	21	21	20	19.2	16.2	14.2	13	12	12	12.5	—	—
		Secondary	15.5	13	10.7	13	13	14	15.5	19.5	20	21	20.2	20	15	12	10.5	13	11.2	—	16

Year			1960							1961											
Month			6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Process	Sewage		20	19.5	20	19	16.5	15	12	11.5	12	15	13.5	16.7	19	19	19.5	19	19	15	12
D.F.	Bed A (Primary)		20	20	19.5	19	16.5	14.7	12	11.5	12	14	14	17	19	20	19.5	19.5	19	15.6	12
	Bed B (Secondary)		19	19	19.5	18.5	16	13.7	11	10.5	11	14	14	16	19	19	19	19.5	18.5	14	10
A.D.F.	Bed C	Primary	19	19.5	19.7	18.5	16.5	14	11.5	11.2	12.2	14	16	16	18.5	19.5	18.5	19.5	19	15	10.2
		Secondary	21	19.2	19.5	19	15.5	14.2	12	11	10	14	14	16.5	19	20	20	19	18	15.2	11.2
	Bed D	Primary	21.5	19.5	20	19.	16	15	13	11.7	10.5	14.5	14.5	17	19.5	20	20	19.2	18	15.5	11.2
		Secondary	19	20	19.5	18.2	16.5	14	10.5	10	12	13.5	14.5	16.5	19.5	19.5	19.5	18	19.5	14	10.5

TAB. 11. *Times of Contact(mins) at different depths and at different rates of rotation of the distributor arms in Bed B.*

	Minutes per Revolution		
	3	9.6	18.8
Depth	Time of Contact, Minutes		
2 ft.	7.44	14.43	11.2
4 ft.	11.28	16.22	19.58
6 ft.	19.27	21.85	22.62

of both carbonaceous and nitrogenous matter. In D.F. the primary bed is chiefly concerned with carbonaceous oxidation and the secondary bed is mostly a nitrifying unit. The separation of the two types of oxidation appears to enhance the nitrifying activity. This division of labour between the D.F. beds is only successful if the carbonaceous oxidation is almost completed in the primary bed. From the results of this investigation it would appear that controlled frequency of dosing, by regulating the speed of rotation of the distributor arms, enable the primary bed to be maintained in a satisfactory condition to effectively remove the organic load in the primary stage.

The choice between D.F. and A.D.F. will depend upon whether a more completely nitrified effluent is required and the amount of supervision available. The prevention of an excessive accumulation of film in the primary bed of D.F. needs more careful control of the frequency of dosing than in A.D.F. On the other hand the alternation of beds in A.D.F. necessitates somewhat more elaborate design of plant and increased operational routine. Of the two processes D.F. is the more flexible. To take full advantage of D.F. it would be necessary to differentiate in design and operation between the two beds. The relative sizes, and therefore the dosage rates, and the size and nature of the medium could be different in the two beds to suit their specific needs. This is not practicable in A.D.F. Different frequencies of dosing in the primary and secondary stages could be more readily provided in D.F. than A.D.F. A further possible development of double filtration could be the elimination of intermediate settlement between the two stages and a natural sequence to this would be to place the primary bed above the secondary, i.e. have one deep bed thus effecting economies in space, distributor mechanisms, pipework and tanks.

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APPENDIX

A Note on the Justifiability of Using Zero Constant Equations to Relate Effluent and Feed

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1. The form of the relationship between feed and effluent varies according to the basic assumptions made. For instance, it has been assumed throughout that this relationship is linear, there being no evidence to the contrary. It is possible to make further assumptions, e.g. that the line passes through the origin, if practical experience indicates that this is reasonable. This hypothesis can be tested for feasibility as described below.

2. The goodness of fit of a relationship to a given set of feed-effluent data can be judged by the scatter of the plotted points about the calculated line. The statistic used to measure this scatter is known as the residual standard deviation, s_0. This statistic is related to confidence limits, e.g. 95% of effluent values can be expected to lie within a distance of $\pm 2s_0$ from the line, measured in the direction of the effluent axis. The position is illustrated by the sketch below in which the dotted lines are limits which will enclose approximately 95% of the data.

3. The method of fitting a regression line ansures that the unconstrained line is associated with the minimum residual standard deviation possible for a given set of data. However, if correlation is low (as in the present investigation, see tables 4 & 5) it is possible for a line differing quite widely from this line to be associated with a residual standard deviation which is very little greater. When the value is not significantly higher (in the statistical sense) than the minimum, this is taken to imply that the alternative line is a feasible representation of the data.

4. Comparisons between the residual standard deviations associated with the unconstrained regression line and with a line through the origin and co-ordinates of mean X and Y indicate a significant difference (at the 5% level or less) in only 8 cases out of a total of 84. That is, 9.5% of results are significant whereas only 5% would be expected on the assumption that both lines fit the data equally well. This discrepancy is not large enough to disprove the hypothesis and it can therefore be safely assumed that any difference, if it exists at all, is marginal.

5. Comparisons of efficiency are straightforward for lines through the origin, since they can be made independently of the feed value.

If efficiency of filtration (B) is defined as:

Difference in indicator levels before and after filtration indicator level before filtration

and the line through the origin is:

$$Y = bX$$

where X, Y are the indicator values of feed and effluent respectively, then :

$$E = \frac{X - Y}{X}$$

$$= \frac{X - bX}{X}$$

$$= 1 - b$$

i.e. The efficiency is simply the difference from unity of the coefficient, and is the same for all feed values.

Moreover, differences in efficiency are equal in magnitude, but opposite in sign, to differences in coefficients.

6. The line through the origin is more stable than the unconstrained line in the presence of freak points (i.e. points which do not conform to the general pattern of a given set of data). A striking illustration is given by the feed-effluent data for the first filter in the double filtration P.V. trial at 100 g.y.d. (Figure 8):

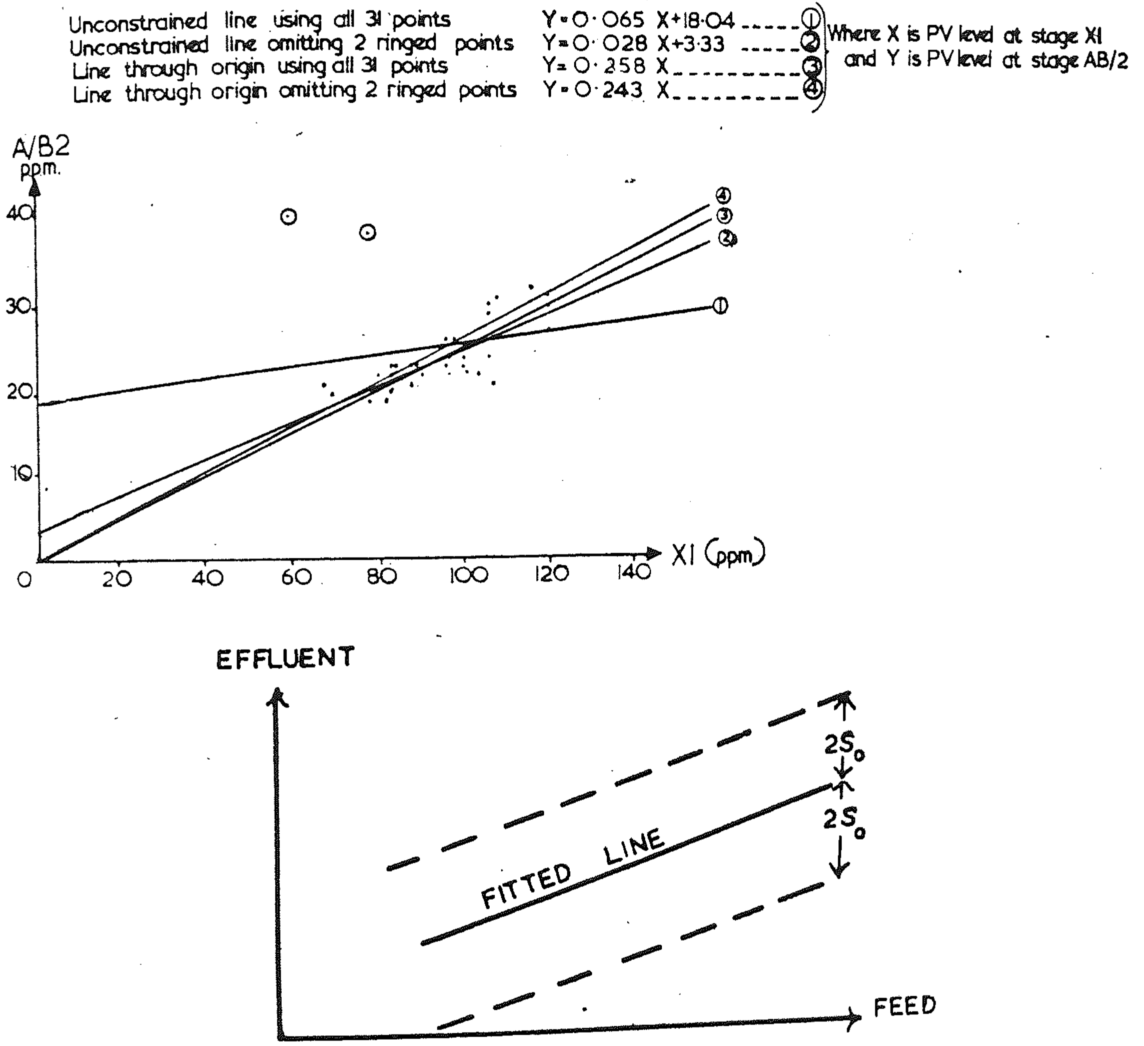

Fig. 8. Comparison of regression lines relating feed and effluent, one passing through the origin and the other unconstrained

Using all the data (31 points) the lines would be:

Unconstrained: $Y = 0.065\,X + 18.04$
Through the origin: $Y = 0.258\,X$

while, omitting the two ringed points, they are:

Unconstrained: $Y = 0.028\,X + 3.33$
Through the origin: $Y = 0.243\,X$

The change in the unconstrained line after omission of the two ringed points is large, while the lines through the origin are relatively unchanged. It should also be noted in this case that the unconstrained line is much closer to the line through the origin when the freak points are omitted and that the constant term is small.

Unless all data are plotted as in Figure 8 (a laborious task) freak points are liable to go undetected. In such an event, the line through the origin gives a better general picture of the data than the unconstrained line.

Summarising the above, it is true to say that in the present investigation, the use of lines through the origin does not conflict with the relevant theoretical considerations. This being so, the choice of which form to use can be made on other grounds.

SUMMARY

Large scale investigations were made over a period of $3^1/_2$ years using four 120 ft. diameter bacteria beds in order to compare the results of treatment of an industrial sewage by double filtration in one direction (D.F.) and alternating double filtration (A.D.F.) in which each bed became primary and secondary on alternate days.

The sewage was applied at overall rates of 100, 150 and 200 g.y.d. The frequency at which successive doses of sewage was applied to the beds was controlled by controlling the rate of rotation of the distributor arms by fitting the distributors with geared mechanical drives powered by electric motors.

Under these different conditions comparisons were made of the overall efficiencies of the two processes and the degree of purificiation achieved in the different stages. The ecological conditions of the beds were assessed by estimating the amount of film and numbers of grazing organisms present in standard volumes of media removed from the beds.

Statistical treatment of the results showed that at all three rates there were no significant differences between the two processes in the overall removal of organic matter as measured by the P.V. and B.O.D. tests on the final effluents, but the proportion of organic matter removed in the different stages differed in the two processes. More oxidisable matter was removed in the primary stage of A.D.F. than in the corresponding stage of D.F. Conversely, more oxidisable matter was removed in the secondary stage of D.F. than in the secondary stage of A.D.F. The oxidised nitrogen concentration in the final effluent of D.F. was significantly greater than in that of A.D.F. at all three rates of application. This difference was greatest at the highest loading rate. Again, different degrees of nitrification occurred in the different stages in the two processes. In A.D.F. the degree of nitrification was much the same in primary and secondary stages. In D.F. most of the nitrification occurred in the secondary bed.

The results of the observations on the ecological conditions of the beds were correlated with their different efficiencies. For efficient operation of a bacteria bed it is necessary to maintain a balanced community of saprobic micro-organisms and grazing organisms such as fly larvae and worms, and prevent the excessive accumulation of film. In the two A.D.F. beds satisfactory conditions were maintained throughout the trials. The excessive accumulation of film comprised mostly of fungus, which the sewage tended to encourage each winter, was prevented. This was achieved partly by each bed receiving the partially purified effluent on alternate days, which limited the growth nutritionally, and partly by controlling the frequency of dosing on the beds by rotating the distributors once each 15 mins. at one period and once every 30 mins., at another period. It was considered that the intermittent dosing also effected control nutritionally by creating periods of starvation between doses. With this method of operation the film in the surface layers of the bed was restricted and the film was more evently distributed throughout the depth of the bed.

The primary bed of the D.F. unit did more work in oxidising organic matter since it received the strong settled sewage each day. Although the surface layers were free from excessive accumulations of film, the controlled frequency of dosing itself was not able to prevent some accumulation of solids within the bed at the highest rate of treatment (200 g.y.d.). This however caused the bed to be only slightly less efficient in removing organic matter than the two A.D.F. beds when they were operating as primary beds.

The populations of heterotrophic saprobic micro-organisms and the grazing organisms feeding on them were limited in the secondary bed of the D.F. unit by the low concentration of organic matter in the partially purified sewage which the bed received each day.

The different degrees of nitrification occurring in the four beds were correlated with the amounts of film present. In the primary bed of D.F. having the greatest amount of accumulated film the least nitrification occurred. In the two A.D.F. beds similar degrees of nitrification occurred, being greater than that in the primary bed of D.F. Most nitrification occurred in the secondary bed of D.F. where the film was restricted and heterotrophic activity limited.

Associated with the absence of seasonal fluctuations in the amounts of film which occur in many

bacteria beds there was no indication of any seasonal fluctuations in efficiency. This suggests that the decrease in efficiency, especially in nitrification, that does occur in those beds which accumulate film each winter is due to this secondary effect rather than to the direct effect of temperature or the metabolic rate of the organisms.

The chief difference between the two processes would appear to be that in A.D.F. the two beds share the organic load whereas in D.F. most of the organic load is removed by the primary bed enabling the secondary bed to specialise in nitrification. Although these two processes are equally effective in the removal of organic matter, nitrification would appear to be encouraged by the separation of the heterotrophic and autotrophic stages of oxidation in D.F. The success of D.F. depends upon the primary bed removing a considerable portion of the organic load; this is achieved by preventing excessive accumulation of film by controlling the frequency of dosing.

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SOUHRN

H. A. Hawkes a S. H. Jenkins

SROVNÁNÍ DVOJITÉ FILTRACE A STŘÍDAVÉ DVOJITÉ FILTRACE PRŮMYSLOVÉ ODPADNÍ VODY NA FILTRECH S KONTROLOVANOU ČETNOSTÍ DÁVKOVÁNÍ. (S POZNÁMKOU O OPRÁVNĚNOSTI POUŽITÍ REGRESNÍ PŘÍMKY PROCHÁZEJÍCÍ POČÁTKEM K VYJÁDŘENÍ POMĚRU KONCENTRACE A ODTOKU A PŘÍTOKU DO ČISTÍRNY OD J. M. STOKESOVÉ A A. B. NEALEHO)

Po dobu 3½ let byl prováděn plnoprovozní výzkum na čtyř biologických filtrech o průměru asi 36 m, aby bylo možno srovnat výsledky čištění průmyslové odpadní vody dvojitou filtrací v jednom směru (D. F.) a střídavou dvojitou filtrací (A. D. F.), při níž se filtry vždy po dnu střídaly ve funkci primárního a sekundárního.

Odpadní voda zatěžovala filtry v souhrnných dávkách 100, 150 a 200 g. y. d. (= gallony na kubické yardy za den; viz převáděcí tabulku na začátku práce). Četnost postupných dávek odpadní vody byla kontrolována ovládáním otoček Segnerova kola mechanickým řízením s ozubeným převodem, poháněným elektromotorem.

Za těchto různých poměrů byla činěna srovnání souhrnných efektů obou procesů a čisticího účinku dosaženého v jednotlivých stupních. Ekologické poměry filtrů byly odhadovány určováním množství biologické blány a počtu zdravých organismů přítomných v standardních objemech materiálu vzatého z filtrů.

Statistické zpracování výsledků ukázalo, že za všech tří dávek zatížení nebylo významných rozdílů mezi oběma procesy v souhrnném odbourání organických látek měřených jako manganistanové číslo (P. V.) a BSK$_5$ na konečném odtoku, avšak poměr organických látek odstraněných v jednotlivých stupních byl u obou procesů odlišný. V primárním stupni A. D. F. bylo odbouráno více oxydovatelných látek než v odpovídajícím stupni D. F. Naopak bylo odbouráno více oxydovatelných látek v sekundárním stupni D. F. než v sekundárním stupni A. D. F. Koncentrace oxydovaného dusíku v konečném odtoku z D. F. byla podstatně vyšší než u A. D. F. při všech třech aplikovaných dávkách zatížení. Tento rozdíl byl největší při nejvyšším zatížení. Rovněž byly zaznamenány různé stupně nitrifikace v různých stupních obou procesů. V A. D. F. byl stupeň nitrifikace téměř stejný v primárním i sekundárním stupni. V D. F. probíhala nitrifikace většinou až v sekundárním stupni.

Výsledky pozorování ekologických podmínek filtrů byly korelovány s jejich rozličným čisticím účinkem. Pro dobrý chod filtru je třeba udržovat vyvážené životní společenstvo saprobních mikroorganismů a organismů, které je požírají, jako např. larvy hmyzu a červi, a zabránit nadměrnému růstu biologické blány. Ve dvou filtrech A. D. F. se podařilo udržet vyhovující podmínky po dobu zkoušek. Bylo zabráněno nadměrnému růstu biologické blány sestávající hlavně z mycelií mykofyt, která měla tendenci narůstat hlavně v zimním období. Bylo toho dosaženo zčásti tím, že každý filtr dostával každý druhý den částečně vyčištěnou vodu, která omezovala růst, pokud jde o obsah živin, a zčásti kontrolou četnosti dávkování odpadní vody, kdy se Segnerovo kolo otočilo jednou každých 15 min. a jindy každých 30 min. Přerušované zkrápění mělo vliv i na dodávání živin tím, že byla zařazena údobí klidu (hladu) mezi údobími dávkování. Touto metodou provozu byla biologická blána na povrchu filtru omezována a mnohem rovnoměrněji rozdělena do hloubky filtru.

Primární filtr v jednotce D. F. zpracoval více organických látek, protože dostával denně koncentrovanou odsazenou odpadní vodu. Ačkoliv na povrchu filtru nebyla přítomna nadměrná biologická blána, kontrolovaná četnost dávkování sama nebyla schopna zabránit akumulaci pevných látek ve filtru při nejvyšším zatěžování (200 g. y. d.). To však mělo za následek jen poněkud slabší čisticí efekt v odstraňování organických látek než tomu bylo u obou A. D. F. filtrů, když byly provozovány jako primární filtry.

Populace heterotrofních saprobních mikroorganismů a organismy, které je požíraly, byly omezovány v sekundárním filtru jednotky D. F. nízkou koncentrací organických látek již v částečně vyčištěné vodě, jíž filtr denně dostával.

Různé stupně nitrifikace, k níž docházelo ve čtyřech filtrech, byly korelovány s množstvím přítomné biologické blány. V primárním filtru D. F., kde bylo největší množství akumulované biologické blány, docházelo k nejnižší nitrifikaci. V obou filtrech A. D. F. probíhala nitrifikace v témže slabém stupni, který však byl stále vyšší než v primárním filtru D. F. Nejintensivnější byla nitrifikace v sekundárním filtru D. F., kde biologická blána byla jen slabá a aktivita heterotrofů byla silně omezená.

V souvislosti s nepřítomností sezónních změn v množství biologické blány, jak k nim dochází v mnohých filtrech, nebyla zde ani známka nějakých sezónních změn v účinnosti. To dává podnět k domněnce, že úbytek účinnosti, zvláště v nitrifikaci, k němuž nedochází u filtrů, v nichž se každou zimu akumuluje biologická blána, je způsoben spíše tímto sekundárním účinkem než přímým vlivem teploty nebo rychlosti metabolismu organismů.

Hlavním rozdílem mezi oběma procesy se zdá být, že při A. D. F. se oba filtry podílejí na zpracování organického zatížení, kdežto při D. F. je většina organických látek odbourána primárním filtrem, což umožňuje, že se sekundární filtr specializuje na nitrifikaci. Ačkoliv oba způsoby jsou stejně účinné, pokud jde o odstranění organických látek, zdá se, že nitrifikaci pomáhá oddělení heterotrofních a autotrofních stadií oxydace při D. F. Úspěch D. F. závisí na primárním filtru; zpracovávajícím podstatný podíl organického zatížení; toho lze dosáhnout zabráním nadměrného růstu biologické blány tím, že kontrolujeme četnost dávek.

РЕЗЮМЕ

Г. А. Хокс и С. Г. Дженкинс

СРАВНЕНИЕ ДВОЙНОЙ ФИЛЬТРАЦИИ И ПЕРЕМЕННОЙ ДВОЙНОЙ ФИЛЬТРА- ЦИИ ПРОМЫШЛЕННОЙ СТОЧНОЙ ВОДЫ НА БИОФИЛЬТРАХ С КОНТРОЛИ- РУЕМОЙ ЧАСТОТОЙ ДОЗИРОВКИ. (С ПРИМЕЧАНИЕМ Й. М. СТОУКС И А. Б. НИЛ ОБ ОБОСНОВАННОСТИ ПРИМЕНЕНИЯ РЕГРЕССИВНОЙ ПРЯМОЙ ПРОХО- ДЯЩЕЙ НАЧАЛОМ ДЛЯ ВЫРАЖЕНИЯ ОТНОШЕНИЯ КОНЦЕНТРАЦИИ СТОКА И ПРИТОКА В ОЧИСТИТЕЛЬНУЮ СТАНЦИЮ.)

В течение 3½года происходило производственное исследование 4 биофильтров имеюй щих в диаметре около 36 м с целью сравнения результатов очистки промышленной сточной воды с помощью двойной фильтрации в одном направлении (Д. Ф.) и переменной двойной фильтрации (А.Д.Ф.), при которой фильтры всегда после одного дня чередовались во функции первичного и вторичного.

Нагрузка фильтров представляла 100, 150 и 200 галлонов на кубический ярд в день. Частота дозировки сточной жидкости была контролирована владением оборотами сегнерова колеса при помощи механического управления с зубчатой передачей, приводимой в движение электродвигателем.

В этих различных отношениях осуществлялись сравнения общих эффектов обоих процессов и эффекта очистки достиженного в отдельных степенях. Экологические условия на фильтрах оценивались определением мощности биопленки и количества хищных организмов присутствующих в стандатрных объемах материала взятого из фильтров.

Статистическая обработка результатов показала, что при всех трех нагрузках не проявились существенные различия между обоими процессами в общей деградации органических веществ, измеряемых как химическая потребность в кислороде (П. В.) и БПК$_5$ в конечном стоке. Но отношение органических веществ разрушенных в отдельных степенях было у обоих процессов различно. В первичной степени А. Д. Ф. деградировалось более окисляемых веществ чем в соответствующей степени Д. Ф. Напротив этого во вторичной степени Д. Ф. деградировалось более окисляемых веществ чем во вторичной степени А. Д. Ф. Концентрация окисленного азота в конечном стоке из Д. Ф. была существенно выше чем при А. Д. Ф. при всех трех применяемых нагрузках. Эта разница являлась больше всего при самой высокой нагрузке. Были отмечены тоже разные степени нитрификации в разных степенях обоих процессов. При А. Д. Ф. была степень нитрификации почти одинаковой в первичной и вторичной степенях. При Д. Ф. протекала нитрификация преимущественно лишь во вторичной степени.

Результаты исследования экологических условий биофильтров были поставлены в корреляцию с их различным эффектом очистки. Для хорошей работы фильтра надо сохранять уравновешенный биоценоз сапробных микроорганизмов и организмов, которые ими питаются, как на пример личинки насекомых и черви, и также предотвращать чрезмерный рост биопленки. В двух фильтрах А. Д. Ф. удалось сохранить подходящие условия в течение экспериментов. Был предотвращен чрезмерный рост биопленки, состоящей главным образом из мицелия грибов, оказывающей тенденцию нарастать главным образом в зимнем периоде. Этого было достижено частично тем, что каждый фильтр получал на каждый второй день полуочищенную воду, подавляющую рост содержанием питательных веществ, и частично контролированием частоты дозировки сточной жидкости, когда ороситель вращался один раз каждых 15 минут, во второй раз 30 минут. Прекращаемое орошение повлияло тоже на подачу питательных веществ тем, что между периоды дозировки были включены периоды покоя (голода). При помощи этого метода подавлялась биопленка на поверхности фильтра и разделялась гораздо равномернее в его глубину.

Первичный фильтр при Д. Ф. обработал более органических веществ потому что он получал ежедневно концентрированную отставшую сточную жидкость. Несмотря на то, что на поверхности фильтра не находилась чрезмерная биопленка, контролированная дозировка сама по себе не была способна воспрепятствовать аккумуляции твердых веществ во фильтре при самой высокой нагрузке. Но результатом этого был только относительно более низкий эффект очистки.

Популяция гетеротрофных сапробных организмов и ими питающихся организмов подавлялась во вторичном фильтре Д. Ф. с помощью низкой концентрации органических веществ в дозируемой частично очищенной сточной воде.

Разные степени нитрификации, наблюдаемые в четырех фильтрах, были поставлены в корреляцию с мощностью присутствующей биопленки. В первичном фильтре Д. Ф. с самой мощной биопленкой была самая низкая нитрификация. В обоих фильтрах А. Д. Ф. протекала нитрификация в тойже самой слабой степени, но которая была выше чем в первичном фильтре Д. Ф. Самая интенсивная нитрификация проходила во вторичном фильтре Д. Ф., где биопленка была тонкая и активность гетеротрофных организмов сильно ограничена.

В связи с отсутствием сезонных изменений в мощности биопленки, наблюдаемых в многих биофильтрах, отсутствовали здесь тоже какие нибудь сезонные колебания эффекта очистки. Поэтому можно судить, что это обстоятельство важнее для хорошей работы биофильтров чем прямое влияние температуры или скорости метаболизма организмов.

Главной разницей между обоими процессами является то, что при А. Д. Ф. оба фильтра принимают участие в обработке органической нагрузки, между тем как при Д. Ф. большинство органических веществ деградируется в первичном фильтре и вторичный фильтр специализируется в нитрификации. Несмотря на то, что оба способа одинаково эффективны, что касается устранения органических веществ, кажется, что нитрификации содействует отделение гетеротрофных и автотрофных стадий окисления при Д. Ф. Успех Д. Ф. зависит от первичного фильтра, обрабатывающего существенную долю органической нагрузки; этого можно достичь предотвращением чрезмерного роста биопленки контролированием частоты дозировки.

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II - 11

THE SEASONAL ACCUMULATION OF SOLIDS IN PERCOLATING FILTERS AND ATTEMPTED CONTROL AT LOW FREQUENCY DOSING

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INTRODUCTION

The theoretical rate at which organic wastes, such as sewage, is oxidised in filters is defined by the oxidation kinetics of the process. In practice the load that can be satisfactorily treated is also limited by the accumulation of solids within the filter which may impede ventilation and the percolation of the sewage resulting in ponding, deterioration in purification and the eventual breakdown of the system. The winter accumulation of solids in filters operating in temperate zones has been variously explained. British workers, Harrison (1908), Reynoldson (1942), Lloyd (1945) and Tomlinson (1946) concluded that the differential grazing activitiy of the filter macro-invertebrates at different temperatures was the cause. American workers generally have regarded the activity of grazers to be incidental or as playing a minor role; the effects of temperature on the microbial activities of the film and the mechanical scouring by the flowing liquid being considered more important, Lackey (1925), Holtje (1943), Heukelekian (1945), Cooke and Hirsch (1958). When the film is dominated by fungal mycelium, as in many filters treating industrial sewage, microbial activity has been shown to be important in determining the accumulation of film. Tomlinson (1942), Hawkes (1965). Investigation on the seasonal accumulation of solids in filters treating a purely domestic sewage carried out over an extended period from 1956, when the filters had just been matured, until 1969, are reported in the first part of the present paper.

Investigations on the filters treating the industrial Birmingham sewage at Minworth, which encouraged luxuriant fungal growths throughout the winter, showed that these growths could be prevented be retarding the rate of rotation of the distributors thus decreasing the frequency at which the sewage was applied to the filter (Tomlinson and Hall (1955), Hawkes (1955)). It was decided to investigate the effects of low frequency dosing on filters treating domestic sewage and in which the film was not dominated by fungi throughout the winter. The results of these investigations form the second part of this paper.

PLANT AND METHODS

Systematic observations were made over a thirteen year period on two adjacent filters of identical construction being 5 ft (1.5 m) deep and made of 1½–2 in (3.7–5 cm) gravel. From 1956 until 1962 the distributors on both filters were identical, being propelled by the jet reaction as the sewage discharged from the four distributor arms to rotate once every 1.25 minutes, giving a dosing frequency of approx. 0.3 minutes. Both filters were fed at equivalent rates through a dosing chamber which resulted in them having periods of dosing alternating with periods of rest, the relative periods depending upon the flow. In 1962 an attempt was made to retard the rotation of the distributor on filter D by hydraulic means involving the turning of some distributor arms so that the jets acted as brakes, the arms were also modified so that each discharged sewage from different quarters of their length. Thus, any part of the filter received a dose of sewage once each full revolution. These measures were partly successful in slowing down the distributor but under windy conditions the modified distributor tended to stop altogether. In July 1963 a mechanised drive was fitted to distributor D and for the rest of the investigation this controlled the rate of revolution at 14 minutes which with the modified arrangement of the jets gave a dosing frequency of 14 minutes. Throughout the whole period the frequency on filter A remained unchanged at 0.3 minutes.

Sampling – Chemical. Throughout one working day each week composite hourly samples were taken of the feed to the filters and the two effluents. Normal analysis was carried out on these samples in the laboratory of the Upper Tame Main Drainage Authority and the results made available for the purpose of investigation. A thermograph recorded the filter temperature at a depth of one foot.

Sampling – Biological. The amount of film and number of grazers in the filters were assessed by removing samples of the filter medium contained in cylindrical perforated canisters approximately 0.1 cubic feet in capacity which had previously been placed in the appropriate position of the part of bed to be sampled. The method used was that described previously (Hawkes (1965)). Each month, six pairs of containers, one for fauna and the second for film, were removed from each bed. Three pairs were from the surface of the filter – one near the centre, one near the circumference and the third at an intermediate position. Another three pairs were taken from positions immediately below the surface three. After removing the sample the canisters were refilled with fresh medium and replaced. Three months were allowed before they were removed again to allow stabilisation.

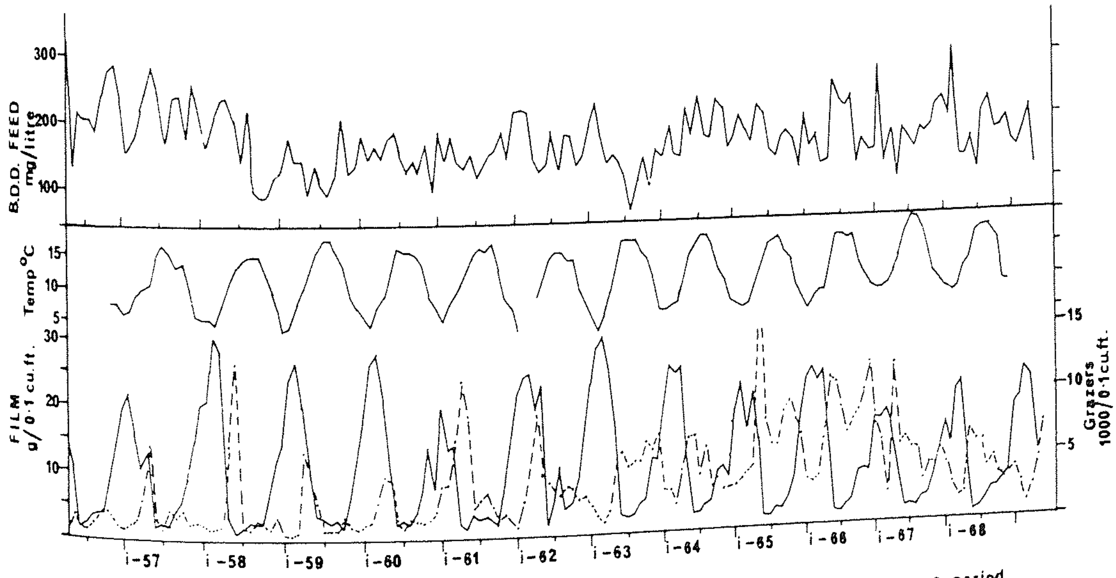

Fig 1 Seasonal fluctuations in film —— and grazers —·— in a sewage filter over a period of thirteen years.

RESULTS

Seasonal fluctuations in film accumulation and macro-grazing fauna. The results of observations on filter A throughout thirteen seasons during which time the operating conditions remained reasonably constant are given in Figure 1.

Each point on the film and fauna graphs represents the mean of the six samples taken from the upper foot of the bed each month. The mean monthly temperatures and the monthly mean BOD of the settled sewage being applied to the bed are also plotted. Throughout the 13 years a regular seasonal pattern of film accumulation followed by an unloading occurred, associated with seasonal changes in temperature. With falling temperatures in the late autumn the film commenced to accumulate; this continued throughout the winter to produce the greatest accumulation later in the winter. With rising temperatures in the spring, there was usually a rapid decrease in film to produce clean conditions in the filter throughout the summer period.

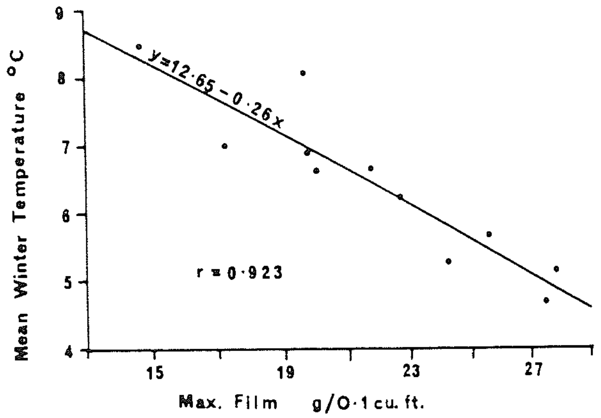

Fig. 2. Regression line showing relationship between the maximum Winter accumulation of film in a filter and corresponding Winter bed temperatures.

Examination of the film and temperature graphs suggests that the degree of winter accumulation of film is related to the severity of the winter. This is demonstrated by the regression line in Figure 2 in which the maximum degree of film accumulates for each year is plotted against the average of the temperatures for the preceding three months.

Fluctuations in the BOD feed occurred, but these were not closely seasonal in their recurrence. Although on some occasions increase in film was associated with increased sewage strength there appears to be a closer correlation with temperature, suggesting that the seasonal fluctuation in film in the filters is caused by seasonal fluctuations in temperature, either directly or indirectly or both. Figure 1 shows that the seasonal fluctuations in macro-grazing fauna population also occurred although these are somewhat less regular than the fluctuations in film. Generally, however, there was a peak in the grazing population at a time of increasing temperatures in the spring associated with the unloading of the film. Following the reduction in film there was usually a decline in the grazing fauna population which then remained low during the summer. The general higher level of the macro-invertebrate grazing population in the second half of the investigations could be due to the use of a sieve of fine mesh during this period. The depression in the grazing fauna populations was greatest in the more severe winters.

Seasonal Changes in Efficiency. The average filter effluent BOD for the four quarters of the year are given in Table 1. Considering the effluent from filter A for the two five-year periods and from D for the period 1956–61 when the dosing frequency was the same, it is seen that the average BOD during the period January–March was significantly higher than at other times of the year. In all cases the lowest BOD values occurred in the

TABLE 1 – Comparison of effluent quality from High Frequency dosed filter A and Low Frequency dosed filter D at different seasons

		1956 – 61				1963 – 68			
		Frequency of Dosing A – 0.3 mins. Frequency of Dosing D – 0.3 mins.				Frequency of Dosing A – 0.3 mins. Frequency of Dosing D – 14 mins.			
		Average values with 95% Confidence Limits			Difference D – A with 95% Confidence Limits	Average values with 95% Confidence Limits			Difference D – A with 95% Confidence Limits
		Feed	Effluent A	Effluent D		Feed	Effluent A	Effluent D	
Jan March	B.O.D.	185.9 ± 14.4	21.7 ± 4.0	21.1 ± 4.9	–0.6 ± 6.3	184.3 ± 22.3	17.3 ± 2.1	15.6 ± 1.9	–1.7 ± 2.8
April June		180.2 ± 25.3	13.2 ± 2.2	12.5 ± 1.8	–0.7 ± 2.7	166.8 ± 22.6	11.0 ± 1.6	13.2 ± 1.4	+2.2 ± 2.2
July Sept		157.8 ± 23	9.5 ± 1.4	9.6 ± 1.2	+0.1 ± 1.9	168 ± 23.8	10.5 ± 1.6	14.0 ± 1.4	+3.5 ± 2.1
Oct Dec		187 ± 31.2	13.3 ± 3.4	12.0 ± 2.0	–1.3 ± 4.0	167.2 ± 17.6	12.3 ± 2.2	15.0 ± 2.2	+2.7 ± 3.1
Jan – March	Ammonium N		15.5 ± 3.8	14.9 ± 3.3	–0.6 ± 5.0		11.7 ± 1.5	6.3 ± 1.1	–5.4 ± 1.9
April – June			6.6 ± 1.2	6.3 ± 1.5	–0.3 ± 1.9		5.1 ± 1.0	5.4 ± 0.8	+0.3 ± 1.3
July – Sept			3.0 ± 0.9	3.1 ± 0.8	+0.1 ± 1.2		3.7 ± 0.5	5.3 ± 0.9	+1.6 ± 0.9
Oct – Dec			5.3 ± 1.7	4.6 ± 1.0	–0.7 ± 2.0		5.8 ± 1.3	5.8 ± 0.9	0 ± 1.5
Jan – March	Oxidised N		13.8 ± 2.2	14.0 ± 2.2	+0.2 ± 3.1		12.2 ± 1.2	20.2 ± 2.5	+10.0 ± 2.8
April – June			30.1 ± 3.2	31.5 ± 3.4	+1.4 ± 4.6		21.3 ± 2.9	26.5 ± 2.4	+5.2 ± 3.8
July – Sept			32.4 ± 2.9	34.2 ± 4.1	+1.8 ± 5.0		30.3 ± 2.5	31.5 ± 2.5	+1.2 ± 3.6
Oct – Dec			23.3 ± 3.7	25.5 ± 3.0	+2.2 ± 4.7		21.3 ± 2.5	26.2 ± 2.1	+4.9 ± 3.2

period July to September, similar and intermediate values occurring in the other two periods. In some cases these differences could be partly accounted for by differences in the BOD strength of the sewage feed but other factors such as temperature and condition of the bed could also be the cause.

The corresponding figures for ammoniacal N and oxidised N show the seasonal changes in nitrification within the beds. The highest ammonia figures and lowest oxidised nitrogen values occurred in the period January–March indicating the lowest degree of nitrification; the most nitrification occurred in the period July–September.

Comparison of ecology and efficiency of a filter on which sewage was applied in frequent doses (high-frequency dosed) and a filter on which it was applied at less frequent intervals (low-frequency dosed). Comparisons can be made using the data from filter D before and after the modification of the distributor to provide a lower dosing frequency, bed A acting as an experimental control. Comparisons can also be made between the two beds for the same period 1963–8 with filter A having high frequency dosing and filter D having low frequency dosing.

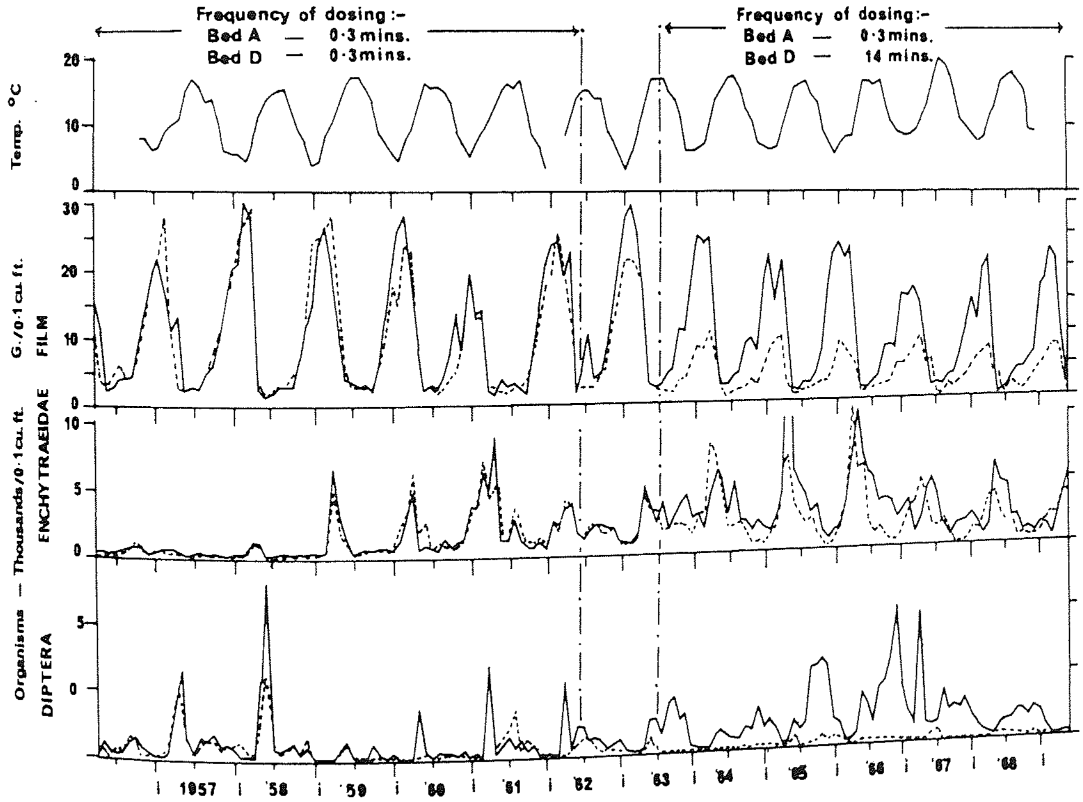

Fig. 3 Effect of reducing the frequency of dosing on film and grazing fauna in Bed D - - - -
(control) Bed A ——

Effect on Ecology. The ecological results are given in Figure 3 in which the seasonal fluctuations of film, and the dominant grazing fauna – enchytraeid worms and dipterous fly larvae – in the two filters are compared before and after the retarding of the distributor on filter D. Each point represents the average of six samples taken from the upper foot of the filter. During the period 1956–62 when the dosing frequency was the same the fluctuations in film in both filters followed a closely similar pattern as did the fluctuations in grazing fauna. The initial attempt to retard the distribution on filter D by hydraulic means during the period 1962–63 is reflected by the reduced winter accumulation of solids and possibly the lower population of dipterous fly larvae in filter D. From July 1963 until 1969 the winter accumulation of film in the upper layers of the low frequency dosed filter was appreciably reduced. Although the enchytraeid worm population in the two beds remained similar, the fluctuations shifted out of phase, the peak in D occurring somewhat earlier in the year than in A. There was a marked decrease in the dipterous larvae population in D following the slowing down of the distributor. The dominant fly larvae in A and in D prior to the modification of the distributor was *Psychoda alternata* with *Anisopus fenestralis* occurring at some periods. In D, after reducing the frequency of dosing, chironomid larvae were the most common dipteran especially in the surface layer of the filter. The relative abundance of total diptera and the group composition of the dipteran fauna in filters A and D are illustrated diagrammatically in Figure 4. The width of the histogram represents the abundance and the vertical divisions the composition.

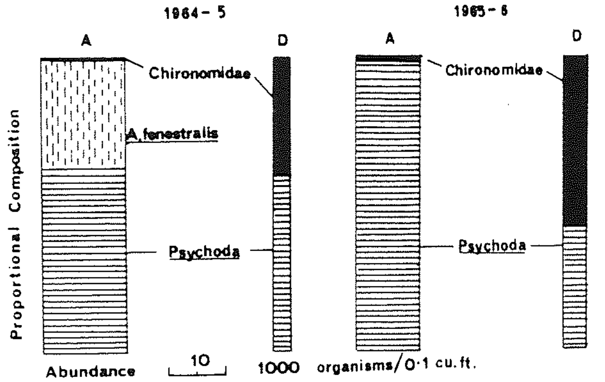

Fig.4. Comparison of abundance and composition of grazing Fauna in high frequency dosed bed A with low frequency dosed bed D.

Effect on Efficiencies. Comparisons both of carbonaceous oxidation as measured by the 5d BOD and of nitrification as measured by the amm.N and oxidised N concentration in the effluents from filters A and D for different quarters of the year before and after the retarding of the distributor on D, are given in Table 1. In the first period, when the distributors were rotating at similar rates, there was no statistically significant difference between the two effluent qualities at any season. Following the decrease in dosing frequency on D differences in effluent qualities occurred. During the winter period January–March the BOD of the effluent from low frequency dosed filter D was slightly lower than that from A, although this was not statistically significant; throughout the rest of the year, it was higher, the difference being statistically significant during the summer period.

Comparing the BOD values from filter D for the different quarters of the year, before and after the reduction in dosing frequency, it is seen that difference between the effluent qualities in winter and other seasons which occurred before, virtually disappeared after that.

A greater effect was evident in the improved nitrification in the low frequency dosed filter especially in the winter months. The oxidised nitrogen concentration was at all seasons higher in the low frequency dosed filter; the difference being statistically significant except during the summer period when the difference was slight.

DISCUSSION

The accumulation of solids within beds is undesirable for several reasons. If excessive it can cause uneven distribution of the sewage within the filter, impede aeration and eventually result in ponding and the ultimate breakdown of the purification processes. The accumulated solids support an increased fly population which may cause nuisances. When the accumulated solids are discharged as humus in the unloading period they may increase the load on the digesters at a time, in the case of unheated digesters, when they can least deal with it. The effects on the efficiency of filters of the accumulation of solids, as in these investigations, to a degree not causing serious ponding is difficult to determine. The reduced efficiency during the winter could be due to a direct effect of temperature or to the accumulation of solids, or both. The fact that the winter decrease in efficiency was reduced in the filter D in which the surface accumulation of solids was limited by low frequency dosing, indicates that the accumulation of solids is one factor responsible for the reduced efficiency in the winter. Figure 5 compares by regression lines the relationship between temperature and nitrification in the one bed at two dosing frequencies. The comparative slopes of the lines show that although in both cases there was a reduction in nitrification with decrease in temperature, this effect was most marked in the high frequency dosed bed which at times of low temperature had the greater accumulation of film. The effects of low frequency dosing on the efficiency are probably the result of two opposing factors: the beneficial effect of the control of film and the reduction in the liquid retention time, which, at least at the lower frequencies of dosing, would be detrimental. The analytical results from filter D show that at times when solids do not naturally accumulate, the efficiency in terms of carbonaceous oxidation was reduced by low frequency dosing. The optimum frequency of dosing for any filter will be determined by the ecology of that filter involving the growth promoting properties of the sewage. Because of seasonal changes in the ecology, different frequencies of dosing may be desirable necessitating the provision of a range of distributor speeds, as provided at different new works of the Upper Tame Main Drainage Authority.

CONCLUSIONS AND SUMMARY

(1) In filters treating a domestic sewage a regular accumulation of solids occurred each winter, this accumulation being greater the colder the winter. Below 10°C a few degrees difference in the average winter bed temperature results in considerable differences in the amounts of solids present.

(2) Whatever the cause of the accumulation, the subsequent unloading of the filter is greatly accelerated by the active grazing of the macro-invertebrate fauna at times of rising temperature.

(3) Low frequency dosing limited the winter accumulation of solids in the surface layer of the filter. There is evidence, however, that within the bed the accumulation of solids was less restricted by low frequency dosing.

(4) Low frequency dosing reduced significantly the population of fly larvae thus reducing the potential fly nuisance. There was also a significant change in the species composition of the dipteran fauna.

(5) The optimum frequency for any filter is determined by the hydraulic consideration of retention time and by the need to maintain the desirable ecological balance.

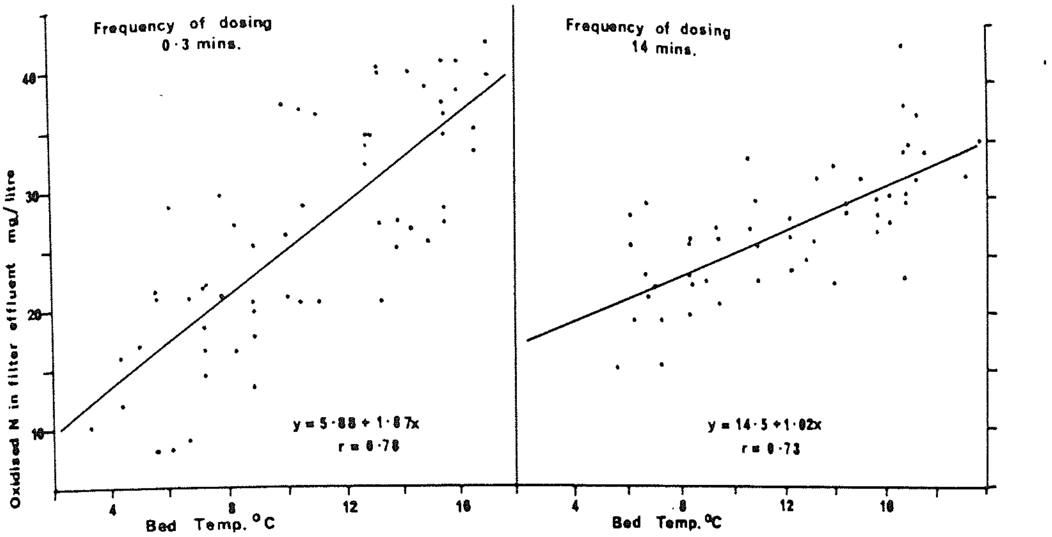

Fig.5. Regression lines comparing relationship between nitrification and temperature in a sewage filter operated at two dosing frequencies.

ACKNOWLEDGEMENTS

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Paper No. 14

The effect of dosing frequency on the seasonal fluctuations and vertical distribution of solids and grazing fauna in sewage percolating filters.

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THE EFFECT OF DOSING-FREQUENCY ON THE SEASONAL FLUCTUATIONS AND VERTICAL DISTRIBUTION OF SOLIDS AND GRAZING FAUNA IN SEWAGE PERCOLATING FILTERS

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Abstract—The seasonal fluctuations and vertical distribution of accumulated solids and grazing fauna populations in two filters having different dosing frequencies were compared. Although the winter accumulation of solids which occurred in the surface layers of the high-frequency dosed filter was markedly reduced by low-frequency dosing, in the depth of the filters the difference was less and, due to the delayed unloading in the low-frequency dosed filter, the solids present were greater for a period in the late spring than in the high-frequency dosed filter. Fungal film which developed in the high-frequency dosed filter in the latter part of the summer was absent from the low-frequency dosed filter. There was a difference in the manner of the unloading of the filters in the spring. In the high-frequency dosed filter the unloading first took place below the surface layers followed by the unloading of the surface solids, whereas in the low-frequency dosed filter the unloading occurred first in the surface layers and proceeded downward. The vertical distribution of solids within the filters was affected by the dosing frequency. With high-frequency dosing there was generally a reduction in the amount of accumulated solids with depth; in the low-frequency dosed filter the solids were either evenly distributed throughout the depth or at times accumulated to a greater degree within the filter. Low-frequency dosing markedly suppressed the population of fly larvae throughout the depth of the filter. It had little effect however upon the populations or distribution of enchytraeid or lumbricid worms. The possible relationship between the different grazing fauna populations resulting from the different dosing frequencies and the timing and manner of the unloading of the solids is discussed.

INTRODUCTION

THE ACCUMULATION of solids in percolating filters by biosynthesis and physical means limits the rate at which sewage and other organic wastes can be treated by this process. Under temperate conditions the winter accumulation of solids in many filters impairs their efficiency. With excessive accumulations of solids the distribution of the sewage within the filter is affected and "ponding" may result; the aeration of the filter by ventilation may also be restricted. The grazing activity of invertebrates such as insects and worms tends to limit the accumulation of such solids. The extent to which this grazing activity is significant in the economy of the filter has been the subject of some controversy, as previously discussed (HAWKES, 1963).

Modified methods of operating filters have been found to be beneficial in limiting the accumulation of solids. Recirculation of effluent to dilute the feed to the filters has been found to be beneficial in this respect. Alternating Double Filtration (ADF) in which a pair of filters operating in series alternately receive settled sewage and settled effluent for successive periods, has also been found to limit solid accumulation (TOMLINSON, 1941). In filters treating an industrial sewage in which excessive fungal growths developed each winter, it was found that the frequency at which the sewage was dosed to the filter, as determined by the rate of rotation of the distributor, was an

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important factor influencing the degree of accumulation of fungal film (HAWKES, 1955). The effect of the dosing frequency on the accumulation of solids in filters treating domestic sewage was subsequently studied. The results of observations over a period of thirteen years on the ecology and efficiency of two filters treating domestic sewage, one of which was modified to give low frequency dosing, have already been reported (HAWKES and SHEPHARD, 1971). In these long term observations the ecological studies were based on samples removed from the upper foot of the filter. During the observations, however, a more detailed study was carried out over a two year period on the seasonal changes in distribution of solids and grazing fauna throughout the depth of the two filters. The results of this comparison are the subject of this present report.

DESCRIPTION OF FILTERS

The two filters under observation were of identical construction, each being 5 ft (1·5 m) deep and made of 1·5–2 in. (3·7–5 cm) grade gravel. During the 2 years of the investigations the distributor on one filter (A) was propelled by jet reaction as the sewage discharged from the four distributor arms to rotate once every 1·25 min, giving a dosing frequency of approx. 0·3 min. On the other filter (D) the distributor was rotated by means of a mechanical drive once every 14 min. The arms were also modified so that each discharged sewage from different quarters of their length, thus any part of the filter received a dose of sewage once each full rotation giving a dosing frequency of 14 min. The overall dosage to each filter was the same.

METHOD OF SAMPLING

To enable sampling of the medium throughout the depth of the filter, perforated cylindrical sleeves were inserted vertically in the filters. Within each sleeve fitted a column of perforated containers 6 in. dia. and 6 in. deep each filled with approx. 0·1 ft^3 of filter medium. To facilitate the removal of the sample-containers from the shaft, lifting rods passed through the centre of the column of containers to which were fitted a perforated plate. By means of two such rods, a long solid one with the basal plate below the bottom container and a shorter tube which fitted concentrically over the upper half of the longer rod (FIG. 1a), the samples were removed at two lifts (FIG. 1b).

In each filter were 18 shafts arranged circumferentially towards the outer part of the filter so as to be supplied from the same distributor jets (FIG. 1c). The filters were sampled at monthly intervals when two neighbouring shafts from each filter were removed, the samples in one being used to assess the degree of accumulation of solids and the duplicate shaft being used to determine the grazing fauna populations. After sampling, the containers were refilled with washed medium and replaced in the sleeves; a full year was allowed for maturing of the media before being sampled again. The filters were sampled for 9 months of each year from October to June. The macrograzing fauna was removed from the medium sample by washing over a coarse grid and collecting the dislodged organisms on a fine strainer. The numbers of different taxa were then assessed on a sectored counting plate and the numbers recorded as organisms per 0·1 ft^3 of filter at different depths. The film was assessed by washing the medium sample in a known volume of water in a revolving drum washing machine. The volatile solid was then determined on an aliquot and the results expressed as grams of volatile

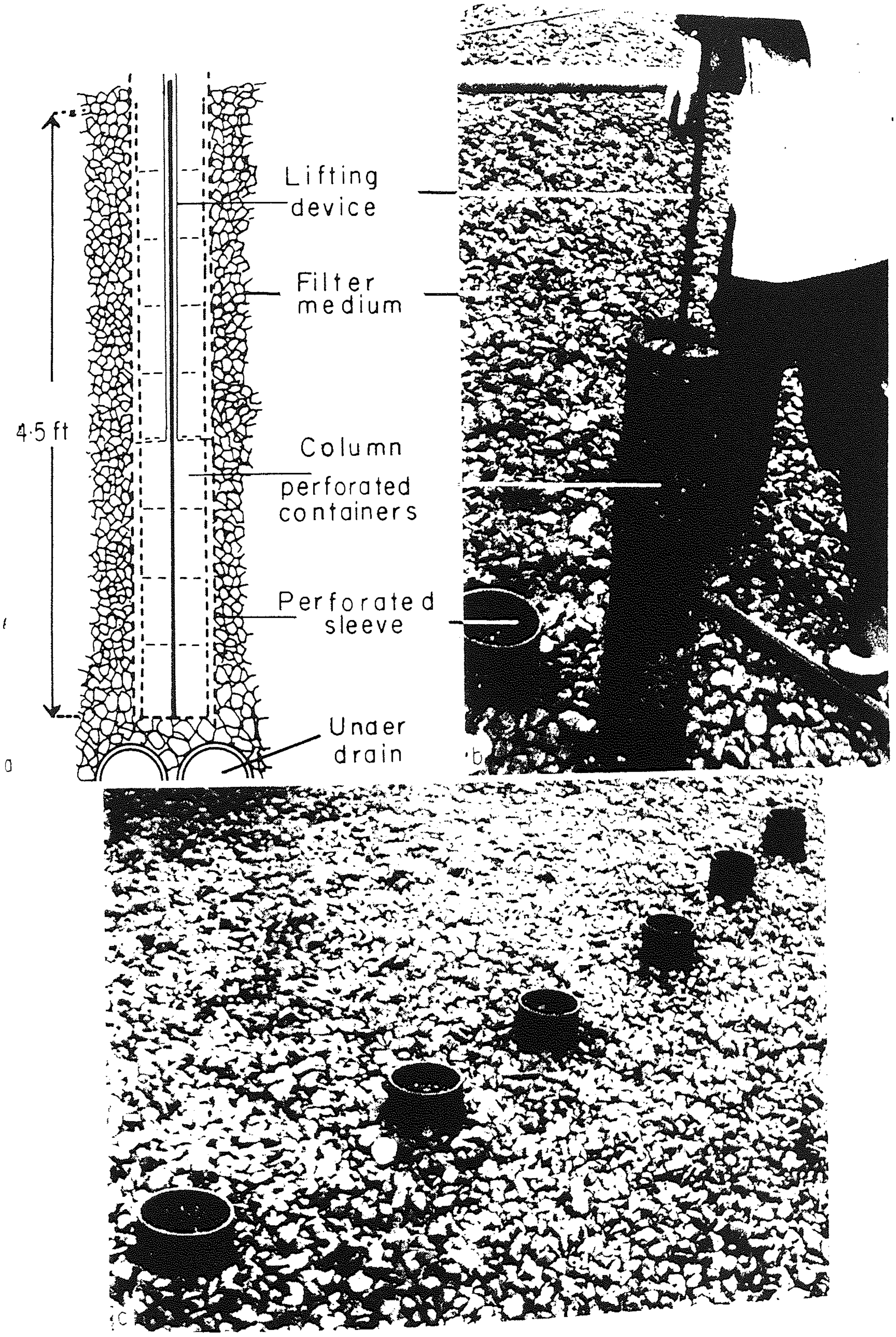

FIG. 1. Method of sampling film and fauna throughout depth of sewage percolating filter. (a) Diagram showing perforated containers and lifting devices situated in sleeve inserted in filter. (b) A half column of containers removed from sleeve. (c) Surface view of filter showing set of sleeves *in situ*.

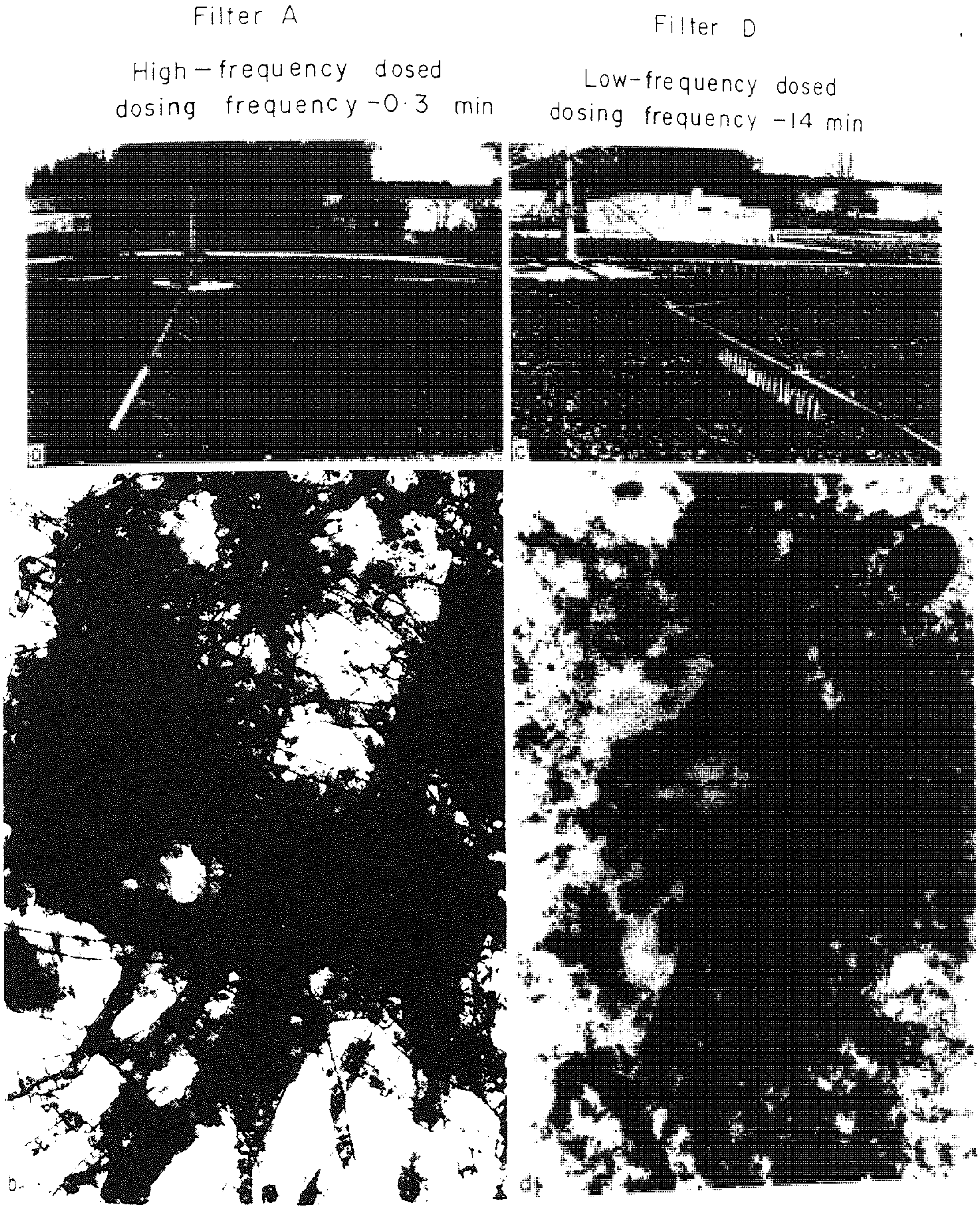

FIG. 8. Comparison of microbial film composition in high-frequency and low-frequency dosed filters. (a) Filter A with reaction-jet propelled distributor giving high-frequency dosing. (b) Photomicrograph of film from beneath surface of filter A showing dominance of fungal hyphae. (c) Filter D with distributor mechanically driven through central geared drive giving low-frequency dosing. (d) Photomicrograph of film from beneath surface of filter D showing absence of fungal hyphae.

solids per 0·1 ft^3 of filter at different depths. Seasonal fluctuations in filter temperature were recorded using a thermograph which recorded the temperature of the filter at a depth of 1 ft.

Because of the limited numbers of shafts available it was not possible to take samples in replicate but the observations were extended over a period of 2 years to establish any seasonal trends.

RESULTS

The results of the two 9-month periods of sampling are shown graphically in FIGS. 2–6. The numbers of organisms and amounts of accumulated solid are represented by the width of the respective histograms at the different depths. FIGURES 2 and 3 show the comparative seasonal changes in the vertical distribution of film, enchytraeid worms, dipterous larvae and lumbricid worms. Generally the results from the 2 years (FIGS. 2 and 3) were similar and showed the same seasonal pattern.

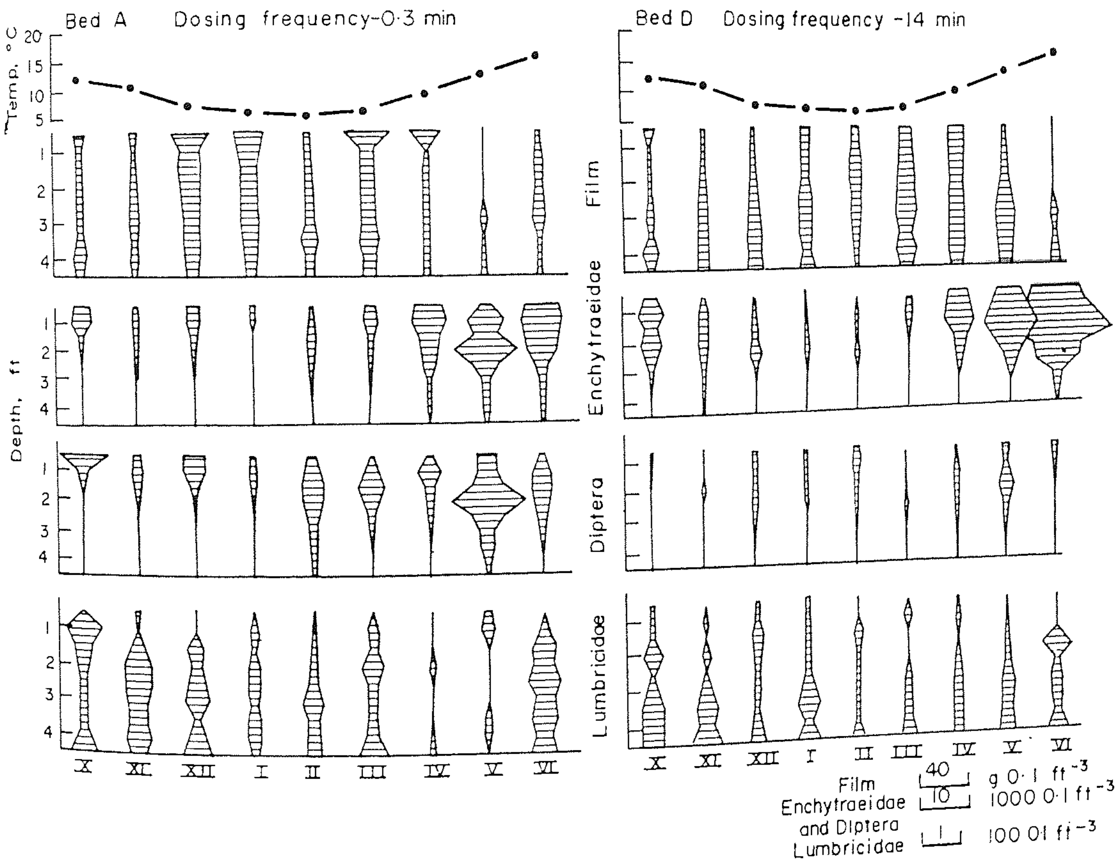

FIG. 2. Seasonal changes in the abundance and vertical distribution of film and grazing fauna in high-frequency (A) and low-frequency (D) dosed filters (1964–1965).

FILM

The results confirm those previously reported (HAWKES and SHEPHARD, 1971) in that the winter accumulation of solids in the upper foot of the filter was greater in the high-frequency dosed bed (A) than in the low-frequency dosed bed (D). The results from the depths of the filters however gave a different picture from that obtained from the surface samples. Whereas in the high-frequency dosed filter (A) there was generally

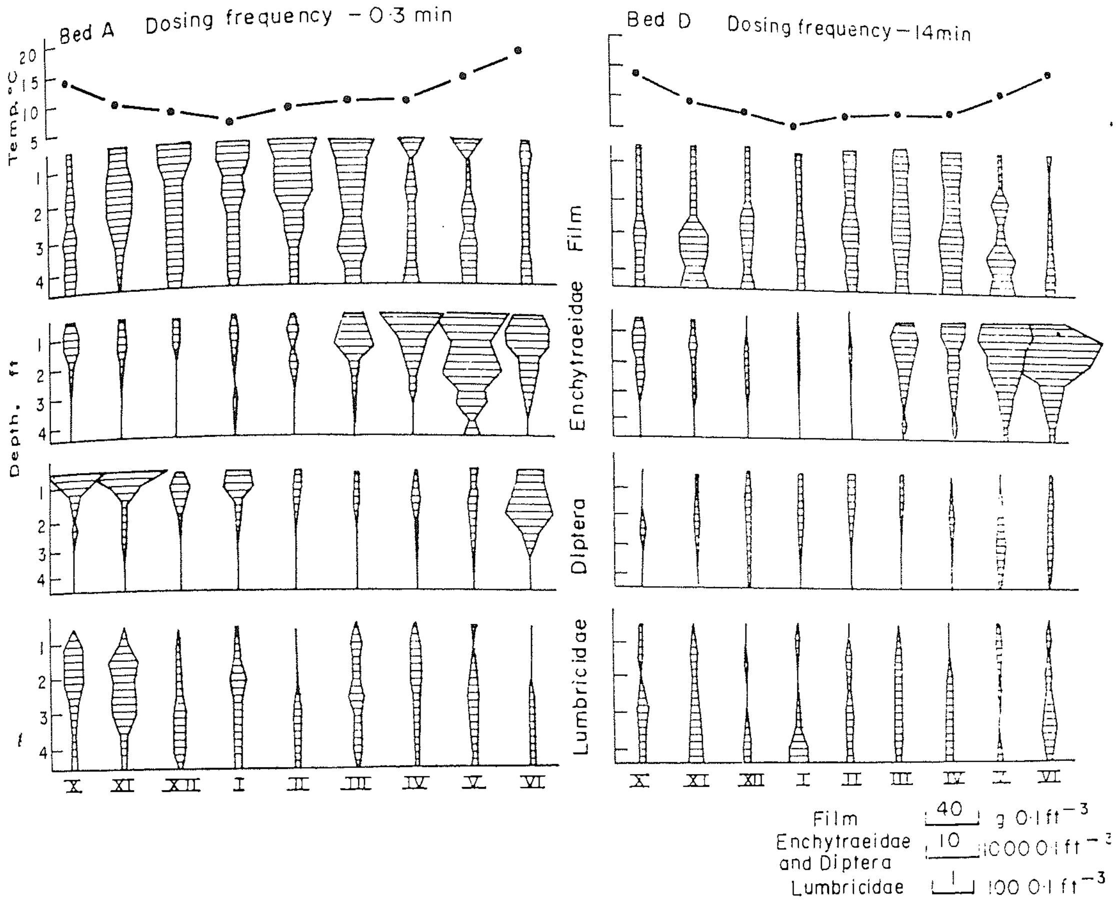

FIG. 3. Seasonal changes in the abundance and vertical distribution of film and grazing fauna in high-frequency (A) and low-frequency (D) dosed filters (1965–1966).

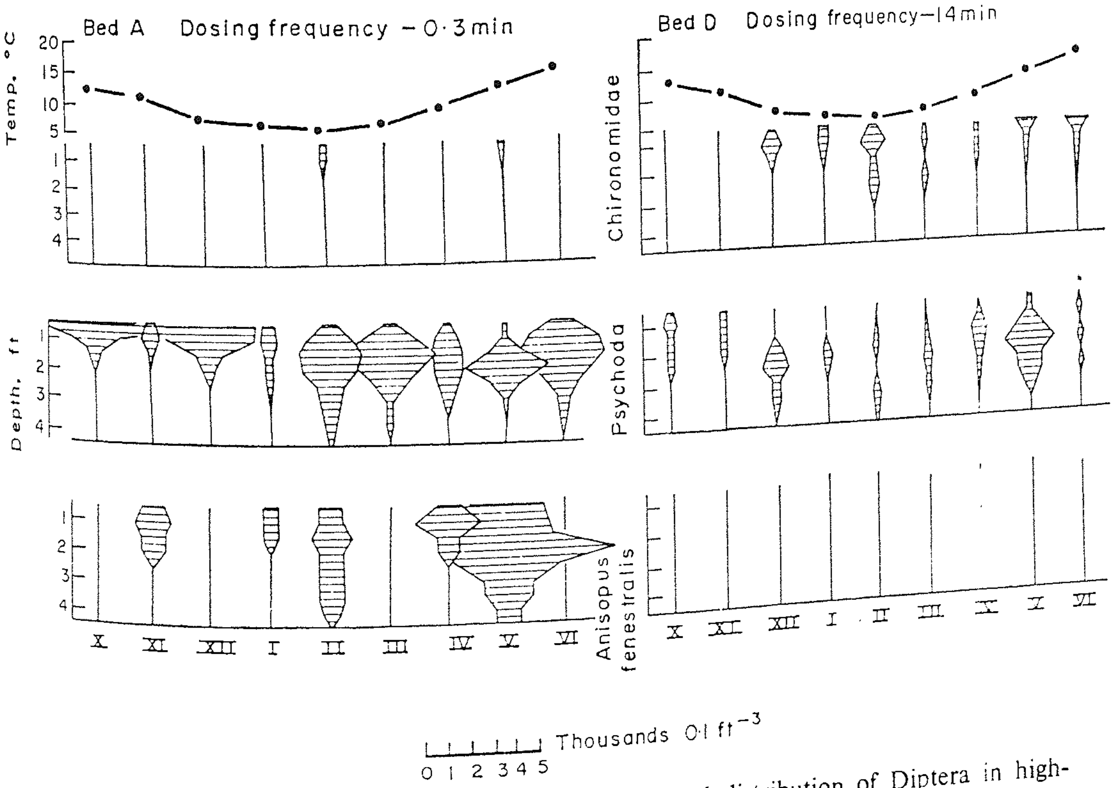

FIG. 4. Seasonal changes in the abundance and vertical distribution of Diptera in high-frequency and low-frequency dosed filters (1964–1965).

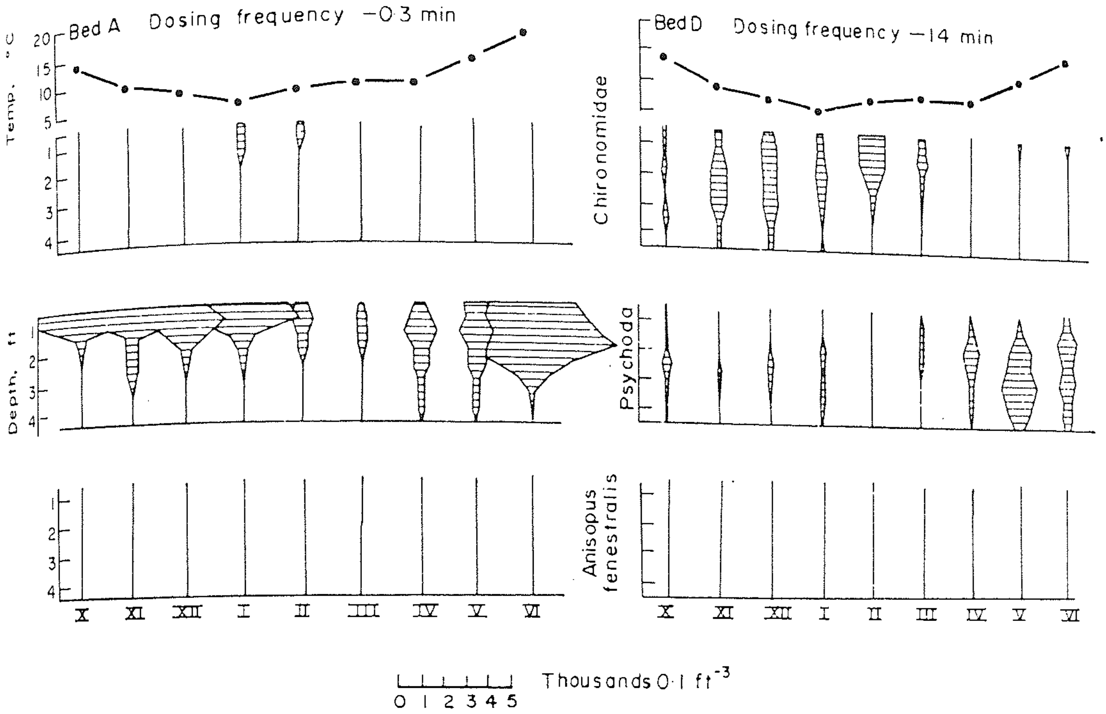

FIG. 5. Seasonal changes in the abundance and vertical distribution of Diptera in high-frequency and low-frequency dosed filters (1965–1966).

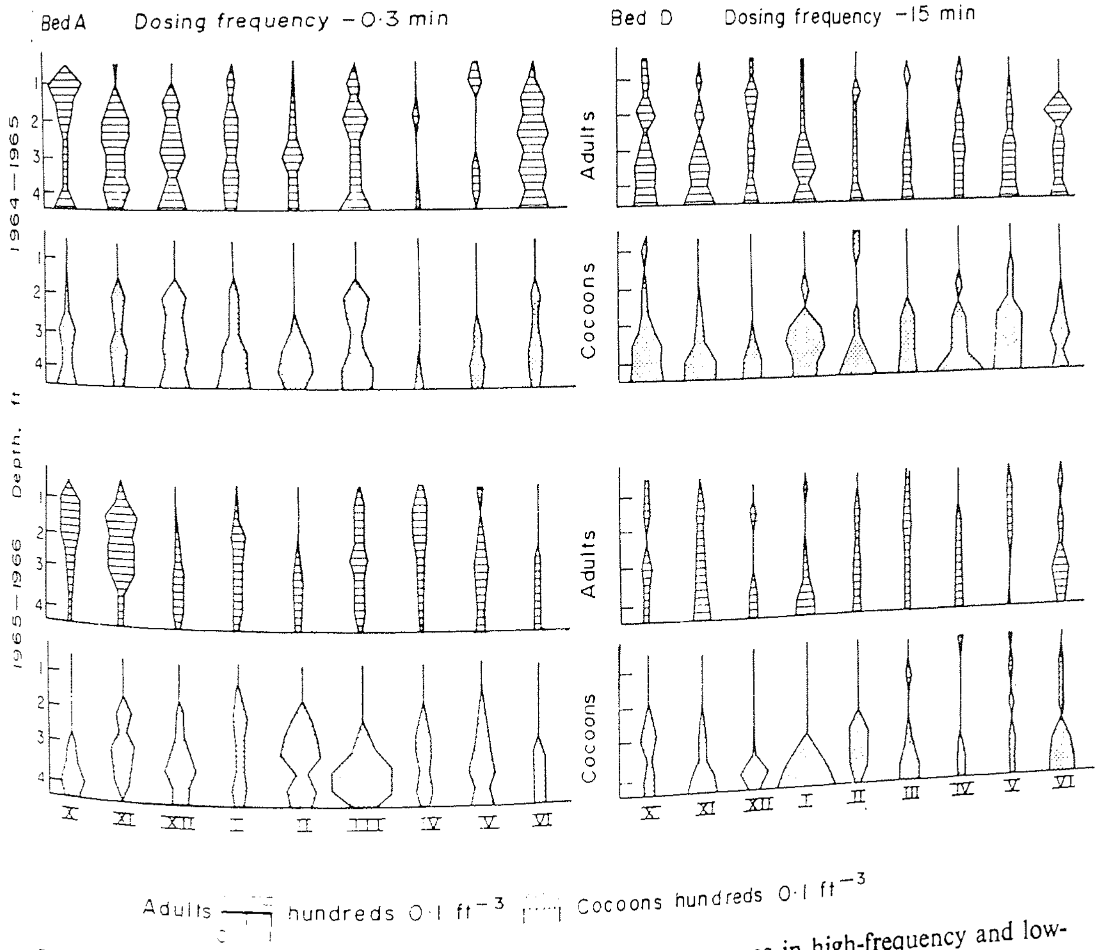

FIG. 6. Vertical distribution of Lumbricidae adults and cocoons in high-frequency and low-frequency dosed filters.

a reduction in the amount of solids with depth, in the low-frequency dosed filter (D) the solids were at times evenly distributed throughout the depth of the filter or accumulated to a greater extent at depths within the filter. At times this resulted in a greater accumulation of solids within the low-frequency dosed filter (D) than in the high-frequency dosed filter (A) even when the surface layers of the latter contained the greater accumulation of solid (FIG. 2, iv—1965) (Fig. 3, v—1966). There was also a difference between the two filters in seasonal fluctuations in solids. In the high-frequency dosed filter A, each year there was a marked reduction in the amount of solids within the filter in the early spring followed by a reduction in the solids in the surface layers. In the low-frequency dosed filter D this unloading of solids (the vernal slough) took place later and in contrast to filter A occurred in the upper layers first followed by a discharge from the depths of the filter. These differences are illustrated in FIG. 7 where the seasonal fluctuations in film in the upper foot of the two filters are compared with the fluctuations in the average film amount throughout the depth of

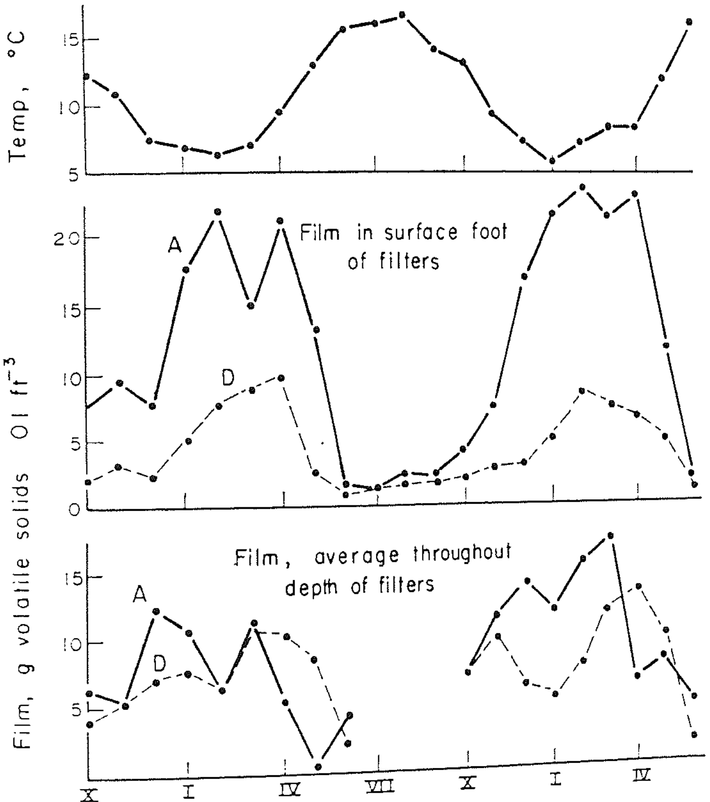

FIG. 7. Comparison of seasonal fluctuations in film in the surface foot with that throughout the depth of a high-frequency dosed filter ●—● A and a low-frequency dosed filter ●- - -● D.

the filter. In the surface layers there was a marked difference during the winter months and the decrease took place at the same time. The differences in the average amounts of solids throughout the depth of the filter was less marked and the decline of the average amounts of solids throughout the filters took place earlier in the high-frequency dosed filter (A) than in the low-frequency dosed one (D) in both years.

Besides quantitative differences, marked qualitative differences in the film from the two filters was observed. In the high-frequency dosed filter (A) the film towards the end of the summer in the surface samples was found to be dominated by fungal hyphae; no such growths were found in the film from the low-frequency dosed filter D (FIG. 8).

The fungus was subsequently isolated and identified as *Subbaromyces* sp. (WILLIAMS, 1971). Unlike the fungi which dominated the film throughout the winter in the filters at Minworth, which treated an industrial sewage, the fungus declined and was overcome by bacterial growths and flocculated sewage solids as these increased throughout the winter.

GRAZING FAUNA

FIGURES 2 and 3 show the comparative seasonal incidence and vertical distribution of different taxa in the two filters. Again these showed very similar patterns in the 2 years. The frequency of dosing had little effect on the vertical distribution or seasonal incidence of the enchytraeid worms. In both filters their populations were markedly decreased throughout the winter and increased in the spring. Generally in both filters there was a decrease in numbers with depth below the upper foot although often there were more in the 6–12 in. sample than in the surface sample (0–6 in.). In both years there was a larger population in the low-frequency dosed filter in early summer. This was probably associated with the larger fly larvae population in the high-frequency dosed filter (A) which reached a maximum at that time.

The dosing frequency had a marked effect on the total dipterous fly population. In the low-frequency dosed filter (D) the population was severely restricted throughout the year compared with that in the high-frequency dosed filter (A). FIGURES 4 and 5 show more detailed results of different dipterous taxa. At this level, differences were evident between the two years in that in one period (1964–1965) *Anisopus fenestralis* became established in the high-frequency dosed filter (A) (FIG. 4), but had disappeared again in the following season (FIG. 5). In both years however, the dosing frequency had a marked effect on the species composition of the dipteran fauna of the filters. In the high-frequency dosed filter (A) the dominant fly larva was Psychoda—mostly *P. alternata*; the Chironomidae were only occasionally present and they were few in numbers. In the low-frequency dosed filter (D) although Psychoda were present their population was much reduced; the Chironomidae however were more abundant than in the high-frequency dosed filter (A).

The presence of an appreciable population of *A. fenestralis* in filter A during 1964–1965 is of interest. This fly is present in the filters at the nearby Minworth sewage works where at times it causes a nuisance. During the previous 10 years of operation the fly was only recorded from the monthly samples on few occasions and then only in small numbers. The fluctuations in numbers from month to month represent three generations, the larval peaks occurring in November 1964, February and May 1965. There was some evidence (FIG. 4) that the invasion of *A. fenestralis* resulted in some suppression of the Psychoda population as had previously been reported for another works (HAWKES and JENKINS, 1951). There was little difference between the population or vertical distribution of the lumbricid worms in the two filters (FIG. 6). In both cases, although they were rare in the surface layers at the time of sampling, they were present through the rest of the filter. In both filters the cocoons were mostly found in the lower half of the filters and were somewhat more numerous nearer the bottom in the low-frequency dosed filter D than in the high-frequency dosed filter A (FIG. 6).

DISCUSSION

For the efficient operation of filters it is necessary to maintain an ecological balance and to prevent excessive accumulation of solids which impair the efficiency, especially in relation to nitrification. The significance of grazing fauna is in reducing the film and accumulated solids. The flies, however, although beneficial grazers in their larval stage may cause serious nuisance in the vicinity when they leave the filters. The results show that the frequency of dosing has a significant effect on both the ecological balance and the species composition of the grazing fauna.

The results from the surface samples of the shafts confirm the findings of the previously reported study (Hawkes and Shephard, 1971), the winter accumulation of solids being markedly suppressed in the low-frequency dosed filter. The results of the present investigation in which samples were taken throughout the depth of the filters, however, show that within the filters the effects of dosing frequency were more complex. Within the filters there was generally less difference in the amount of solids present but, more significantly, there was a difference in the seasonal incidence and vertical distribution between the two filters, related to differences in the dosing frequency. Although throughout the winter the solids with the low-frequency dosed filter (D) were less than in the high-frequency dosed one (A) the spring unloading occurred earlier in the latter filter, resulting in a greater accumulation of solids being present in the low-frequency, dosed filter (D) during the spring and early summer. Besides the timing of the unloading, there was also a difference in the way the unloading occurred. In the high-frequency dosed filter (A) it took place from below upwards, the surface layers being the last to unload. In the low-frequency dosed filter (D) it took place from above downward, the surface layers being first to unload. Thus although the surface layers of both filters unloaded at the same time, in the high-frequency dosed filter (A) this represented the completion of the process whereas in the low-frequency dosed filter (D) it was the initiation of the unloading.

If, as has been claimed (Hawkes and Shephard, 1971), the unloading of the filters is largely brought about by grazing activity, then the different times and manner of unloading in the two filters should be related to differences in the incidence and distribution of the grazing fauna. Comparing the results from the two filters for the period 1964–1965 when there was a most marked difference in the unloading (Fig. 2), it is seen that the earlier unloading in filter A between March and April was associated with a larger dipterous larvae population than in filter D. The enchytraeid worm population was similar in both filters at the time but increased later in filter D associated with the unloading of that filter. The spring increase in the Psychoda population occurs in the depth of the bed below the surface layer and this would account for the earlier unloading in the sub-surface layers in filter A. The enchytraeid worms usually decrease in numbers throughout the depth of the bed. The unloading in filter D in the absence of a large Psychoda population, takes place from above downwards, associated with this distribution of the enchytraeid worms. Although the enchytraeid worm population was at most times greater than the dipterous larval population, the latter probably grazed more actively associated with their higher metabolic rate. This would account for the earlier unloading in filter A.

Thus, although low-frequency dosing reduced the rate of accumulation of film during the winter, it suppressed the insect grazing population so that the solids which had accumulated were discharged later in the spring than in the high-frequency dosed filter. Although this is somewhat of a disadvantage regarding the condition of the filter the reduction of the fly population is beneficial in reducing the chance of fly nuisance.

The results provide no evidence to support the commonly held view that during the winter there is a general migration of grazing fauna to the warmer depths of the filter. There was a general decrease in the total population throughout the depth of the filters during the winter period. Psychoda did, however, show a marked difference in their vertical distribution in the summer and spring. The chironomids differed in being more common throughout the winter period.

The appearance of *A. fenestralis* is ecologically interesting. It is significant that it only became established in the high-frequency dosed filter A and was absent from the adjoining low-frequency dosed filter D during this period. At Minworth it was found that the Anisopus population could be suppressed by low-frequency dosing (HAWKES, 1955). The remarkable disappearance of Anisopus the following season (FIG. 5) without any control measures being applied suggests some natural controlling factor probably involving the competition with Psychoda.

SUMMARY OF CONCLUSIONS

(1) The winter accumulation of solids in the surface layers of filters treating domestic sewage was considerably reduced by low-frequency dosing achieved by retarding the speed of rotation of the distributor.

(2) The accumulation of solids within the filter however were less affected by the dosing frequency.

(3) The dosing frequency affected the vertical distribution of solids in the filters. In the high-frequency dosed filter there was generally a reduction in the amount of accumulated solids with depth; in the low-frequency dosed filter the solids were either evenly distributed throughout the depth or at times accumulated to a greater degree within the filter.

(4) Low-frequency dosing caused the spring unloading to be delayed by 1–2 months and thus for a period in the late spring the accumulated solids in the low-frequency dosed filter exceeded those in the high-frequency dosed filter.

(5) In general, in the high-frequency dosed filter the unloading first occurred below the surface layer followed by an unloading of the surface solids whereas in the low-frequency dosed filter the unloading first occurred in the surface layers and proceeded downward.

(6) The fungal film which occurred each summer in the surface layers of the high-frequency dosed filter was absent from the low-frequency dosed filter.

(7) Low-frequency dosing markedly suppressed the population of fly larvae throughout the depth of the filter. It had little effect upon the populations or distribution of enchytraeid or lumbricid worms.

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Laboratory Studies on the Effects of Temperature on the Accumulation of Solids in Biological Filters

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INTRODUCTION

The rate at which sewage can be treated in a biological filter is often limited by the accumulation of solids in the filter, which interfere with the sewage flow and ventilation and eventually cause ponding and breakdown of the process. In addition the solids may support a large fly population which causes nuisance.

Hawkes and Shephard[1,2] reported investigations over several years on seasonal variations in the film accumulation, purification rates and macroinvertebrate populations of two biological filters at the Langley Mill works of the former Upper Tame Main Drainage Authority. The results showed that the film increased in the winter period and a marked reduction in the population of grazing invertebrates such as enchytraeid worms and dipterous fly larvae, especially *Psychoda* as shown in Fig. 1a to c. Associated with the low temperatures, the depressed population of grazers and increased film, there was a decrease in the efficiency of percent BOD removal, shown on Fig. 1d, and a more marked decreased in nitrification (Fig. 1e). The extent to which the reduced temperatures of the increased solids were responsible for the reduced efficiency could not be established from these observations. However, on reducing the winter accumulation of film in the surface layers of one filter by retarding the rate of rotation of the distributors so as to reduce the frequency of dosing, it was found that the winter reduction in efficiency was less than in the control filter in which the solids accumulated. It was concluded that the accumulation of solids at least contributed to the reduction in efficiency.

The cause of the seasonal fluctuation in filter film has been variously explained. Lloyd[3], Reynoldson[4] and Tomlinson[5] consider that the activity of grazers is of primary importance in controlling the film and at reduced temperatures in the winter their reduced populations and suppressed activity allow the film to accumulate. Holtje[6], Heukelekian[7] and Cooke and Hirsch[8] account for the fluctuations in film in terms of differential microbiological activity at different temperatures. To investigate the causes of these observed fluctuations in film in the filters, experiments were carried out on laboratory scale filters under controlled conditions of temperature with and without macrograzers.

MATERIALS AND METHODS

Apparatus. Each experimental filter consisted of a rigid white polythene cylinder of 100 mm internal diameter and 450 mm long, funnelled to a narrow outlet at the lower end and with a solid airtight lid (Fig. 2). The cylinder was filled with a medium of 'Allplas' polythene spheres 20 mm diameter, supported by a plastic grating to a volume of 2·832 l. Settled sewage was applied by means of a peristaltic pump to the filter through a tube passing through the centre of the lid. Within the filter, the tube formed a three-armed distributor to give even application to three points on the surface of the medium. The pump operated on a ten minute cycle for a period between 80 and 100 s, adjusted to give the required hydraulic loading. The effluent discharged via a simple water trap which formed an airtight seal and allowed for slight variations in pressure within the filter and for the removal of discharged humus. Air was supplied to each filter at a rate of about 1·2 l/min from a compressed air system. It entered via a hole in the bottom funnelled part of the filter, having first passed through a copper coil to equilibrate the required temperature. The air exhaust was via a second hole in the lid. A single experimental unit is shown in Figure 2. Settled domestic sewage from the Langley Mill Sewage Works at which the field investigations were carried out was used for the experiments. The filters were dosed at a rate of 5·38 l/d, corresponding to the top quarter of a bacteria bed being dosed at 0·48 m³/m³ d. The average BOD of the feed was about 180 mg/l.

Analytical Methods. For each filter, the BOD of the feed and effluent, the wet weight of the film and the CO_2 output were determined weekly.

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The wet weight was obtained by suspending the complete filter from a modified balance and subtracting the original dry weight. By using the plastic spheres as medium the initial weight was reduced to a minimum. The CO_2 output of the film was measured using a Grubb-Parsons Infra-Red Gas Analyser (IRGA) as the difference in CO_2 concentration between atmospheric (control) air and air from the filters; this was recorded on a Kent chart recorder. The IRGA was calibrated using a mixture of air and 5 per cent CO_2 in nitrogen and results were expressed as mg CO_2 produced per hour. The CO_2 output fluctuated in phase with the dosing cycle and the reading taken was the average of these fluctuations. These fluctuations were of considerable interest and their cause was investigated and this aspect of the work is reported later.

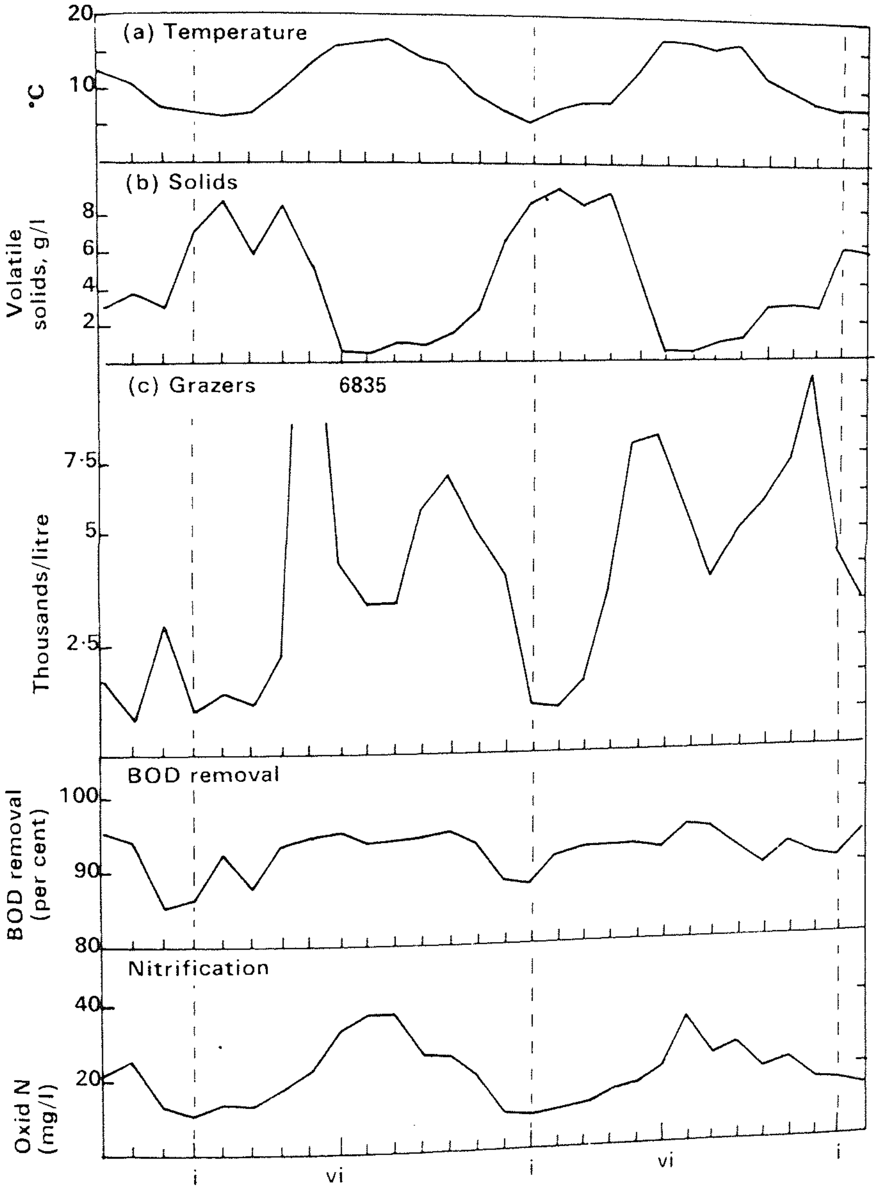

Fig. 1. Seasonal fluctuations in: (a) temperature; (b) solids; (c) macrograzers; (d) BOD removal; (e) nitrification in a percolating filter treating settled domestic sewage

Experimental Programme

Three experimental filters were set up in each of two adjacent, thermostatically-controlled rooms (A and B). Within each room other environmental conditions and operating procedure were constant, so that data from each set of filters could be collated for statistical purposes. The programme of Experiments I and II is shown in Table 1.

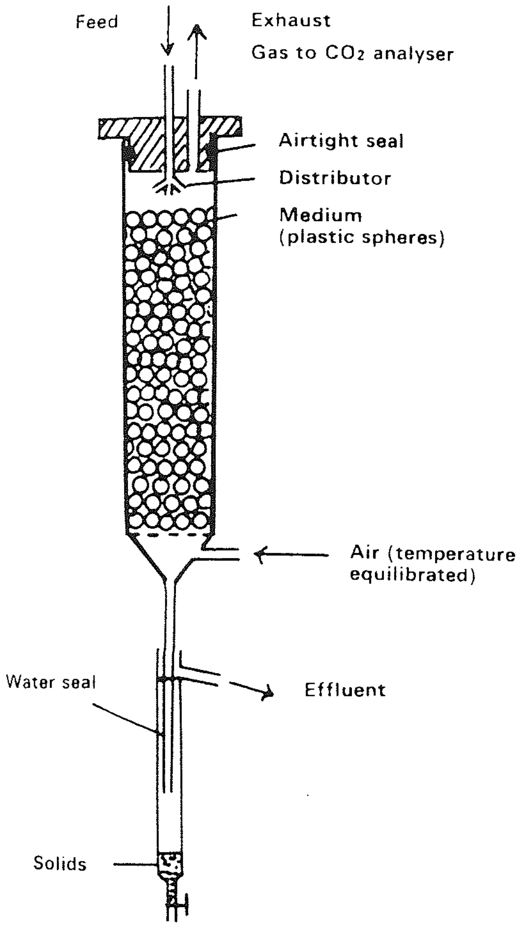

Fig. 2. Experimental filter

Table 1. Experimental Programme Details

	Period	Duration —weeks	Temperature	
			A1 A2 A3	B1 B2 B3
Expt. I	1	14	20°C	20°C
Macrograzers	2	15	20°C	5°C
Absent	3	14	20°C	20°C
Expt. II	4	10	20°C	20°C
Macrograzers	5	14	20°C	5°C
Introduced	6	6	20°C	20°C

In both experiments, the filters in Room A served as controls and were maintained at 20°C throughout. The filters in Room B, after an initial period of equilibration at 20°C (Period 1), were reduced to 5°C (Period 2) to observe the effect of reduced temperature on film accumulation, purification rate and CO_2 output. Finally, Room B was returned to 20°C (Period 3) to see how the filters re-adapted to mild conditions. All temperature changes were made in daily steps of 5°C over 3 days. The filters were operated continuously, the division between the two experiments being marked by the introduction of grazers. About 100 adult flies of the genus *Psychoda* were introduced into each of the 6 experimental filters. The initial introduction appeared to be unsuccessful in one or two filters but a breeding population was successfully established with a second batch of flies. This marked the start of Period 4 of Experiment II.

At the beginning of Period 6 the filters in Room B were observed closely to see if the fly population had survived prolonged exposure to 5°C during Period 5. It was found that in one filter a breeding population became re-established without any reintroduction of flies. In the other two filters the flies did not survive and larvae and adults were introduced to try and re-establish the population. This was achieved satisfactorily in one of the filters, but in the other a breeding population had still not developed when the experiment was concluded.

RESULTS

Experiment I—macrograzers absent. The accumulation of solids in each of the filters A1–3 and B1–3 throughout the experiment are shown in Figs. 3a and b in which the averages for each of the two sets of filters A and B are also compared (Fig. 3c).

During Period 1, under similar conditions at 20°C, the solids increased steadily and there was a close similarity between the individual filters. Throughout Period 2 solids continued to increase in filters B1–3 at 5°C, whilst in the control filters A1–3 maintained at 20°C the amounts of solids levelled off and then tended to exhibit irregular cycles of unloading and increase. These cycles were not always in phase and there were therefore at times considerable differences in the amounts of solids in the individual filters A1–3. Similar fluctuations continued in these filters during Period 3. In this period there was a general reduction in the amount of solids in filters B1–3 following the increase in temperature to 20°C. There were however wide differences between individual filters. In one filter (B3) there was an immediate reduction in solids which continued for some weeks to reach a level lower than that at the end of Period 1 at which time the temperature had been reduced. In B1 this reduction in solids occurred after a lag period of two weeks, and to a level equal to that at the end of Period 1. In B2 although there was an immediate decrease this was not substantial and most of the solids accumulated during Period 2 at 5°C were retained.

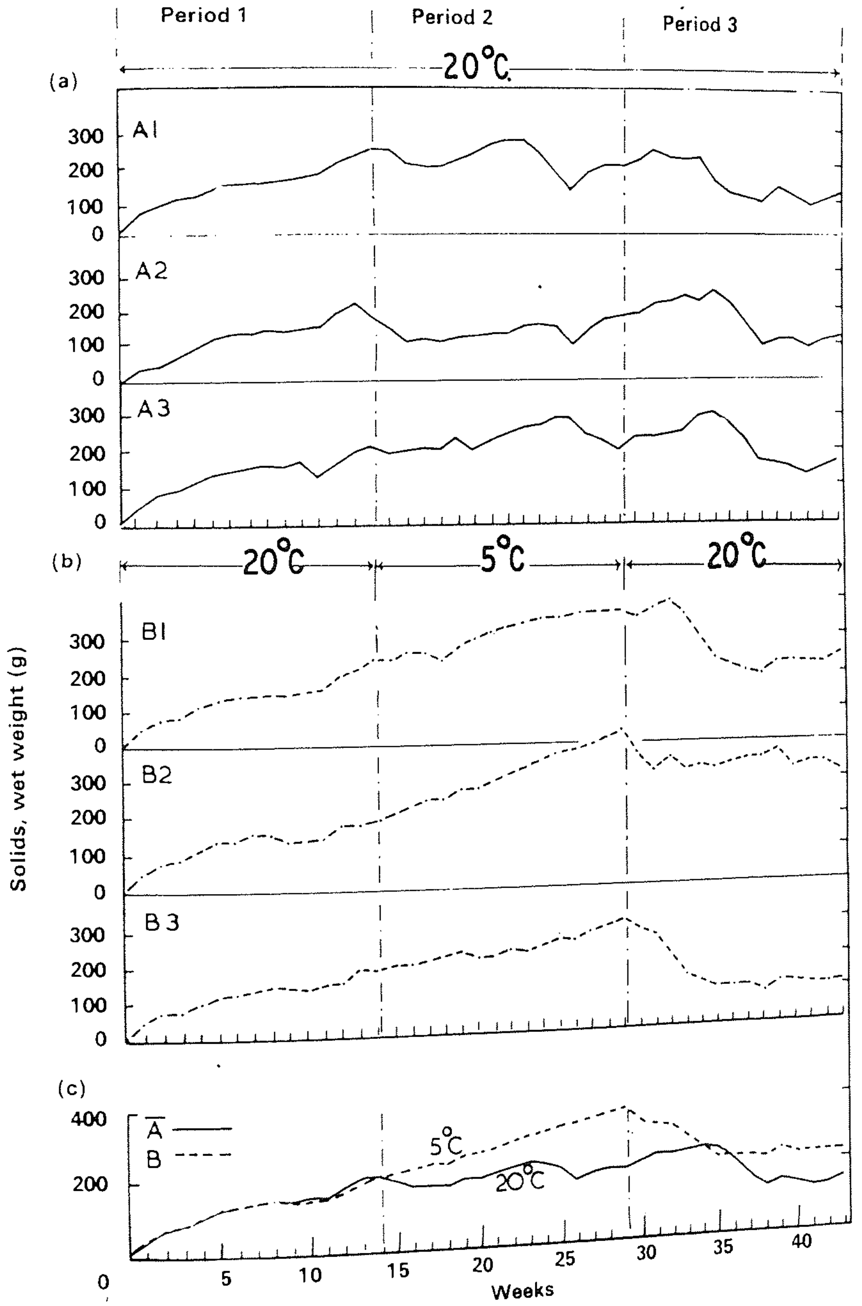

Fig. 3. Accumulation of solids in experimental filters at different temperatures. Macrograzers absent

The average amounts of solids in the two sets of filters in the different periods reflects these changes (Fig. 3c). Statistically there was no significant difference between the average film levels in the two sets of filters in Period 1, but there were significant differences ($p = {>}0{\cdot}05$) in Periods 2 and 3.

The average purification rates, as measured by the percentage BOD removal are compared in Fig. 4b. It is seen that during Period 1, under identical conditions, the average purification rates were similar, sometimes reaching around 80 per cent. It will be recalled that this represents the removal in the upper 0·45 m of a conventional filter. During Period 2 in the filters A1–3, remaining at 20°C, this level of removal was maintained, but in filters B1–3 at the reduced temperature there was a gradual decrease in efficiency compared with filters A1–3 to a level of approximately 50 per cent. In Period 3 after the temperature had been returned to 20°C the efficiencies of filters B1-3 rapidly improved to be the same as that for A1-3 although substantial differences in the amount of solid persisted for some time (Fig. 4a).

The comparative respiratory rates as measured by the carbon dioxide output from the respective filters during the three periods is shown in Figure 4c. During Period 1 under similar conditions the average rates were similar; following the lowering of the temperature to 5°C in filters B1-3 there was an immediate and significant reduction in CO_2 output which persisted throughout this period. Immediately on increasing the temperature to 20°C the rate of CO_2 output rose again but only after some weeks was it equal to that in filters A1-3 which had operated at 20°C throughout the three periods.

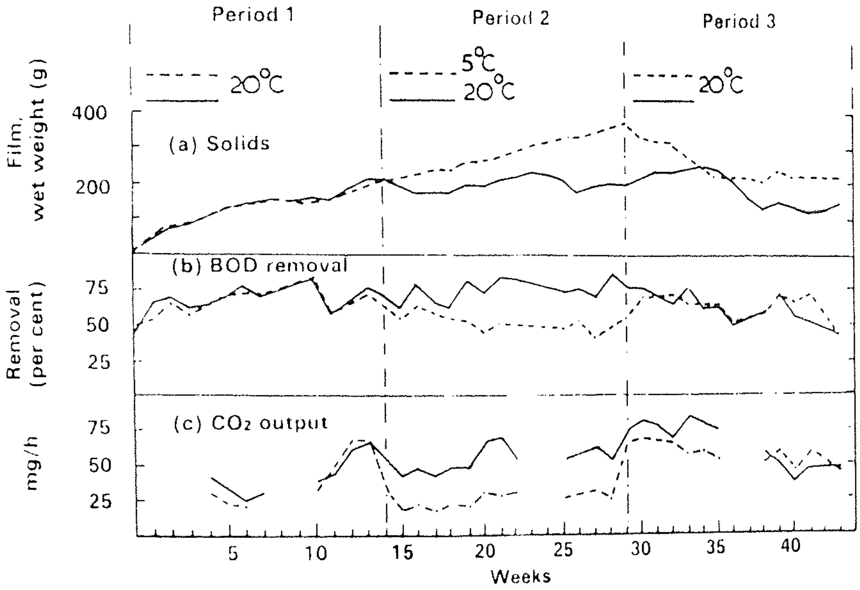

Fig. 4. Effect of temperature on: (a) solids accumulation; (b) per cent BOD removal; (c) CO_2 output of experimental filters. Macrograzers absent

Experiment II Macrograzers introduced. The accumulation of solids in each of the filters A1-3 and B1-3 after the introduction of *Psychoda* is shown in Figs. 5a and b. During Period 4, with both sets of filters at 20°C, there was a reduction in the amount of solids present in all filters once an effective grazing population had become established; the reduction being most marked in filters B1-3 in which appreciable amounts of solids were still present following the incomplete unloading of these filters in Period 3 of Experiment I (Fig. 3b).

Throughout the Periods 4, 5 and 6, filters A1-3, maintained at 20°C had a very uniform amount of solids present. This was about half the amount present in these filters at the same temperature during Experiment I when macrograzers were absent.

In filters B1-3 during Period 4 at 20°C the solids decreased to similar levels to those in A1-3. After lowering the temperature to 5°C however at the commencement of Period 5, the solids increased in all three filters at a similar rate as in Period 2 at 5°C in the absence of macrograzers (Fig. 3b). This suggested that at 5°C there was a complete suppression of grazing activity. During Period 6 after increasing the temperature to 20°C again, the filters behaved differently. In B2 in which the *Psychoda* had survived, the solids were reduced to the level at the commencement of Period 5; in the other two filters no such unloading took place, presumably because the *Psychoda* in these filters had not survived the period at 5°C. Statistical analysis of the mean amounts of solids present in the two sets of filters (Fig. 5c) showed that there was no significant difference in Period 4 but the difference was significant ($P < 0{\cdot}05$) during Periods 5 and 6.

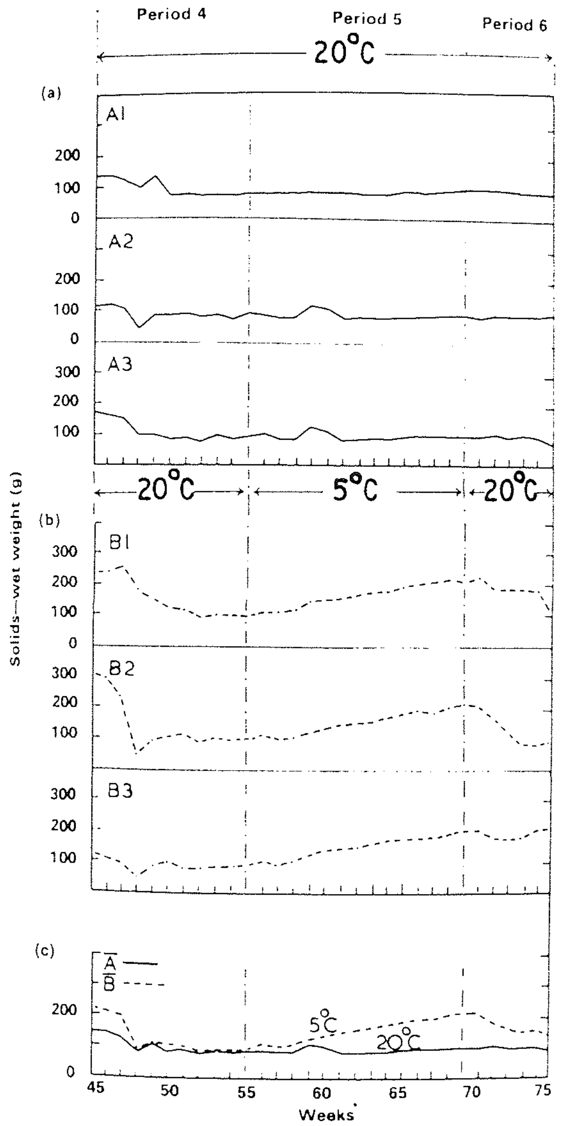

Fig. 5. Accumulation of solids in experimental filters at different temperatures. Macrograzers present

With the reduction in temperature to 5°C at the commencement of Period 5 there was a decrease in BOD removal rate in filters B1–3 (Fig. 6b). As in Period 2 the difference between the BOD removal rates of the filters (A1–3) at 20°C and those at 5°C (B1–3) increased during the period with increasing difference in the amounts of solids present in the respective sets of filters. During Period 6 following the return of the temperature of filters B1–3 to 20°C, the BOD removal rate increased to that of filters A1–3 (Fig. 6b).

The comparative respiratory rates, as indicated by the carbon dioxide output of the two sets of filters during Periods 4, 5 and 6, after introduction of grazers, is shown in Fig. 6c. In Period 4 at 20°C the two sets of filters had similar carbon dioxide outputs, on lowering the temperature to 5°C the CO_2 output from B1–3 fell and only recovered when the temperature was returned to 20°C at the commencement of Period 6, but as in Expt. 1, it remained for several weeks below that of filters A1–3 which had been maintained at 20°C throughout.

DISCUSSION

Solids Accumulation

As outlined in the introduction, the seasonal fluctuation in the amounts of solids present in biological filters has been variously explained by the effects of temperature fluctuations on either the grazing activity of macro-invertebrates or on the microbiological activity. In Expt. I in the absence of macrograzers, more solids accumulated in the filters at 5°C than at 20°C. Although this does not prove that differential macrograzing activity is not significant in accounting for seasonal fluctuation in solids in filters, it does prove that other factors can be involved. Three possible explanations are offered:

(i) If the solids accumulate by the biosynthesis of a zoogleal slime or fungal mycelium attached to the meduim, as the thickness of this growth increases the basal layers become anaerobic and are broken down detaching the growth from the substratum and thereby causing it to be discharged (Cooke and Hirsch[8], Sanders[9]). This would account for the cycles of accumulation and sloughing which occurred in the filters at 20°C in the absence of grazers. At lower temperatures this microbiological breakdown of the film would take place more slowly permitting a greater degree of accumulation to take place before sloughing.

(ii) Sewage purification in filters may be considered as taking place in two stages; the initial rapid physical adsorption of the organic matter on to the surface of the film and then itssubsequentbiooxidation(Renn,[10]; Cooke,[11]; Eckenfelder,[12]). At reduced temperatures the rate of biooxidation would be reduced but the physical process of adsorption would be less affected. Thus the rate of oxidation of the removed organic material would be reduced, causing these solids to accumulate. This possibility is discussed further in relation to the relative rates of BOD removal and respiration at the two temperatures.

(iii) In the absence of macro-grazers, such as insects and enchytraeid worms, it is possible that microorganisms such as nematodes, rotifers or even phagotrophic protozoa could assume the role of grazers in the system. The different amounts of solids present at the two temperatures could then be accounted for by the effect of temperature on micro-grazing activity. Microscopical examination of the films made during the experiments showed these organisms to be present, although their populations were not assessed.

The findings that increased amount of solids accumulated in the filters at the lower temperature, although in keeping with the situation in full scale filters, are in contradiction to the findings of earlier workers. Tomlinson[5] excluded macro-grazers from baskets of stones set into the surface of a filter and found that there was a greater accumulation of film in the baskets at higher temperatures. Green *et al*[13] studied the growth of microbial film on vertical screens at different temperatures fed with an industrial sewage; they found that most growth occurred at 20°C and least at 5°C. In these experiments however growth was measured over a short period probably during the early phases before a steady-state condition had been achieved as in the present investigations.

Comparing the filters in the two experiments, without and with *Psychoda* introduced, it is seen that in filters A1-3 maintained at 20°C throughout Periods 4–6 the amount of solids, after an intial reduction following the introduction of the *Psychoda*, remained at a uniformly low level throughout (Fig. 5a). The amount present was

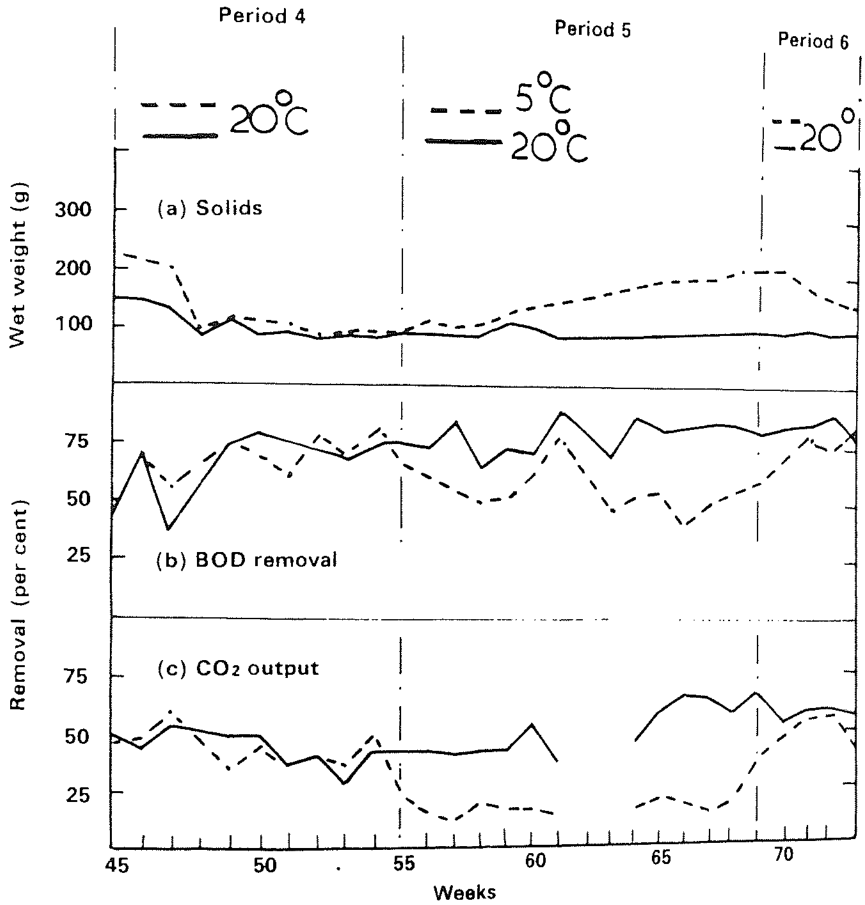

Fig. 6. Effect of temperature on: (a) solids accumulation; (b) per cent BOD removal; (c) CO_2 output of experimental filters. Macrograzers present

approximately half that present in these filters at the same temperature in the absence of macrograzers during Periods 1–3; it also showed less fluctuations. It would appear that at 20°C in Periods 4–6 the solid was being controlled by grazing activity, at a level below which the solids controlling mechanism became operative in the absence of macrograzers.

In filters B1–3 during Period 4 at 20°C after the introduction of *Psychoda* the solids were rapidly reduced from the high levels existing at the end of Experiment 1 and then remained at a uniformly low level throughout Period 4 as in filters A1–3 under similar conditions (Fig. 5b). Following the lowering of the temperature to 5°C, the solids increased throughout Period 5 at a similar rate to that in Period 2 at the same temperature but with macrograzers absent. It would appear that at 5°C the grazing activity of the *Psychoda* was completely suppressed and solids accumulation was then governed by the same mechanism as in Experiment 1.

On returning the temperature to 20°C in the one filter (B2) in which the *Psychoda* had survived, the solids again declined to the low level existing in Period 4 before lowering the temperature. In the others it levelled off at an amount similar to the average level of the filters at 20°C during Periods 1-3 in the absence of macrograzers.

Efficiency—Per cent BOD Removal

The BOD removal efficiency of filters varies seasonally usually being the greatest at summer temperatures when the solid accumulation is low, and least at low temperatures and high degree of solid accumulation. To what extent each of the latter two factors are responsible for reduced efficiency in the winter is difficult to establish. Lloyd[3] considered that while excessive accumulation was detrimental to efficiency, the film might be so severly reduced by grazers in the summer that were it not for the enhanced activity of the microorganisms at the higher temperatures, the efficiency could be impaired. Subsequent observations by Hawkes,[14], Wuhrmann,[15] showed that, in practice, only a very thin film is needed for maximum efficiency and this was confirmed by laboratory studies (Water Pollution Research[16]) which showed that for efficient purification only a thin film a fraction of a mm thick is necessary. Sanders[9] suggested that theoretically the efficiency of a zoogleal film is impaired by increasing film thickness, since only the surface layer of the film respires aerobically, the lower layers consisting of accumulated organic matter which acts as an alternative metabolic substrate to the organic matter in the sewage.

Hawkes[17] compared the efficiency of two large operational filters in both of which the temperature fell in the winter but in only one of which did the solids accumulate, this being avoided in the other by low frequency dosing. Associated with the reduced temperature and increased solids the efficiency of the one filter decreased appreciably whereas in the other in which no excessive accumulation of solids occurred there was no decrease in efficiency. This would suggest that solids accumulation was the major factor affecting the efficiency, temperature being indirectly involved. It could however be that both factors acting together were responsible.

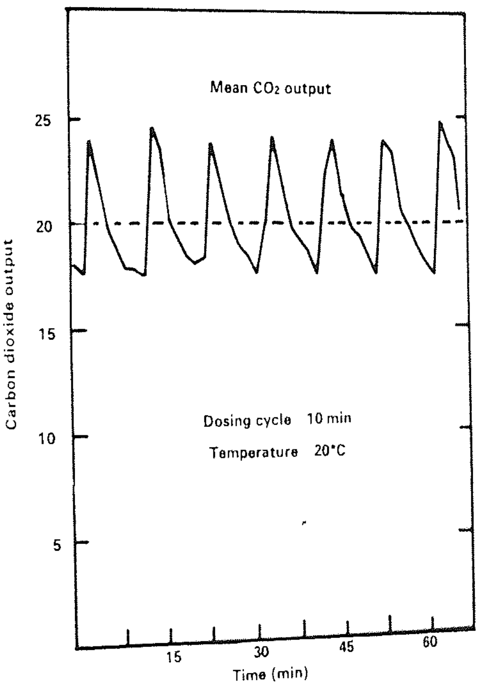

Fig. 7. Fluctuations in carbon dioxide output from an experimental filter intermittently fed with settled sewage

In both experiments of the present investigation, with and without grazers, the efficiency of the two sets of filters in periods 1 and 4 at 20°C was very similar. Lowering the temperature of one set of filters (B1–3) to 5°C however caused an immediate drop in efficiency. As the film accumulated in these filters at 5°C the difference in efficiencies between these filters and those maintained at 20°C increased. On returning the filters B1–3 to 20°C there was a rapid recovery in the efficiency, even before the solids had equilibrated. From these results therefore it would appear that reducing the temperature had a direct effect, as evidenced by the immediate initial fall in efficiency and a secondary effect by causing the solids to accumulate, as evidenced by the progressive decrease in efficiency with increasing solids accumulation at 5°C. The recovery of the filters B1–3 before the solids had unloaded after returning the temperature to 20°C was further evidence of the direct effect of temperature. This also supports the theory that the effect of solid accumulation on BOD removal efficiency is most significant at lower temperatures.

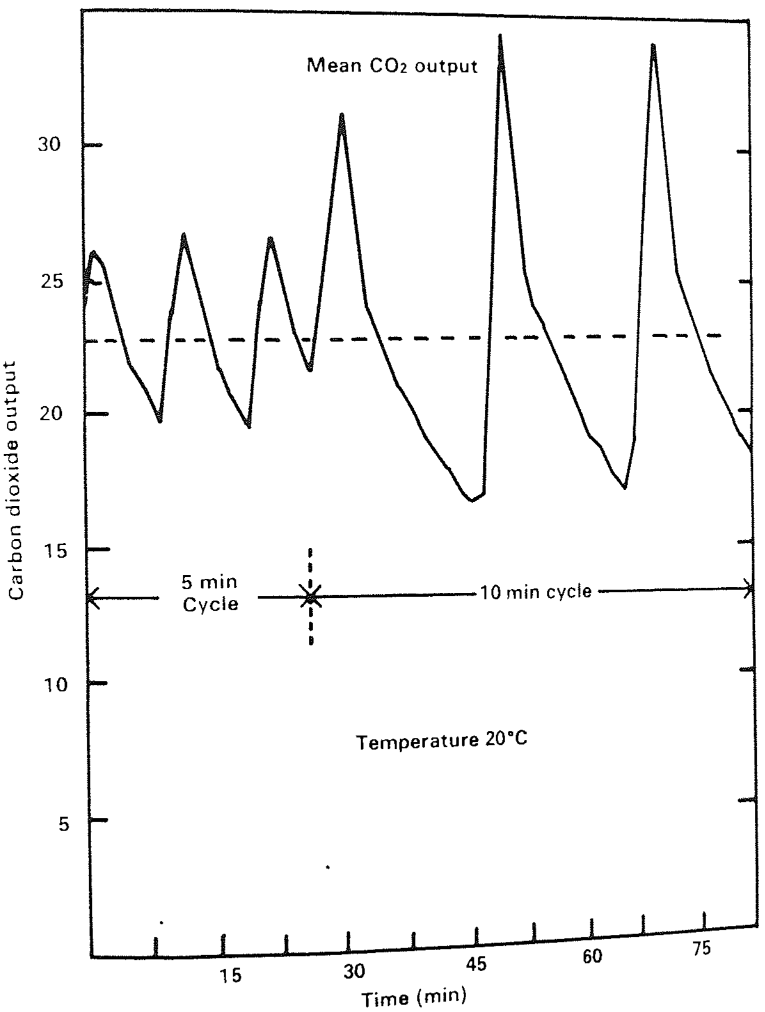

Fig. 8. Effect of changing dosing periodicity on fluctuations in carbon dioxide output. (Overall sewage application rate constant)

At 20°C the filters without micro-grazers had approximately double the quantity of solids present than after grazers were introduced yet the BOD removal efficiency was not significantly different. In these cases however the solids were not present in excessive amounts even in the absence of macro-grazers. The results are at variance with those of Hawkes[17] which showed no direct temperature effect on efficiency. However, the temperature ranges involved in those investigations were between 20°C and 10°C compared with 20°C to 5°C in the present investigations.

Respiratory Rate

At 20°C both sets of filters had similar outputs of CO_2. On reducing the temperature of one set (B1–3) to 5°C there was a marked and immediate reduction in CO_2 output to approximately half that of that from the filters at 20°C (A1–3). Unlike the effect on the BOD removal efficiency, which increased with increasing accumulation of solids at 5°C, the difference in CO_2 output remained fairly uniform and rapidly recovered when the temperature was returned to 20°C.

The differential response of BOD removal and respiration to reduced temperature could explain the accumulation of solids at low temperatures independently of any effect on grazing activity. Although on lowering the temperature to 5°C the BOD removal was reduced, the proportion of the removed BOD which was oxidized was markedly less than at 20°C, thus a greater proportion was stored in the filter as organic solids. As these increased it would appear that the adsorptive capacity of the film was impaired, for the BOD removal efficiency declined further (Fig. 4a & b).

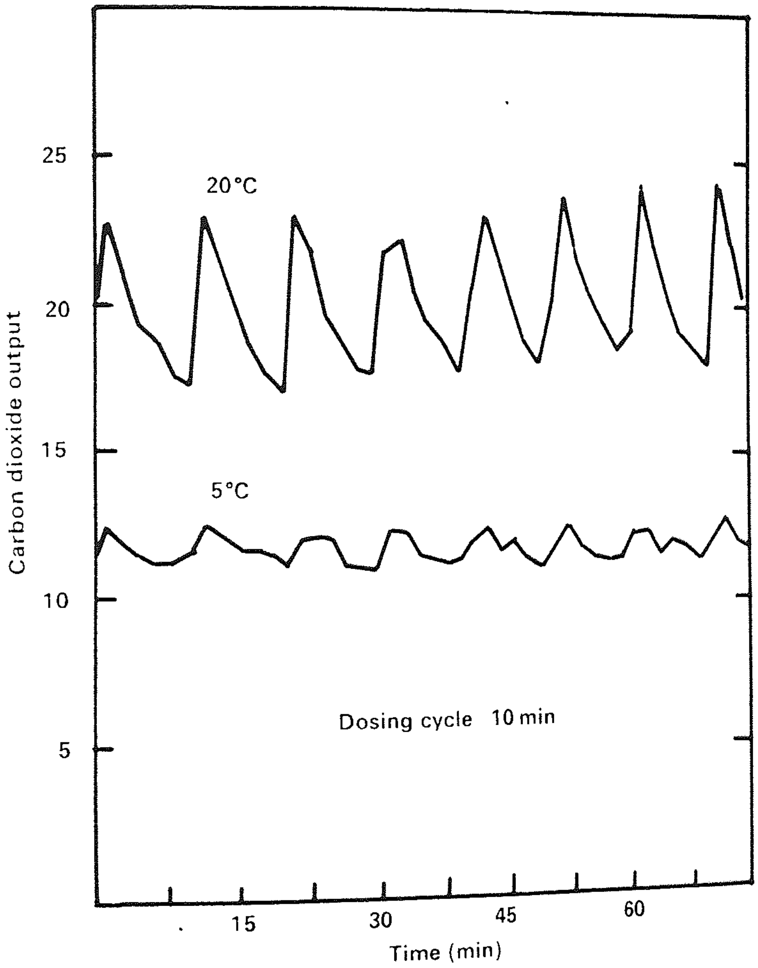

Fig. 9. Carbon dioxide output from two filters treating the same sewage at equivalent rates but operating at different temperatures

SUPPLEMENTARY INVESTIGATIONS INTO CYCLIC FLUCTUATIONS IN THE CO_2 OUTPUT FROM THE FILTERS

Observations

The CO_2 output was detected by infra-red gas analysis and recorded on a chart-recorder and showed a regular pattern of fluctuations (Fig. 7). These were observed to be in phase with the dosing cycle. This was confirmed by changing the dosing periodicity to 20 min (Fig. 8) without changing the overall rate of dosage. With the resultant change in periodicity there was a corresponding increase in the amplitude, the average level of CO^2 output was unchanged. At lower temperature (5°C), the fluctuations persisted but associated with the overall lower output the amplitude of the fluctuations was reduced (Fig. 9).

Discussion

It was considered that an interpretation of these observed fluctuations could throw some light on the different theories regarding the mode of BOD removal and oxidation. When first observed, the peaks in CO_2 output immediately following the dosing of the filter suggested that at least some of the organic matter was immediately

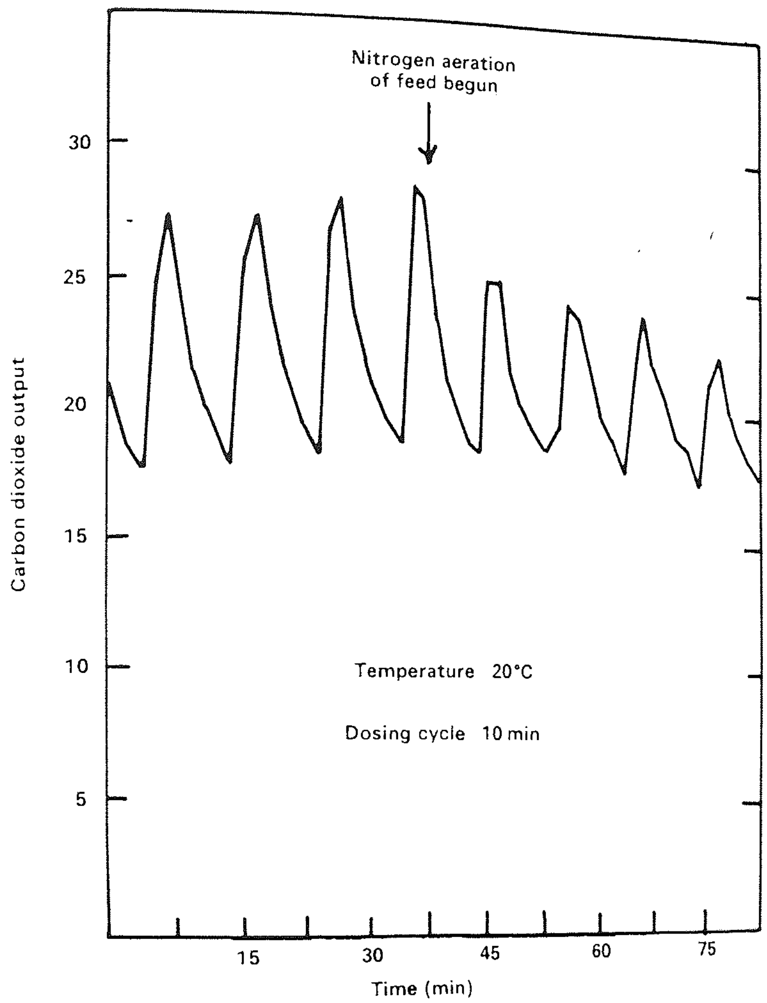

Fig. 10. Effect on carbon dioxide fluctuations of aerating feed with nitrogen to remove dissolved carbon dioxide

oxidized. However, recalling that the feed liquor in the storage container would probably be saturated with carbon dioxide; on delivering the dose into the filter this dissolved carbon dioxide would be scrubbed out. This could have been the cause of the peaks following dosing. The possibility of the peaks in CO_2 output being due to the scrubbing out of the gas from solution in the feed liquor was investigated.

Nitrogen gas was bubbled through the sewage being fed to the filter with the intention of scrubbing out the carbon dioxide before entering the filter. The results of this experiment are shown in Fig. 10, which shows a progressive reduction in the amplitude of the peaks following the commencement of the nitrogen bubbling. This showed part, at least, of the CO_2 peak was due to the scrubbing out of dissolved CO_2 previously generated in the feed liquor.

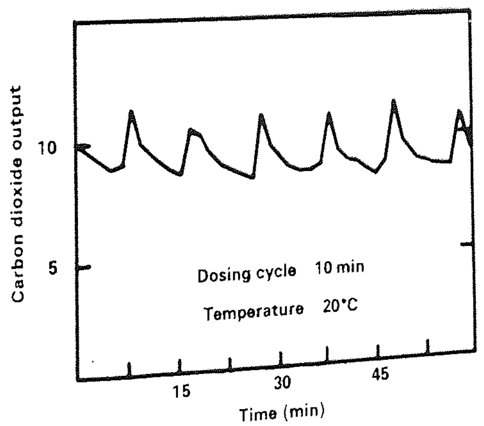

Fig. 11. Fluctuations in carbon dioxide output from a filter intermittently fed with sterile synthetic sewage free from dissolved carbon dioxide and inorganic carbon

In a further experiment a feed liquor comprising of a synthetic sewage without any inorganic carbon source, was used. The feed, the container and dosing tubes were all sterilized to prevent bacteria generating carbon dioxide before the dose entered the filter. The absence of inorganic carbon was confirmed by analysis. Fig. 11 shows that under these conditions the CO_2 output from a filter dosed with this feed at 20°C fluctuated in phase with the dosing produced CO_2. Although the volumetric dosing rate was the same as had been used with sewage, the amplitude of the peaks was much reduced. Their existence, however, confirms that some of the organic matter in the feed was being spontaneously oxidized as it came in contact with the film in the filter. Another possible explanation however is that, in the intervals between dosing, carbon dioxide accumulated in the liquor held in the film and this was displaced by the turbulence produced by the subsequent dose. With the experimental procedure used it was not possible to distinguish this effect from spontaneous oxidation.

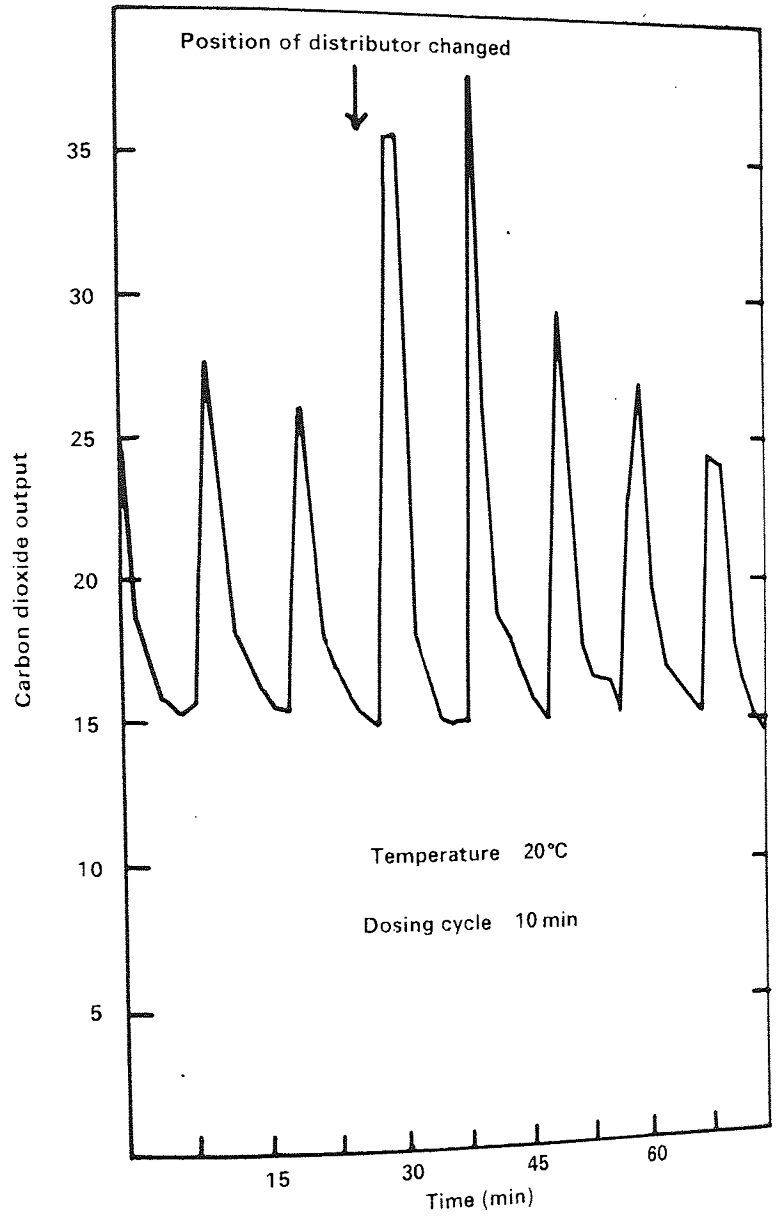

Fig. 12. Effect on carbon dioxide output of changing position of distributor

In another test a filter was operated at 20°C, the standard rate and dosing frequency (10 min), During the course of the run the lid of the filter was rotated through 60 degrees, causing the three-armed feed to discharge at three different points on the surface of the filter, thus changing the flow distribution within the filter. The immediate result was a sharp increase in the height of the peaks but during the next four cycles they returned to the previous level (Fig. 12). This increase in peak amplitude could represent increased spontaneous oxidation by film previously starved on nutrient or it could possibly represent the release by turbulence in film previously having quiescent conditions.

The results from this series of experiments indicate that at least some of the organic matter applied to the filter was immediately oxidised by the microorganisms in the film.

Proposed Explanation of Seasonal Fluctuation in Solids in Sewage Percolating Filters Treating Domestic Sewage.

Consider the two major components of the filter eco-system:

(1) The Film—comprising

(a) Biotic solids—biosynthesised solids in the form of microorganisms.

(b) Abiotic solids accumulated from suspended solids, flocculation and adsorption of solids in the feed or resulting from biological activity within the filter, for example faeces of grazers and dead organisms.

(2) The Macrograzers

The populations of macro-invertebrates which feed on the film.

The fluctuations of solids in a mature filter, with an established macrograzing fuana population may be considered as resulting from three major temperature dependent processes:

(i) Temperature induced fluctuations in the microbial populations of the film. Although the growth rate of most microorganisms of the film increases with increasing temperature within the range experienced in sewage filter operation, the carrying capacity of the filter medium is less at higher temperatures, as demonstrated in the present investigations. Thus during the winter a greater amount of microbial biomass is present than at summer temperatures.

(ii) Temperature induced fluctuations in the accumulation of abiotic solids. Due to the differential effect of temperature on the rates of BOD removal and oxidation the rate of abiotic solid accumulation increases with decreasing temperature.

(iii) Temperature dependent grazing activity of macro-invertebrates. Within the temperature range existing in filters the macro-invertebrates such as enchytraeid worms and dipterous fly larvae grow and graze more actively with increasing temperature. At low winter temperatures the population of macrograzers is suppressed. Thus low temperatures reduce grazing activity which in turn allows solids to accumulate.

All three processes therefore tend to result in a high accumulation of solids at low temperatures and a low accumulation at high temperatures. The relative importance of the three factors may well differ at the different phases of the seasonal fluctuation. Under summer conditions although the solids could be limited by microbiological activity, in the presence of an active macro-invertebrate population it is probably controlled at a lower level by grazing activity. Under these conditions however the population of macro-invertebrates is itself controlled by the limited food available. In the autumn, the effect of decreasing temperature on microbiological activity would tend to increase the accumulation of solids. At these temperatures however macrograzers would be less affected and initially increase as a result of improved food supply. Their activity reduces the rate of solids accumulation. With further decrease in temperature to winter conditions, the grazers are then affected both in terms of reduced populations and individual activity, and as a result the solids increase rapidly to winter levels. In the spring with rising temperatures the solids would be expected to decrease due to microbiological activity. A more rapid discharge of solids however usually occurs as a result of increased grazing activity of a peak population of grazers which becomes established in the presence of ample food supply and favourable temperatures. This large and active grazing population rapidly reduces the solids to summer levels where it is again limited by microbiological activity at higher summer temperatures and may be further reduced by the food-limited grazing population.

Earlier workers (Lloyd,[3], Reynoldson[4], Tomlinson[5]) had explained the seasonal fluctuations in solids in filters in terms of a differential effect of reduced temperatures, the grazing activity being suppressed to a greater degree by low temperatures than the growth rate of the film microorganisms. The results of the present investigations suggest that the effect of grazing activity is to supplement the effects of microbiological activity in producing the fluctuation in solids.

Grazers are probably of importance mostly in delaying the winter accumulation of solids and accelerating the spring discharge of solids from the filters. They probably therefore play a more important role in domestic sewage filters than in filters treating sewage with a high proportion of industrial effluent which support winter growths dominated by fungi (Hawkes[18]).

SUMMARY OF CONCLUSIONS

1. In the absence of macrograzers the accumulation of solids was controlled at higher temperatures by microbiological activity.

   The possible mechanisms of microbiological control are:

   (a) As the solids increase the micro-organisms forming the attachment layer on the substratum die, weakening the attachment and causing the sloughing of the film with the solids. This results in a fluctuating level of solids with alternating periods of build-up and sloughing.

   (b) Grazing by microfauna such as nematode worms.

   (c) The differential effect of temperature on the rate of BOD removal and the rate of the oxidation of the removal BOD. At higher temperatures a higher proportion of the BOD removed would be oxidised and therefore less solids would accumulate.

2. Reducing the temperature from 20°C to 5°C caused an immediate and marked reduction in the rate of oxidation as indicated by the CO_2 output. The rate of oxidation only recovered after the temperature was raised again to 20°C.

3. Reducing the temperature from 20°C to 5°C caused a less marked immediate effect on the BOD removal rate. This however declined further as the solids accumulated.

4. The reduced BOD removal efficiency at low temperatures is at least partly due to the increase in the accumulated solids in the filter.

5. Conclusions (2) and (3) above supports the suggested explanation of the mechanism (1c) of solids control involving the differential rate of BOD removal and oxidation.

6. At 20°C in the presence of a population of *Pyschoda* larvae the amount of solids was controlled at a more uniform and lower level by grazing activity than when controlled microbiologically.

7. At 5°C there was no effective grazing by *Psychoda* larvae and the solids increased at a rate similar to that in the absence of *Psychoda*.

8. There is evidence from the pattern of CO_2 output from the filters in relation to the dosing cycle that some of the applied organic matter is immediately oxidised by the micro-organisms. Another fraction may be stored and subsequently oxidised.

9. The above conclusions form the basis of a hypothesis to explain the seasonal fluctuations in the solids in filters in relation to temperature changes.

ACKNOWLEDGMENTS

This investigation was carried out as part of the research programme of the Department of Biological Sciences, University of Aston and the authors wish to acknowledge the use of the facilities of the University in carrying out the investigation and in preparing this report. The settled sewage for the experiments was kindly supplied by the former Upper Tame Main Drainage Authority.

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The above Paper was presented for discussion at a meeting of the West Midlands Branch held in Birmingham on 26 March 1975.

West Midlands Branch

DISCUSSION ON PAPER BY M. R. N. SHEPHARD, M.Sc., M.I.Biol. AND
H. A. HAWKES, M.Sc., F.I.Biol. (Fellow) entitled:

Laboratory Studies on the Effects of Temperature on the Accumulation of Solids in Biological Filters

This paper, which was published in Part 1 1976, of *Water Pollution Control,* pages 58-72, was discussed at a meeting of the West Midlands Branch held in Birmingham on 26 March 1975.

DR. E. B. PIKE (Water Research Centre, Stevenage Laboratory), opening the discussion, noted that the work described by the authors represented a continuation of research into the performance and biology of biological filters, which could be traced back to the classical studies at Minworth started over 35 years ago. The development of this work would surely make a fascinating historical record. Even so, the authors had noted that there was still speculation over the reasons for the well-known seasonal fluctuations in the accumulation of film within biological filters, and whether this was attributable to seasonal effects upon grazing activity, differential microbial activity, or even to physical factors. Dr. Pike produced a time-series analysis of weekly records, extending over four years for a high-rate experimental filter[1] (Filter 30; basalt medium, 75–125 mm) in which three trends in the degree of removal of BOD were discernible: a progressive decline in performance, the yearly seasonal cycle in which removal was least in the winter, and smaller regular short-term cycles occurring about five-times yearly. This indicated the complexity of the biological filter as an ecosystem and that much careful experimentation was still needed to explain the mechanisms underlying performance. One had the choice of carrying out either carefully controlled experiments in the laboratory, often under rather artificial conditions, or more lengthy investigations of pilot or full-scale installations in which such factors as seasonal changes could not be controlled. The authors had taken the first course. Dr. Pike said that the paper contained excellent work; he had only a few queries for the authors but he thought that, as was usual in this field, the results gave rise to more speculations about the performance of biological filters.

He wondered whether the experimental periods were long enough, as Fig. 3 showed that film continued accumulating throughout Period 1. Adult *Psychoda* flies were introduced at the beginning of Period 4; Dr. Pike asked the authors whether they had considered the length of Period 4 in relation to the breeding cycle, which he had calculated as about 19 and 26 days respectively for *Psychoda alternata* and *P. severini* at 20°C.

He noted that, at 20°C, in the 'A' series of tubes, the mass of slime accumulated in Periods 4 – 6, when *Psychoda* were present, was about half that in Periods 1 – 3, when this species was absent. However, the removal of BOD was similar under both conditions, although the production of CO_2 was lower in Periods 4 – 6. These features posed questions about the behaviour of the ecosystem and he wondered whether the authors were able to relate the production of CO_2 to the removal of BOD, and whether they had measured the rate of production of humus sludge. The data would suggest that the presence of *Psychoda* had approximately doubled the specific growth rate of the sludge biota, if the rate of production of humus solids had remained unaltered. Dr. Pike asked whether this had been the case. The lower production of CO_2 in the presence of *Psychoda* – but with the same removal of BOD – suggested either that there was a greater rate of production of slime at the expense of respiration, or that incompletely oxidized metabolites such as fatty acids were being produced. He wondered whether the data could permit analysis for carbon balance to explain these features. The latter alternative was not in agreement with the observed lower accumulation of film or with the results of work by Solbè and others[2], which showed that the presence of macrofauna suppressed production of volatile fatty acids. Solbè and Tozer[3] had calculated that the respiration of macrofauna accounted for only 4 per cent of the total dissipation of carbon in a pilot-scale filter.

Dr. Pike commented that the facility for measuring the concentration of CO_2 in the stream of effluent gas was a sensitive and valuable indicator of respiratory activity in the filters. The results were not unexpected and several conclusions could be drawn. The immediate response to dosing (Figs. 7-12) showed that the microbial population was adapted to the substrate in the feed and that respiration was controlled by the level of substrate, so that the filters were not overloaded in the conventional sense. The immediacy of response also indicated that oxidation of the waste was concurrent with adsorption of wastes on the microbial film. Dr. Pike thought that the measurement of CO_2 evolution would also enable the effects of dosing frequency on respiration to be measured in the laboratory.

MR. A. D. WHEATLEY (University of Aston), referring to Dr. Pike's remarks on solids, commented that since sewage was a heterogeneous mixture one might expect a whole range of processes to occur in a biological filter associated with the removal of organic matter. On the simplest level, for example, it might be expected that the soluble organic matter would be more readily available for assimilation. His own work at Langley, in common with that of others elsewhere, did seem to indicate much better removal of the purely soluble component. His first question was, therefore, whether the effluent SS had been measured and if so, whether there was any evidence that the loss in efficiency at lower temperatures was due to poor removal of solids, possibly following a lag phase as the filter became saturated with solids. His second question was whether the build-up of organic matter was due to the presence of fungi, as had so often been shown in the past. Finally, he asked whether or not it was possible to quantify the number of *Psychoda* in relation to their influence on the organic matter within the filter; what, for example, was the difference in numbers of *Psychoda* larvae between A and B in the second phase of the experiments.

MR. H. H. HOPPER (Upper Trent Division, Severn-Trent WA) asked why polythene spheres of 20 mm diameter had been chosen for the medium. What influence would this have on the retention of solids when compared with the larger medium as normally used on full-scale plants? In a full-scale filter at winter temperatures, a relatively large amount of the solids consisted of slowly decomposing sludge, that is, organic matter adsorbed but not oxidized. The proportion of sludge to film increased with time as long as low temperatures prevailed (Fig. 4). Under these circumstances would it be correct to assume that both aerobic and anaerobic conditions existed? He pointed out that if this was the case two separate substrates would be involved, the film and the sludge, and he asked if this would lead to errors in monitoring respiration by measuring CO_2 output taking oxygen uptake into consideration.

MR. T. H. KIRBY (Mander, Raikes and Marshall) drew attention to the practical applications of the work reported in the paper having regard to the design of low-rate biological filters. He observed that the accumulation of solids in a filter had been shown to be proportional to the temperature and he enquired if it would not be reasonable to specify a finer grade medium for filters constructed in warm climates than for those in cooler areas of the world.

MR. R. CROWTHER (Upper Tame Division, Severn-Trent WA) said that there appeared to be a tendency for the micro-organisms to produce biomass rather than carry out bio-oxidation when the temperature was reduced. Was it possible that the enzymes involved with growth were less temperature-dependent than those involved in bio-oxidation. A quick survey of the literature seemed to indicate that this might be so. Ingraham[4] quoted the following data obtained by Dorn and Rahn:

	Optimum temperature °C	
	Streptococcus lactis	*Streptococcus thermophilus*
Multiplication rate	34	37
Population density	25–30	37
Fermentation rate	40	47
Acid production	30	37

If this phenomenon was also found in the bacteria of the filter bed then the lowering of the temperature might indeed give rise to higher population densities. Ingraham also discussed briefly the biochemistry of 'psychrophilic' bacteria. Some of the organisms commonly found in filter slime, such as species of *Acaligenes, Flavobacterium, Pseudomonas* and *Achromobacter*, possessed the ability to grow at low temperatures. The present concept of filter slime was as a biochemical 'soup'. Viable cells formed only a small part of the slime. Ingraham had shown that the enzymes only functioned at low temperatures when the cell was intact. Mr. Crowther suggested that it would be interesting to determine whether the biochemical 'soup' contained sufficient intact cells to function at low temperatures or whether the low temperatures demanded a larger number of viable bacteria in the slime. If the latter was correct then it might be a cause of the increased biomass.

MR. R. W. MARTIN (Tame Division, Severn-Trent WA) said that it had been observed that in a high-rate filter using a plastic medium large quantities of film accumulated. This was largely of a bacterial nature with only small numbers of flagellates, ciliates and nematodes. The grazing fauna normally associated with such filter beds appeared to be restricted to a few Enchytraeid worms, together with *Psychoda*, which had been seen floating on the surface in the humus tanks. He asked how this related to conditions in a normal stone filter bed.

MR. N. BOOTH (Imperial College) presented some results obtained in further studies on the apparatus but

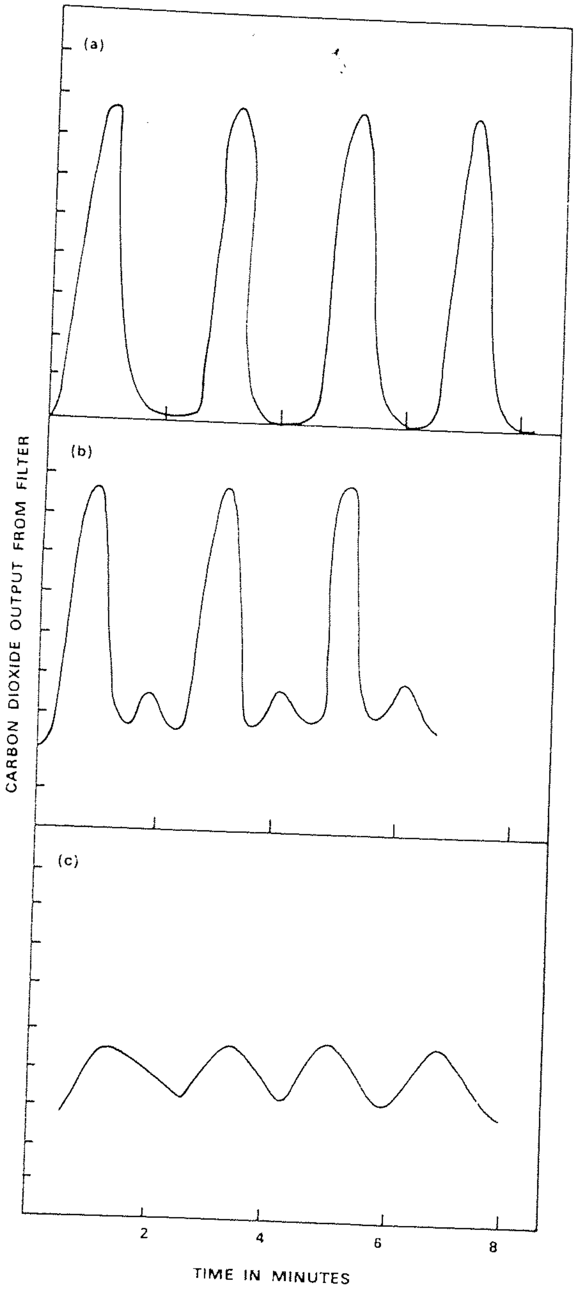

Fig. 13. Fluctuations in the CO_2 output from filters in relation to frequency of dosing with settled sewage.

(a) Clean filter without film.

(b) Filter with film developed.

(c) As (b) but with CO_2 due to scrubbing from feed liquor eliminated.

with modified filters. The filters were operated at approximately one-third of the loading used by the authors and on a two-minute or ten-minute cycle, and were not maintained at a constant temperature. The amount of CO_2 produced was therefore less than that recorded by the authors. He said that his results were in agreement with those presented in the paper, except that the shapes of the traces from the print-out were more variable, depending on operating conditions. In further tests with a clean sterile filter with no film development, with tap water or with sterile waste-water no CO_2 was evolved. With waste water large regular peaks were produced but the basic rate of CO_2 output was minimal (Fig. 13a). This suggested that the peaks were due to the respiration of organisms in the waste water and the scrubbing out of CO_2 from that dissolved in the feed. The filter was then matured and a further set of tests was carried out. These showed that the basic level of CO_2 had risen and the peaks had a characteristic double-hump shape (Fig. 13b). The double-hump peaks were only obtained when short lengths of tubing carried the exhaust gases to the infra-red gas analyser, probably because of mixing in longer tubes. Using an identical but sterile filter as a blank and by passing the exhaust gas through the reference tube of the gas analyser, the true respiratory activity of the film in the matured filter was indicated. This showed that, although the basic level of CO_2 was unchanged, the peaks were now single and of the same order of size as the smaller of the double-hump peaks (Fig. 13c). It would appear, therefore, that of the two humps of the peaks, one represented the CO_2 scrubbed out physically and the second the respiratory activity of the film. It was possible, however, that the second hump could have resulted from the accumulation of CO_2 within the filter being displaced by successive doses of feed liquor.

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REPLY TO DISCUSSION

MR. HAWKES (Aston University), replying to the discussion, thanked the contributors; one advantage of presenting research papers to Branch meetings of the Institute was that one got one's results and conclusions discussed. This was most valuable in influencing further research and partly made up for not receiving reprints of the paper, which all researchers would appreciate.

In reply to Dr. Pike, it was agreed that ideally the individual periods should have been of longer duration especially those with *Psychoda* present. The duration was, however, influenced by the duration of the student's research programme. Carbon balance on filters was a simple and theoretical concept but difficult to achieve in practice. Initially it was hoped to attempt a balance, and provision was made for the collection of humus solids. Not all the synthesized organic matter produced in the filter left the filter as particulate humus solids; some would be in solution. With the limited resources available (there was no service analytical laboratory) it was decided to develop the work as a comparative study. The CO_2 output for the filter was found to be related to the amount of film present, hence a lower CO_2 output in the presence of *Psychoda*. The respiration rate of the film, however, would be proportional to the CO_2 output per unit weight of film.

In reply to Mr. Wheatley, the SS in the effluent were not measured regularly. Since the solids discharged from a filter were not necessarily those applied, much of the humus having been synthesized, it was not possible without labelling the solids in the feed, to measure the amount removed.

Since the filters were being used to measure by weight the rate of film accumulation, they were not disturbed by sampling the medium, but if fungi occurred they did not form excessive growths and the filters never ponded. For some reason the population of *Psychoda* larvae was not measured.

Replying to Mr. Hopper, it was explained that in order to measure increments in the weight of film by weighing the whole filter, a light filter was advantageous and plastic spheres had been chosen as medium for this reason. The sewage trickled on to the filter and thus the flushing action, present in a full-scale filter, was not significant and as a result solids accumulated. The spheres were in fact roughened by shaking with sand before use. With a thick film, anaerobic conditions probably existed in the filter. Anaerobic respiration using the sludge as substrate would, however, produce CO_2 so that by measuring the CO_2 output from the filter the overall respiratory activity (breakdown of organic matter) would be measured.

The authors considered that Mr. Kirby had interpreted the results correctly in deducing that under the same loading conditions, smaller media could be used in the warmer climates, with consequent improved efficiency.

Mr. Crowther had put forward an interesting hypothesis that enzymes involved in growth were less temperature dependent than those responsible for bio-oxidation. However, presumably biosynthesis could not occur without bio-oxidation and hence growth would be affected.

High-rate filters with plastic media, referred to by Mr. Martin, usually had a restricted macro-grazing fauna and, because of their heavy loading, they usually carried heavy growths of film. In contrast to conventional filters they were probably less dependent on grazing fauna for controlling the film.

Mr. Hawkes commented that the further information provided by Mr. Booth, which was the outcome of his M.Sc. course project at Aston, threw further light on the phenomenon. It was evident that there were two components of CO_2 output, one of which was the CO_2 scrubbed out of the feed dose. The remaining component probably represented surges in metabolic activity of the film on receiving a dose of feed, but he agreed with Mr. Booth that it could also be due to the displacement of interstitial CO_2 accumulated from respiratory activity of the film. Considering, however, that the filters were force ventilated, this component would not be expected to be great.