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pp 288

PROCESS RATES WITHIN SLOW SAND FILTERS

by

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ABSTRACT

In order to predict the efficiency with which an organic material may be biodegraded in slow sand filtration, and to conduct the fundamental study of headloss development and turbidity penetration, so as to be able to uprate the slow sand filter, a study is made on the biological and clarification kinetics and aspects of uprating. It is seen that the effect of dominant biological purification in slow sand filtration as contrasted to the dominant physical, hydrodynamic and surface chemical clarification in rapid sand filtration, is not adequately described in the present kinetics and formulations.

An investigation has been conducted on 10 mg/l phenol solution flowing through a bed of builders sand. Two pilot slow sand filters (each measuring 3.20 x 1.83m) at a waterworks near London, were adapted, to monitor pressure within the bed, and with taps to obtain isokinetic samples of water at eight levels through the depth of each filter. The primary filtrate available on the works was used as influent, with the inflow controlled by an overflow and automatic flow controllers and the outflow by an orifice plate and a control valve. Phenol concentration was determined by the Aminoantipyrine Chloroform Extraction Method as modified by the Metropolitan Water Board, sensitive down to values of 1 μg/o. Turbidity was read on a Hach Turbidimeter, reading down to 0.01 FTU.

From these experiments an empiric correlation has been developed between the level of biodegradation and operating parameters based on three regimes of varying degree of degradation in slow sand filtration. The work has shown overwhelming phenol removal in schmutzdecke and the top 5cm of the bed (87% of residual) and considerable phenol degradation throughout the 0.5m bed (46% of residual), especially in the middle of the run, down to a total of over 99%. Phenol shortened the run length from 6 weeks to 2 weeks. There is evidence of significant phenol production, presumably from aquatic plants, in the control filter and in unused test filter, averaging 5 to 200 μg/l. Headloss increased exponentially, almost entirely occurring in the top layer of the filter. In the rest of the filter headloss developed during the first half run

recovers during the second half. Turbidity removal takes place throughout the bed. The slow sand filter could be operated at 0.2 m/h if adequately conditioned influent is used.

The application of the slow sand filter in rural communities of developing countries and in the metropolitan cities of industrialised countries has been discussed after an extensive review of the relevant scientific and technical literature.

To The Memory of

Gauran Devi

My inspiring mother who left for heavenly abode while I was pursuing this study abroad.

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CONTENTS

LIST OF PLATES, TABLES AND GRAPHS

CHAPTER 1

INTRODUCTION AND HISTORICAL DEVELOPMENT

1.1 Introduction

Filtration for public water supplies has been in use for some one and a half centuries. In the USA, since the beginning of this century, the emphasis has been solely towards the development of rapid sand filters, but in Europe, Britain and India, attention has been paid to the development of both slow and rapid sand filtration. In spite of water being so important in society's life, the development of the filtration process has proceeded slowly, usually by trial and error innovations, with a poor understanding of the filtration mechanisms. In more recent years, theoretical and experimental studies on the rapid sand filtration have shown it to be a dynamic, complex process, relating the particulate removal phenomenon with depth in the rapid filter and time of operation. On the other hand, the dual media or multi-media rapid filters have been developed, to lengthen the rapid filter runs, because the bulk of the particulate matter is removed in the upper layers of fine sand, leaving the lower layers to function principally as a support for the finer sand, which can be regarded as inefficient situation. In a slow sand filter it is even more true that the top layer of fine sand along with the schmutzdecke removes much of the particulate matter and therefore the lower layers could be considered ineffective. But the dominant mechanism of biological purification in a slow sand filter is altogether different to the physical mechanisms in rapid filtration. It should be possible to make use of this phenomenon for the removal of fine turbidity and degradation of dissolved organic substances in the depth of the slow sand filter. Moreover, it has been a continued objective to reduce land requirements, by uprating the slow sand filter providing no adverse effect on the filtrate occurs.

The long held assumption of the perfect safety of the filtrate from the combination: coagulation, rapid filtration and chlorination received a severe jolt after the 1955 Infectious Hepatitis epidemic in Delhi, which put the effectiveness of rapid filters in doubt. The search for

processes, better for bacteria removal, created new interest in slow sand filters, and brought them into focus for research and use.

Slow sand filtration is reliable, compact and simple in design and operation. It has been suggested as a panacea to the water supply problems in villages of India. World Health Organisation favours the use of these filters in rural areas of developing countries to overcome the drawbacks of illiteracy and backwardness. Modern conditions dictate the use of natural resources with consideration and discrimination, and it will be difficult to match the slow sand filters when it comes to the conservation of resources. In industrialised countries, the optimisation of surface water sources, results in heavy introduction of industrial and organic pollution into them. Slow sand filters can deal with such impurities more effectively, if any are encountered in the raw water. Moreover, in affluent cities, the greater economic prosperity and more social amenities call for an increasing standard of water quality, for which the community is prepared to pay the price. In such circumstances it is possible to obtain drinking water of an extremely high degree of purity and aesthetic quality by the use of slow sand filters as secondary filters, by making use of their unique biological purification mechanism. It may be emphasised that when choosing treatment methods for new supplies, based on reliability, simplicity, conservation of resources, high standard of quality and economy, it may be more readily attainable through the use of slow sand filters than through any other comparable method. Therefore, it is puzzling why the oldest and the most scientific and versatile method of filtration is one of the least understood and only a little scientific research has been carried out into it. It looks paradoxical that rich countries have shown reluctance in adopting it because it is allegedly costlier and the developing countries have so far failed to sieze the imagination of using it widely, because it is not modern.

Some recent experimental work on slow sand filtration has been carried out by the Metropolitan Water Board of London (Windle Taylor 1971-73), and at Zurich and St. Gallen (Schalenkamp 1971).

These experiments indicate the advantages of biological purification of slow sand filtration, and the possibility of increasing the slow sand filtration rate by using an adequately conditioned influent.

The aims of the proposed research are, (1) to study the headloss development, and the turbidity penetration in a slow sand filter, (2) to study the degradation of an organic-rich influent, (3) to develop a mathematical model for the degradation of an organic solution in a slow sand filter, and (4) to find out the impact of these studies on the possibility of uprating slow sand filtration.

1.2 Water Supply Development in India

The importance of an adequate water supply had been recognised, at the early stage of the start of the Five Year Plans, even though there were overwhelming constraints due to the priorities of industry, agriculture, population control and defence. The following table shows the financial plans for the development of water supply and sewerage.

TABLE 1.2.1

S. No. of 5 Year Plans	Million Rupees	Million Pound Sterling
1 (1951 - 1956)	490	26
2 (1956 - 1961)	760	41
3 (1961 - 1966)	1,053	57
4 (1969 - 1974)	3,730	200

In India 88% and 95% population is yet to be served with piped water supply, and sewerage, respectively, (CPHERI, 1971). In rural India where 83% of the population abides, only 22 million out of 438 million are served with piped water supply (Mohanrao, 1971). According to an estimate the mortality incidence due to enteric diseases, (typhoid, dysentry etc.), is 360 per 100,000 population (Dietrich and Henderson, 1963), which can be accounted for by inadequate water supply and sewerage facilities. The amount of money involved in supplying safe water to the entire rural population is Rs 9000 million, and water supply and sewerage to the rest of urban population is Rs 10,000 million (Roy, 1973).

In 1972 the twenty-fifth World Health Assembly endorsed the targets for community water supplies in the developing countries for the Second United Nations Development Decade (1970 - 1980) as follows:-

In urban areas 60% of the population to be served by house connections and the remaining 40% by public standposts.

In rural communities 25% of the population to have reasonable access to safe water.

Based on the past trend (1962 - 70) it can be said with certainty that the Development Decade II target for house connections in urban sector will be fully met. Based on the financial allocations during period 1970 - 74, which is roughly three times that of the last Development Decade, the DD II

target for public stand posts in urban sector will also be largely met. But the 1970 - 74 investment level will be insufficient to meet DD II target in the rural sector of India. Recently, about the targets for rural areas a similar observation has been commented by Pineo and Subrahmanyam (1975).

1.3 Historical Development

Twenty five centuries ago, Tirthankar Mahavira (in India) ordained his ever travelling Bhickshus (lecturers) never to drink unconditioned water, to protect them from the ill effects of varying qualities of water, and advocated the use of certain carbon, charcoal and ash, for treating the water. Baker (1949) has quoted Sushrut Sanghita, describing the usefulness of copper stored water, and sand filtration. It was James Peacock who first conceived the usefulness of filtration for public use, and patented it in 1791 (Skeat, 1969). John Gibb in 1804 built an experimental filter at Paisley (Scotland), and sold the surplus water. James Simpson at the age of 28, after experimenting for over a year, designed the first permanent filter in 1829, for Chelsea in London.

During those days filtration was considered a means of straining out suspended material causing turbidity, and pathogenic bacteria was unknown. The first regular water examination was initiated in 1858 in London, which later in 1885 also included the bacteriological examination, after the discoveries of Pasteur, Koch and Escherich.

By 1892, filtration became established, and its construction started in many countries. By 1870, the pressure type mechanical filters came in use and the first mechanical filters were installed in the USA in 1885. It was in 1892 that the convincing proof of the effectiveness of water filtration was provided by the experience of two cities; Hamburg and Altona, both situated on the River Elbe. Hamburg delivered settled unfiltered water, suffered a cholera epidemic and lost 7,500 lives, while the downstream Altona, supplying filtered water, escaped almost unscathed.

The first decade of this century saw the construction of many rapid gravity filters; Candy pressure filter in 1900, Jewell machanical rapid gravity filter in 1901, and Paterson in 1910. Glenfield and Kennedy in 1945, introduced the microstrainer for plankton removal. Since then many improvements have been introduced, mostly related to the reduced land requirement rather than to the water quality.

It was pointed out recently in the Loughborough Conference (Jain 1973),

that little research had been done in slow sand filtration. The only exception was the Metropolitan Water Board. The first major thrust towards uprating was achieved by the introduction of primary rapid filters in London, which made slow sand filtration possible at rates up to 0.15 m/h. (Ridley, 1967). Coppermills works have recently worked at 0.2 m/h (Turner 1974). There are notable advances in the in situ cleaning (Lavel et al, 1952, Burman et al 1961) and the mechanical cleaning (Lewin 1961). These have been critically discussed by Ives (1971) and Skeat (ed. 1969).

Even today the performance of the biological or slow sand filter in producing high quality water has not been surpassed, (Huisman 1974). No wonder that many of the major cities in the industrialised countries use slow sand filters and are continuing to build them, as it produces better quality water than chemical coagulation (Allen 1973). For example, Amsterdam, Antwerp, London, Paris, Springfield (Massachussets), Zurich, and various cities in Sweden and Japan. The biggest harbour in the world, Rotterdam, uses slow sand filters as an essential part of the drinking water treatment system (Van Damme 1973). The latest are Coppermills slow sand filtration works, inaugurated in 1972, in London's Lee Valley, of a capacity of 490 million litres a day, operated by computerised remote control, (Turner, 1974).

CHAPTER II

OPERATIONAL ASPECTS OF A SLOW SAND FILTER

2.1 Operational Description

A slow sand filter consists of:-

(a) A filter tank for maintaining a constant head of water above the filter medium, to cause pressure to make the filter to flow.

(b) A bed of sand supported on gravels.

(c) An under drainage system for supporting the filter medium, and causing least headloss to filtered water.

(d) A system of control valves, to regulate the rate of filtration and to measure the rate, to monitor the headloss in the bed, and for recharging after cleaning at the end of the run.

The open filter tank contains overlying water to be filtered, the sand bed and the under drainage system. The controls are located in the adjacent chamber. The rectangular filter tanks are 2.5 m to 4 m deep, 0.3 to 0.4 hectare in area and built wholly or partly underground. The walls are made of brick, stone or concrete, and the under drainage of porous concrete, porous unjointed pipes or tiles, supporting the sand bed over a layer of about 0.2 m or less gravel. The sand bed is 0.6 to 1.2 m deep, and the depth of supernatant water is 1 - 1.5 m.

The two greatest assets of a slow sand filter are, its biological purification, and its simplicity. Once constructed on sound engineering design, there is little that can go wrong, while following the simple routine operation. The operation is determined by the filtration rate, controlled and measured at the filtrate outlet. An automatic control valve in the inlet chamber adjusts the constant head of water in the filter tank, supplied by a storage pond, under gravity or through a pump. The constant head in the filter tank assists efficient scum removal due to constant level overflow outlets and checks diminishing output or excessive raw water overflow wastage. The filtration rate (explained in section 2.2) is controlled by the regulating valve on the outlet pipe, which is closed partially in the beginning of the run, and opened proportionately to compensate for the headloss build up in the bed due to clogging. In the early stages of the filter run, the daily headloss build up will be very

small, but in the later stage, it will necessitate a positive opening of the valve. To be able to measure the filtration rate, a venturi meter is installed on the outlet pipe, immediately before the control valve. In small installations, a very much cheaper device, in the form of manometer gauge is substituted, but it cannot measure the flow rate.

Excessive algal bloom in the raw water considerably shortens the filter run. This is dealt with in several ways. By the application of algicides, pretreatment by microstrainers or coarse rapid filters, cutting the sunlight by covering the filters, or by by-passing the turbid raw water into the filter tank. Chemical application as a permanent device is fraught with danger, as it could adversely affect the bacterial activity of the filter bed.

Dissolved oxygen content in the raw water is important to prevent anaerobic conditions due to the oxygen demand of bacteria in the bed. Some growth of algae in the raw water is conducive to oxygenation of water. Aeration of incoming water or recirculation of cascaded filtrate helps to prevent anaerobic conditions developing. There is no danger of the bed going anaerobic if the filtrate oxygen content does not fall below 3 mg/l. In large water works, sampling and analysis are carried out daily, but in small installations with two or three filters, an infrequent but regular analysis should be attempted. A simple ammonia test will reveal nitrification in the filter if ammonia is not detected in the filtrate, indicating depletion of oxygen. The significance of sand size, mechanisms, and the filter cleaning have been discussed later in sections 2.3, 2.4 and 2.5 respectively.

Vlaed (1955) and Ridley (1967) stressed the unsuitability of highly turbid waters for slow sand filters. For best results, Huisman quoted 10 mg/l for the average turbidity of influent water, even though short periods of 100 - 200 mg/l could be handled satisfactorily. The water from storage reservoirs in London has turbidity usually less than 10 mg/l, but the reason why this water is provided with primary rapid filters or microstrainers has been explained by Ridley in his paper (1967) for the sake of high concentration of algal cells, up to 10^7/l during short peaks of algal blooms.

The chemical coagulation before slow sand filtration has been generally considered undesirable, due to the finer flocs clogging the filter and reducing the run. There is also danger of the aluminium hydroxide precipitating in the lower layers, due to low PH caused by alum dosing (Ives 1957).

To eliminate taste or odours from an influent water, activated carbon is applied to the inlets of the slow sand filter. The powdered carbon which

settles on the bed surface, adsorbs the offensive compounds. Carbon should not be added as a routine as it shortens the run and reduces the photosynthesis in the schmutzdecke. Sometimes carbon powder might be separated from the sand during washing of the scraped material, if not mixed with the dirt.

2.2 Filtration Rate

Rate of filtration can be regarded as the second most discussed topic in filtration, after the fundamental understanding of the processes of purification. It is of significance in slow sand filtration, because of its direct effect on the residence time of the influent water in the filter, which contributes to the biological purification. Two important rates of filtration are, the natural rate of filtration underground which is nearly 0.05 m/h, and the traditional rate of slow sand filtration, mentioned in text books for design purposes, as 0.1 m/h (2 Imp gall/sft/h).

Recently Huisman (1974) has written 0.1 to 0.4 m/h, as the design rate of slow sand filtration. It appears the upper limit is based more on favourable speculation rather than on any existing practice or mature experience. In view of the potential of economising for large installations it is suggested that a pilot scale study extending over a year to include seasonal and climatic effects should be worthwhile. In the S.W.T.E. 1967 Symposium, based upon his experience in the Metropolitan Water Board, Ridley gave filtration rates of about 0.05 m/h for slow sand filters acting alone, and about 0.15 m/h where preliminary treatment was provided. Too high a velocity of flow can cause a breakthrough of organic matter into the effluent (Huisman 1974) which suggests the usefulness of organic-rich influents in studies of uprating.

In the middle of the last century, slow sand filters are reported to have operated satisfactorily on untreated surface English waters at the rate of 0.1 to .3 m/h (.04 to .12 Amer galls min./ft^2) (Weber 1972). If that was the case, then there is hardly any advancement on uprating, because (except Coppermills) all filter works in London operate at .07 to .13 m/h, using influent from primary rapid filters and storage reservoirs.

In rapid filtration, straining is mostly independent of the rate of filtration, there is little influence on inpore sedimentation as only fine particles 4 - 20 micron size are involved, adsorption also is influenced little, and turbidity-wise there is not much deterioration of effluent. In slow sand filtration, uprating has to be considered carefully, as the biological activity there is very much time dependent. The purifying

micro-organisms in the first instance are present only in the top 30 - 40 cm, but the increased filtration rate carries their food deeper in the bed and the purifying organisms adapt themselves there. But due to lack of oxygen and enough food, the bacteria establishment is only limited. This results in impaired influent purification. Vloed reported (1955) that full rate must not be applied to a clean slow sand filter, it should be stepped up from about 0.02 m/h, and increased to full rate in about a day, depending upon the temperature and the season.

Too low velocities, less than 0.05 m/h, on the other hand can cause taste due to decomposition of algae (Ridley, 1967, and Huisman 1974). Algae are reported sometimes to give leached out oil as a metabolic product (Steel 1960).

The slow sand filter is sensitive to the filtration rate and raw water quality, as the food in the influent water is vital for the degrading organisms. Therefore, uniformity in the rate and influent quality are conducive to optimisation. To achieve this, it is usual to maintain a constant raw water head, and regulate the rate of filtration by adjusting the exit head to compensate for the clogging, controlled and measured by a venturi meter.

2.3 Sand Sizes

The size of the sand has bearing on the length of the run, the grain surface area, the initial headloss, and slightly on the rate of filtration. The grain size is described in several ways. The most common being, in terms of effective size (de) and the uniformity coefficient (U). The concept of effective size was introduced by Hazen (1892) and defined as the sieve size in mm through which 10% of the sample will pass by weight. The coefficient of uniformity is the ratio d60/de, where d60 is the corresponding sieve size in mm through which 60% of the sample by weight will pass. In rapid filters a uniform sand is essential to save it from stratification when backwashed, but a slow sand filter is free from this drawback, and expense on sieving can be reduced. For the sake of porosity and regularity in pore size, sand with U between 3 and 1.5 is satisfactory. However, de is of great significance in a slow sand filter. As the slow sand filter is not backwashed, permanent permeability of the bed is necessary, and deep silt penetration is undesirable, therefore, a finer sand is always used. The desirable values of de as enunciated by the several authors are shown in the following table.

TABLE 2.3.1

S.N.O.	Author	Prescribed de mm
1	Huisman, 1974	0.15 - 0.35
2	Holden, 1970	0.2 - 0.5
3	Skeat, 1969	0.3
4	M.W.B. 1966 - 67	0.3
5	Fair, Geyer and Okun 1959	0.25 - 0.3 - 0.35
6	Vlood, 1955	0.25 - 0.35

Theoretically, in a slow sand filter bed, the best de is that which does not permit penetration of those suspensions which are not degraded by the bacteria, below the top 2 cm. In practice, both finer and coarser than the de generally recommended, have been found to work satisfactorily. A higher uniformity can be achieved by mixing two or more types of stock sands (Huisman, 1974). A finer sand is useful for improving straining through smaller pore openings, the larger surface area of smaller grains will enhance inpore sedimentation and adsorption, and it will be substantially conducive to the growth of the biological film on grain surfaces improving the filtrate further. It is more economical to use finer sand with less depth, than to adopt coarse sand with deeper bed, to achieve the same grain surface area, which is (6/de) (1 - f) square metres per m^3. Thus filtrate quality is significantly affected by the grain size.

The Metropolitan Water Board generally uses a sand of 0.25 mm de. It appears that the tendency is more towards using finer sand. Finer sand is necessary to check silt penetration going deep into filters, which is likely to happen when primary rapid sand filtrate is filtered through secondary slow sand filters at higher rates.

2.4 Mechanisms of Filtration

Mechanisms of biological purification are described in Chapter 3. In this section mechanisms of filtration, which partly deal with slow sand filters but largely deal with rapid sand filters are described. In fact, purification clarifications mechanisms are complex, and in practice, there is no clear cut division between various stages, as these interact with each other in most cases.

Transport Mechanisms

Van de Vloed (1955) had attempted to explain the rapid filtration mechanisms largely in terms of surface energy. Cleasby and Baumann (1962) demonstrated that the flow in the filter pores, washed or clogged, is laminar. Mints (1966), showed pictures to prove that particles smaller than pores are removed during filtration. He stressed sedimentation as the transport mechanism, even though mechanical straining and chance contact were mentioned. It was Ives in the I.W.S.A. 1969 Vienna Congress, and Ives and Gregory in the S.W.T.E. 1967 London Symposium, who presented and elaborated the several transport and attachment mechanisms; which advanced the understanding of rapid water filtration. The several mechanisms can be listed as (a) straining, (b) sedimentation, (c) inertia, (d) interception, (e) diffusion, and (f) hydrodynamic.

Straining

It is the dominant process for the retention of particles too large to pass through the pores. It is largely independent of the filtration rate, and takes place at the bed surface. As is clear from the Fig. 2.4.1., the pore size within a tightly packed bed of spherical uniform sized sand grains is about 1/7 of the diameter of the grain. Considering 0.3 mm de of a normal slow sand media, the smallest pore size is about 43 m, which is not capable of intercepting colloids (1 m or less) or bacteria (length usually 1 m, but up to 15 m). Within the bed, small particles agglomerate by striking each other, while travelling the tortuous routes, and are retained by the straining mechanism, whenever they become large enough. The schmutzdecke in a slow sand filter assists in straining mechanism, but this is accompanied by increasing headloss, and ultimately a stage is reached when the bed needs cleaning.

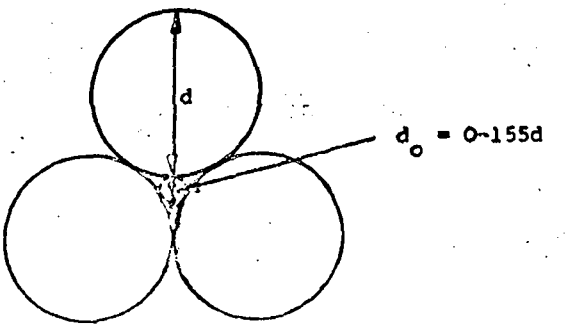


Fig. 2.4.1. (Huisman, 1974) Relation between grain size and pore size.

Sedimentation

In-pore settling of suspension in connection with the slow sand filter was suggested by Hazen (1904), followed by Vlced (1955), mentioned by Mints (1966), and further investigated (Ives, 1960) and elaborated by Ives (1967 and 1969), by visual demonstration of particles collecting as caps on the tops of grains, even in up flow filtration. Hazen has explained the removal of particles smaller than the pore size as analogous to sedimentation in a basin filled with a very large number of trays. In this connection considering a cubic metre of spherical sand grains of 0.3 mm diameter, 40% porosity, the number of grains will be $0.6 \times 10^6 / [(\pi/6) \times 27 \times 10^{-6}] = 42.4 \times 10^9$ with a gross surface area of $42.4 \times 10^9 \times \pi \times 9 \times 10^{-4} \times 10^{-2} = 12{,}700\ m^2$. Assuming 1/6 of the area to be horizontal facing upwards, ½ in contact with other sand grains, and 1/3 of the remainder exposed to scour, the effective surface area of an equivalent settling basin would be $(1/6 \times ½ \times 2/3) = 1/18 \times 12{,}700 = 700\ m^2$.

Effective settling area in 1 m^3 is 700 m^2.

Filtration rate (approach velocity, Vf) = 0.2 m^3/m^2 h.

So for 1 m^3, flow rate is 0.2 m^3/h per m depth.

In terms of effective settling area, over flow rate is therefore

$\frac{0.2}{700}$ m^3/m^2 h

Using Stokes formula, u, the settling velocity is

$$u = \frac{1}{18} \frac{g}{\nu} \frac{\Delta\rho}{\rho} e^2 \qquad 2.4.1$$

where e = particle diameter

ρ = density of water

$\rho + \Delta\rho$ = density of suspended matter

g = accoleration due to gravity (9.81 m/s^2)

ν = kinematic viscosity of the fluid

For water at 10 °C, $\nu = 1.31 \times 10^{-6}\ m^2/s$, and the equation becomes

$$u = \frac{9.81 \times .01}{18 \times 1.31 \times 10^{-6}} e^2\ m/s$$

$$= 0.416 \times 10^4\ e^2\ m/s$$

Also, $u = \frac{0.2}{700 \times 3600}$ m/s

Therefore, $e^2 = \frac{0.2}{700 \times 3600 \times 0.416 \times 10^4}$ m^2

$= \frac{0.2 \times 10^{-10}}{7 \times 0.36 \times 0.416}$ m^2

$= 0.19 \times 10^{-10}$ m^2

$= 19 \times 10^{-12}$ m^2

$e = 4.36 \times 10^{-6}$ m or 4.36 μm

Smaller and lighter particles will be only partially removed.

Vloed (1955) was highly appreciative of the large surface area of finer grains, that is available in a slow sand filter, but his stress was confined more to the surface energy rather than to sedimentation.

Inertia

When a suspended particle has specific gravity higher than that of water, the particle maintains a trajectory which causes it to collide with the grain as shown in Fig. 2.4.2. The inertial action has been calculated by Ives (1960) as a dimensionless product.

$$n = \frac{\rho_s e^2 V_p}{18 \mu D} \qquad 2.4.2$$

where, ρ_s is the particle density
μ is the dynamic viscosity of the fluid.
e is the particle diameter
V_p is the approach velocity through pores.
D is the grain diameter.

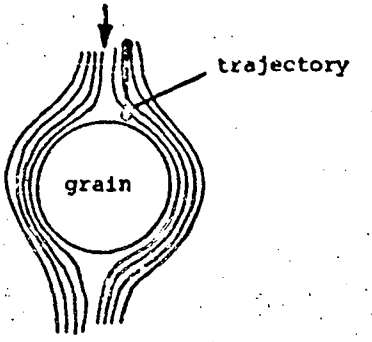


Fig. 2.4.2. Simplified diagram of particle transport by inertia.

Insignificant occurrence of the force of inertia in water filtration was also calculated by Yao (1968), and shown experimentally by Ison (1967) in an up flow filter. The phenomena has been recognised of significance in air filtration, but not in liquids.

Interception

Interception is applicable to smaller particles but is similar to straining, and also has application in air filtration. When a particle in a streamline approaches the grain surface within its own radius, the particle will just touch the grain surface and be intercepted by the grain. The concept was introduced to water filtration by Stein (1940), and investigated experimentally by Ison and Ives (1969), and Yao (1968), and enunciated as,

$$I = \frac{e}{D} \qquad 2.4.3$$

where I is the force of the interception
e is the particle diameter, and
D is the grain diameter.

Diffusion

Particles mainly smaller than 1 μm move at random in water, due to thermal energy of the water molecule; the motion known as Brownian movement. Thus the particles come in contact with the containing surface. Movement is not affected by the filtration rate or the depth of the filter. The mechanism is expressed in terms of the Peclet Number,

$$p = \frac{D\ Vp}{E} \qquad 2.4.4$$

where E is the Stokes-Einstein diffusion coefficient, expressed by Kt/3πμe, where K is Boltzmann's constant, t is absolute temperature, Therefore,

$$p = \frac{3\pi\mu eDVp}{Kt} \qquad 2.4.5$$

Hydrodynamic Action.

A spherical particle in a uniform liquid shear field, experiences a difference in drag on each side, resulting in the rotation of the particle, creating a spherical flow field. Due to the pressure difference in a direction lateral to the flow, the particle moves to the area of higher velocity, crossing the area of flow. The lateral force is complex and time dependent in a non uniform non stationary shear field as encountered in a filter bed consisting of interconnected pores of different sizes. Non spherical particles whose centre of mass and hydrodynamic centre do not coincide will experience out of balance forces and rotate at a non uniform rate and manner. Non spherical particles, as mostly encountered in deep bed filtration appear to adopt random drifting motion across the streamlines.

At University College London, Ison performed experiments to observe hydrodynamic drifts of particles, by keeping all other transport mechanisms negligible or constant and varying only the Reynolds Number for flow through the filter. The filtration efficiency changed presumably due to change in shear field configuration and flow pattern, brought about by the hydrodynamic effect of change in Reynolds' Number.

$$R = \frac{V_f D \rho}{\mu}$$

where R = approximate value of Reynolds' Number in water filtration -

V_f is the approach velocity

D is the grain size

In a recent detailed document devoted exclusively to the advanced study of the scientific basis of filtration, Ives (1975) has proposed four more Reynolds Numbers, involving shear gradient, velocity of the particle relative to the liquid, the angular velocity of a rotating particle, and the frequency of a pulsating fluid flow due to pore size sequence- in an effort to bring out the intrinsic dependence of the hydrodynamic transport mechanism on particle size.

Another aspect of the hydrodynamic phenomenon is the resistance felt by the particle during close approach to a pore wall, due to the fluid viscosity. This effect is really too small to affect the transport mechanism, but is worth considering when surface forces are affecting a particle.

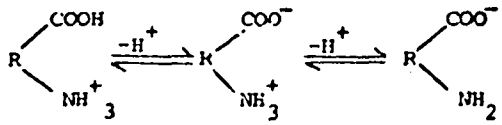
Attachment Mechanisms.

Attachment forces hold the particle in place, after they have made contact with the grain surface. These forces are a) electrostatic attraction, b) Van der Waal's force, and c) adsorption. Vlaed (1955) had treated surface forces as more of a single entity. Mints (1966) was able to differentiate between Van der Waals's forces, but a clearer exposition was made at the S.W.T.E. 1967 Symposium by Ives and Gregory (1967). Recently Gregory (1975) has provided a most comprehensive description of the electrical phenomena at interfaces, electrokinetic effects and the electrical interaction between particles.

Electrostatic Attraction.

The attractive force between two opposite charges is inversely proportional to the square of the distance between the charges. Various transport mechanisms help in the particle contacting the grain, then if the particle and the grain have opposite charges, the particle will be retained. However it will be repelled if the charges are the same, and the particle will continue on its course. Because of crystalline structure, clean quartz sand grain has a negative charge, it therefore attracts positively charged particles of colloidal matter as crystals of carbonates and flocs of alum and iron, and metallic cations.

Particles of biological origin in nature have a surface charge due to acidic or basic groups. Proteins with both types of groups present in them have a positive charge at low Ph and a negative charge at the raised Ph. At a characteristic Ph value there can be zero charge described by Gregory (1975) as



Bacteria and algae, are mostly negatively charged as they show the point of zero charge (pzc) in the acid region of Ph. Silica particles are negatively charged for all Ph above 2.2. Clay particles due to their crystalline structure have a negative charge in water. Particles and grains are repelled from each other in the beginning of the run, but during and immediately after the ripening of the filter, some grains due to accumulation of particles have a charge reversal and behave as positively charged grains, which attract negative particles. The reversal of charge process is continued in the life of the bed.

Ives and Gregory (1967) reported the sand potential low as -25 mv, and negligible electrical effects due to extremely small range of action and reported no validity in Vlood's statements that electrostatic forces can be effective up to 300μm from the grain surface.

Van der Waals' Forces.

This force is universally attractive. It has a minor effect in transport mechanism but is effective in holding particles on grains when the contact has been made. The force although powerful at a very short range, has only limited range of action being mostly less than 50 nm. The combined interaction has been dealt with by Gregory (1975) in detail. He has clearly explained combination of electrical repulsion and Van der Waals' attraction to give a total interaction with the help of diagram.

Adsorption.

This phenomena is significant in slow sand filters. During the ripening of

/the filter

organic particles held on the filter surface or on the grain surface are act upon by bacteria and other microorganisms, producing a gelatinous material kn as Zoogloea. This slimy film on the surface of the schmutzdecke and the grain surface, consists of bacteria, their metabolic products, including polysacchar and partly assimilated organic material. Particles from the raw water adhere to it during filtration, out of which organic particles are assimilated by the bacteria and the inorganic particles remain adhered to the film until the filter is cleaned.

2.5 Cleaning

Cleaning of the slow sand filter is a simpler affair. At the end of the run, based on the ultimate headloss, about 1.5 m, the overlying water is run down, and the suspended solids and colloidal matter deposited at the very top of bed are removed by scraping off the surface layer to a depth of 1 or 2 cm. This operation can be carried out by unskilled workers using hard tools, or by mechanical equipment as described later in this section. When a filter is cleaned in this manner, both dead and living algal material and the bacteria are also removed, and a ripening period is necessary before satisfactory level of bacteria in schmutzdecke reaches again to obtain a satisfactory bacterial quality of filtrate. Method and level of cleaning affects the length of the run. Total influent solids, higher filtration rates, finer grained media, and the periods of algal bloom, shorten the filter run. It is considered prudent to design and operate the filters in such a way that under the worst conditions, the length of run is never shorter than 2 weeks, otherwise it will affect cleaning costs and increase the length of the unreliable ripening period. After 20 - 30 cleanings, resanding may be required. Commonly it is more economical to use the same sand for resanding after washing, than to use the new sand. The scrapings must be stored immediately after washing the sand, otherwise the entrained organic matter will decompose, and the accompanying tastes and odours may be impossible to remove. One thing to be watched, while reusing the washed sand is that the de of the grain has not increased materially, due to loss of finer particles during washing. The practice followed a century ago, of returning the washed sand immediately to the bed, was abandoned, because the lower layers clogged persistently.

Mechanical Aids

The first fully mechanised system for cleaning the slow sand filters was developed by the Metropolitan Water Board in London (Lewin, 1961). Amsterdam, and Berlin also, are now using mechanical aids for this purpose, and cities in industrialised countries find it attractive to solve the manpower shortage by using mechanical aids. A portable conveyor belt is used to transfer the scraped sand from the bed, whence it is transported to the central washing site. To prevent compaction of the bed, modified light agricultural tracked vehicles are used for scraping the top, which allow the soil pressure not to exceed 33 K N/m^2. The skimming machines fitted with blades, scrape off the desired amount of sand to a preset depth of 1 to 3 cm. The scraped sand is carried to the rear by the

conveyor belt, and discharged into a following tractor dumper. Rake attachments fitted at the rear of the tractors, leave the filter bed surface in a level and finished condition, Considering the capital outlay on equipment, the saving in operational cost is not impressive, and the motorised vehicles on the beds carry a hazard of pollution from oil drippings.

Hydraulic Cleaning

By this method the slow sand filter cleaning has been approached in another way. Hydraulic cleaning systems have been installed at Paris (Laval, 1952), London (Lewin, 1961 and Burman et al, 1961), Antwerp, Istanbul and some other cities. Backwashing a slow sand filter is objectionable from two points of view. During backwashing the filter media may stratify to the disadvantage of operation and it is necessary to avoid excessive disturbance of the lower active layers.

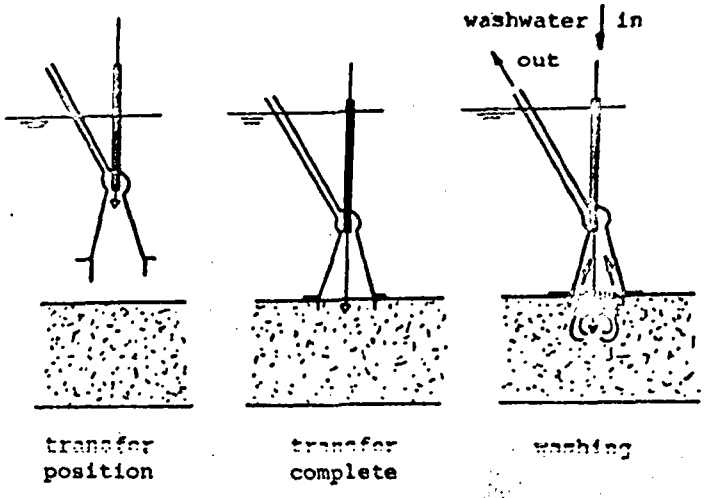


Fig. 2.5.1. In situ sandwashing, mode of operation

In the in situ filter cleaning, Fig. 2.5.1., the lances points pressed about 20 centimetres below the top of the bed, release water, which rises to the surface, dislodging the impurities and carrying them from the upper sand layer to the lower and upper chambers of caisson boxes. From there it is pumped out into the drain running along the filter. The cleaning advances in strips of 30 cm width and controlled by the adjustment of the box apertures and the suction pumps. Each strip is washed in about one minute, then the lances are withdrawn, boxes lifted and the gantry

moved further. If the schmutzdecke is too heavy or consists of the filamentous algae, then the surface mat is first raked mechanically by gantry attachements, before strip backwashing. Hydraulic cleaning can be said to be the quickest, as the filter does not need to be drained down. However, the equipment cost is high, and because of supporting structural requirements it cannot be used on existing filters. In addition there are some serious operational defects. During backwashing, due to separation of grains, finer grains are stratified on the top, which reduces permeability and shortens the filter run. Algae remaining in the overlying water cause accelerated clogging after the filter wash; also the impurities are carried deeper in the bed due to unavoidable uneven wash water distribution. Overall, it is not possible to regard the hydraulic cleaning a favourable method of filter cleaning.

CHAPTER III

BIOLOGICAL ASPECTS

3.1 Mechanisms of Purification

The various purification mechanisms involved are biological processes, microbiological processes, microbiological oxidation and chemical. These purification processes which occur on the surface and within the bed are responsible for breaking down the intercepted and dissolved impurities into simpler compounds. It is important to note that Huisman has considered only the suspended impurities, and ignored the discussion of biological purification in terms of dissolved impurities in the influent water. For influents polluted heavily by industrial wastes, and carrying dissolved traces of industrial and organic wastes, the effect of biological purification is equally important.

The zoogloeal film on the grain surface, containing bacteria, bacteriophages, and some predatory micro-organisms as protozoa and rotifera, and the schmutzdecke on the bed surface are instrumental in holding organic impurities, and bacteria, from the raw water. Selective bacteria assimilate organic impurities for cell growth and to provide energy for metabolism. The metabolic products are transported down to the lower layers by the water and converted into living matter by other organisms there, and the cycle is thus continued till the degradable organic matter is broken down into water, carbon dioxide and relatively stable inorganic salts like sulphates, nitrates and phosphates, which appear in the mineralised filtrate.

The bacteria are most active in the top of the bed because the maximum amount of food and oxygen is available there. The bacterial activity diminishes with depth, because of the decreasing food and dissolved oxygen in the water. Below a depth of 30 - 40 cm, the biological activity is on a much smaller scale, but the microbiological degradation products from the upper layers are biochemically converted here into ammonia nitrates and nitrites.

Wood (1955) stressed that the large surface area available in a slow sand bed due to smaller grain size, affected the amount of energy available at the water-grain interface and enhanced adsorption of particles on the grain. Ives (1971) admitted that a mechanical description of the slow sand filter

not justified as the real mode of operation, which is biological and biochemical.

Huisman (1974) has described how the influent water stays in the filter tank over the bed for 3 to 12 hours, so that the purification of water actually starts there. While the water is waiting to be filtered, larger particles settle to the schmutzdecke, smaller particles coalesce with each other, and the planktonic algae photosynthesize, improving the dissolved oxygen.

Prechlorination of slow sand filter has been favoured by Baumann (et al 1963) based on the results using residual chlorine doses of average 8.8 mg/l, but is not favoured by Huisman (1974). It is difficult to conceive compatibility of such high chlorine doses, with the live biological purification in the slow sand filter. Ives (1971) pointed out the stress laid by Vlood, Ridley and Huisman on the unsuitability of slow sand filters for highly turbid waters. But none made it clear if the rapid filters were suited for highly turbid waters, even without pretreatment such as coagulation, for only on such a basis could a proper comparison be presented.

Schmutzdecke

On the surface of the slow sand bed an organic layer about 1 cm thick develops as the filtration proceeds, and is known as the schmutzdecke, (German : literally 'dirt layer'). It is slimy and gelatinous and consists of filamentous algae, diatoms, bacteria, particles of organic and inorganic origin, other forms of living and dead algae, parasites, protozoa, rotifers and other forms of life. The schmutzdecke is intensely active: live micro-organisms use suspended and dissolved organic matter of the incoming water for cell growth and metabolism. Living bacteria and dead algae in the raw water are consumed in this layer, and are converted into intermediate organic matter or simple inorganic salts. Nitrogenous compounds are also broken down and the released nitrogen is oxidised. Some colour is removed and a great part of turbidity due to suspended particles is removed. Due to biological oxidation in the schmutzdecke, there is a demand on the dissolved oxygen, which is vital for the bacteria to function properly in the rest of the bed.

3.2 Types of Organisms Present

With the introduction of rapid sand filters towards the end of the last century, the previously called sand filters became slow sand filters to differentiate from the newly developed rapid gravity filter. It is interesting that the two filters were differentiated on the basis of filtration rate, rather than the much more fundamental basis of the processes of purification. With the advancement of biosciences since then, and the understanding of mechanisms of filtration during the last two decades, the true difference is beginning to emerge and some now prefer to call slow sand filters, biological sand filters. In practice, however, slow sand filters are still popularly identified as such. A valuable description of the organisms usually encountered in the water supplies, sewage and the slow sand filters is given in the recent volume, Water Treatment and Examination (Holden, 1970).

Ps aeruginosa is one of the three main species of the Pseudomonas group. It is the only species pathogenic to man, where it is associated with various suppurative conditions. There are suggestions that its enumeration should be included in routine bacteriological examination. Because of its partial resistance to chlorine, it is supposed to prove a suitable indicator for adequacy of chlorination for virus inactivation. Ps fluorescens is the most commonly occurring saprophytic species, and its strains were isolated from soil by Burman (1954), which produced antibiotics effective against E Coli. The most predominant bacteria in sewage treatment plants are pseudomonads and the Achromobacteriaceae.

Cl. perfringens and E. Coli show a fairly close correlation when sewage or manure find access to a water supply. Pure waters as from underground sources are normally free from these microorganisms. Cl. perfringens and its spores are mostly removed during slow sand filtration, or coagulation with rapid sand filtration. In an investigation, water filtered at about 0.14 m/h reduced the Cl. perfringens spores from 37 to 5 in 100 ml. The numbers were lower when the zoogloeal film had developed well. Chlorine doses as usually applied in water works do not destroy spores, which are resistant to drying, sunlight, ultraviolet light, and ozone.

Salmonella typhi and Salmonella paratyphi B are pathogenic and cause typhoid and paratyphoid, sometimes known as Enteric fever. Salmonellas succumb easily to other organisms and cannot survive in sunshine. Houston (1908-15) made a most extensive study of the viability of S. typhi in the waters of the rivers Thames, Lee and New River. He used cultivated and uncultivated strains of the pathogen and investigated their destruction by

storage, and at 37°C temperature. Later experiments tend to confirm that the survival of enteric organisms is much longer in purer water. Thus purified water is more prone to dangerous contamination. Windle Taylor (1953-54) reported vigorous growth of S.paratyphi B on the raw jute yarn used for jointing cast iron mains. Laboratory results appear to be conflicting but the period of their survival outside the body depends on environmental circumstances. In the tropics death of these organisms occur quicker than in temperate zones.

The examination for E. Coli can be regarded as the most important single observation in the water analysis. Its relative abundance in water is of fundamental significance as an index of recent fascal pollution. Even though E. Coli is fairly widespread, yet compared with other Coliform Bacteria, its distribution is much more limited. The presence of Coliform Bacteria other than E. Coli do not indicate recent excretal pollution but denote a later stage of atmospheric contamination or the contamination due to surface washings or the growth on decaying vegetation or other organic matter.

Valuable fundamental researches on the slow sand filter especially in the fields of bacteriology and biology have been reported by Windle Taylor in various water examination reports published by the Metropolitan Water Board in London. A recent study was on the microbiological population in the top 100 mm and bottom 100 mm of slow sand filter beds conducted immediately after skimming the beds in the normal way. The following table (3.2.1) taken from Windle Taylor (1971-73) gives the number of microbes found in the bed when filtered at normal and fast rates.

Table 3.2.1 (from Windle Taylor, 1971-73)
Microbial content of sand at normal and fast filtration rates

m/day filtration rate		3.6	9-15	3.6	9-15
depth		surface	surface	bottom	bottom
Per ml	37°C Colony Count	65,200	82,500	6,320	10,200
	37°C Spore Count	53,800	62,500	5,000	8,620
	22°C Colony Count	500,000	256,000	85,000	100,000
	Fungi	533	433	45	39
	Yeasts	3	27	0	1
	Streptomycetes	11,900	9,930	1,030	1,030
	Micromonospores	115,000	61,000	5,770	11,600
	Fluorescent Pseudo Monads	600,000	217,000	136,000	228,000
Per 100 ml	Coliform Organisms	9,210	3,340	60	23
	E. Coli	105	263	18	6
	Clostridium Spores	9,900	17,500	2,400	2,900
	Cl. Perfringens Spores	6,000	8,000	280	620

Table 3.2.1 shows only small differences in counts between slow and fast rate beds and not constant for all categories of organisms. The deep sand has counts lower than the surface samples, but they are still significant to play role in the filtration process. It is interesting to note that generally the number of organisms at the bottom are slightly more in the case of fast operated filter than the other filter, indicating somewhat self adjusting activity of the filter organisms by better distribution throughout the filter depth, in a situation when more food is available at the bottom of the bed due to higher filtration rate, and less contact time available to organisms at the top.

The predatory (bacteria which prey on other bacteria) bacterium Bdellovibrio bacteriovorus has attracted attention from the point of view of removal of bacteria by slow sand filtration. Windle Taylor has reported that it is difficult to separate Bdellovibrios (size 0.45 micron) from protozoa for investigation purposes, but it is assumed that Bdellovibrios are present in slow sand filter beds, and myxobacteria are probably more numerous.

Pseudomonas and Achromobacter are one of the most commonly occurring bacteria in filters. These are known to utilise phenol in water. During summer, after resanding, yellow pigmented aerobic sporing bacilli have been reported in high numbers (Windle Taylor, 1953-54). The secondary slow sand filters appear to be a natural habitat for these organisms and are suitable for their multiplication (Windle Taylor, 1969-70).

Algae

Algae are common organisms encountered in slow sand filter tanks. The effect of season on algae growth is sometimes under-rated; when particular groups assume dominance during certain times of the year. Successional pattern of algae in eutrophic waters of southern England has been described by Holden (1970). For slow sand filters, the stages of succession of algae growth was described in the S.W.T.E. Symposium by Ridley (1967). He stated that in the tank water over the slow sand beds, the first species of algae to appear were the small unicellular green algae, followed immediately after about five days by diatoms, or the seeded algae from previous filter run, or from the influent. After about ten days of filter run filamentous algae including the well-known blanket weed (Cladophora) could establish themselves.

Chlorophyta or green algae group is very common in fresh water with diverse form, size and character. The genus Chlamydomonas has some 600 species and is found almost everywhere. This small unicellular organism passes through filters and is a cause of complaint from consumers. The

diatom genus Ankistrodesmus is extremely resistant to the normal copper sulphate dosage. Some of these species can pass through filters. Scenedesmus, another small green algae is a filter passer. Bigger filamentous forms such as Cladophora Enteromorpha and Hydrodictyon reproduce rapidly in a slow sand filter tank and their metabolism may produce undesirable smell and taste. Euglenophyta is grass green and is present in organically rich water and is motile, so can be a nuisance in penetrating the filters. Some genera of smaller species of the diatoms (Bacillariophyta), also penetrate filters. Some other forms like Cyclotella and Stephano discus are notorious for clogging the slow sand filter. These can also penetrate as they are small disc shaped algae. Its filamentous form as Melosira can be problem in rapid filters or microstrainers. Diatoms as a group are fairly expensive in terms of algicides or disposal. Some of the very small unicellular Xanthophyta (yellow green algae) are impossible to remove in a rapid filter and sometimes even in a slow sand filter. Filamentous yellow-green Xanthophyta, such as Tribonema are of common occurrence in eutrophic impoundments and causes clogging of rapid filters or microstrainers during mid-summer blooms. But small or big, all Xanthophyta are delicate and can be eliminated by the application of copper sulphate or 1-5 mg/l of chlorine. Among Chrysophyta, Synura can be regarded as the most troublesome in water works, as only small numbers will produce cucumber tastes, which is accentuated by chlorination. The blue-green group Cyanophyta (Myxophyceae) includes unicellular, colonial and filamentous forms, which are found in all types of climates, but most species are susceptible to small doses of copper sulphate. Many of them float on the water surface, so may not trouble filter processes.

Invertebrate animals

There are numerous invertebrates which inhabit the filters or the storage reservoirs because of supporting environmental factors. Microscopic Protozoa are grouped as Rhizopoda, Flagellata, Ciliophora and Sporozoa. Some other invertebrate animals are discussed in the next section 3.3. Crustacea, a division of the Arthropoda form a major population of impoundment fauna and are important to the biological balance. Planktonic Cladocera such as Daphnia and Bosmina, and Cyclops and Diaptomus are important fish food. The Harpacticoid copepods are common in the schmutzdecke. Insecta which form midges and chironomus are a nuisance at waterworks are described adequately by Holden (1970), with means for their control.

In a recent study on ciliate Protozoa in slow sand filters, Lloyd (1973) located ciliate Protozoa and the Rotifera in a high percentage of samples

throughout the year. In mature beds (not newly cleaned), the largest organisms found were Oligochaeta (worms) including Nais Müller, Stylaria Lamrack and Aelosoma Ehrenberg. The Nematoda, Gastrotrichia and Turbellaria were abundant only when the detritus had penetrated 2-10 cm. Among the ciliated Protozoa the commonest were Peritrichia and Spirotrichia. Holotrichia and Suctoria happened to be less common. Rotifera were very common. The most common Peritrichia were the genus Vorticella, especially V. campanula Ehrenberg, V. convallaria Linnaeus.

This indicates a very diverse population of aquatic organisms, characteristic of waters with low pollution and a reasonably balanced ecology.

3.3 Function of Organisms

Certain algae and protozoa are predatory on some bacteria, and thus play a part in removing bacteria from the water. Protozoa are well known for reducing typhoid bacteria and some other pathogenic bacteria. The protozoa are capable of feeding on a great variety of bacteria, especially where these are in large concentration. Protozoa select bacteria for food, but usually do not accept red, purple and green pigmented bacteria. Growth of one organism may affect that of the other bacteria by the depletion of oxygen, the production of hydrogen sulphide and the oxidation of organic matter etc. Competition for food or the production of toxin by one class of bacteria may eliminate another class of bacteria.

Ps aeruginosa in sewage is antagonistic to E.Coli, and releases many antibiotics which act against closely related organisms. However, in purified water, Ps aeruginosa and E.Coli are able to coexist. Clostridia and their spores are of interest as these indicate faecal pollution and are undesirable in certain industrial uses. During water treatment the intention is to remove as many spores as possible, and also to reduce their multiplication during filtration. The Cl. perfringens test gives valuable support to the E.Coli results and serves as additional evidence of the enteric character of the contamination. On account of the high resistance of spores of Cl. perfringens, they can survive in water long after the time of the pollution, and are thus valuable in demonstrating remote pollution, because E.Coli and S. typhi are expected to perish much earlier, even though introduced to water at the same time.

Algae

Treatment problems can be gauged by the nature and quantity of suspended matter in raw water. If the raw water impurities consist almost entirely of silt and organic debris, the rate of clogging will be predictable in coagulation - filtration; but an increasing number of algae in the source will cause problems of quantity or quality at the waterworks. Biological examination of water is useful in assessing the probable rate of clogging of slow sand filters, either by accumulation or by the reproduction of algae in the overlying filter tank water. According to Van de Vlood the autotrophe zone of algae is not very necessary for the satisfactory functioning of the slow sand filter, especially in view of the satisfactory operation of those filters even when covered or filtering upwards. The autotrophic zone enhances the dissolved oxygen content of water, but is disadvantageous in several ways as explained by Ridley. Algal cells,

particularly diatoms could cause filter clogging. Over productive filamentous algae could break up the schmutzdecke causing deterioration of the filtrate. Ridley also pointed out that living or dead algae could produce taste or odour in the filtrate, as algae are an excellent substrate for the multiplication of abcteria. Certain species of algae also produced polyphenols which could react with chlorine to give out undesirable chlorophenolic tastes.

Algae act as a producer of organic matter, and determined patterns of primitive animals which feed on algal cells or organic detritus. Algal blooms or sufficient growths of algal cells cause discolouration of the water. Some species of Chlamydomonas form a slimy layer on the sand grains of the filter and are difficult to remove during filter cleaning. This slimy layer on grains is stimulated by the presence of chlorine in the influent water, and when the filter is drained and dried, the slime combines with sand and calcium and may result in cementation of the bed surface. Synura (Chrysophyta) can be easily removed by conventional filtration, but serious taste problem will occur if they fragment and run through filters. The greenish-golden brown species of Peridinium and Ceratium among the Pyrrophyta group cause strong fishy tastes in water supplies and high rate of decomposition in filter tanks or the impoundments. Blue green algae Cyanpyta causes major problems, and the larger organisms quickly clog rapid and slow sand filters, and many species produce unacceptable tastes, which are accentuated by chlorination. Cyanophyta are as bad as diatoms in their nuisance value to a waterworks as a well established bloom when decomposing can cause deoxygenation of the whole water mass, resulting in major taste problems. Among brownish Cryptophyta two genera, Cryptmonas and Rhodomonas are very common and may cause unacceptable colour problems even after coagulation and filtration.

Invertebrate Animals

Some of the groups are of nuisance value because they have to be removed at some stage, but there are others which may be responsible for affecting the physical or biological quality of a works. Protozoa utilise complex organic material. Amoeba, Arcella and Diffugia are typical Amoeba Protozoa, and they utilise algal cells, small animals and organic detritus. Flagellata in many groups are parasitic. The genera Myxobolus, and Myxidium among the Sporozoans have been reported to cause infection in carp with resultant mortality. The genus Euspongilla among Porifera grow on walls and ingest dead and alive algae which are normally present in the filter tanks. Hydrozoa also colonises the filter walls and the leaves of

macrophytes and feeds on crustacea. Among Platyhelminthes (flat worms), three classes , Monogenoidea, Trematoda, and Cestoda act parasitically on hosts like fish, molluses and small crustacea. In Rotifera, the genus Keratella reproduces profusely in slow sand filters and feeds on algae. Genera Asplanchua are carnivorous. Rotifera sometimes penetrate filters and are a cause of comsumer complaint. Nematoda include many groups and species; known as thread worms, they live in mud and colonise the zooglocal film in the slow sand filter, and may penetrate filters. Bryozoa house under rapid filter drains but rarely cause problems. Slow sand filters are the ideal environment for the colonisation of sedentary Mollusca animals which include snails, limpets and mussels. The zebra mussel infests the waterworks rapidly, but can be controlled easily with chlorine (Greenshields and Ridley 1957); however, mass killings are not advised to avoid smell and taste. The outflow mains from reservoirs support mussels which feed on organic debris (Windle Taylor, 1964). Crustacea if formed in great quanitity can interfere with filtration and in larval stages can penetrate sand filters. The larger crustacea divided into two groups, the Isopoda such as Asellus and the Amphipoda such as Gammarus and Niphargus roproduce in the slow sand filter tank water using organic food, but are removed by filtration.

The commonly occurring Rotifera and Spirotrichia are strongly thigmotactic and feed largely on the grain surface. The ciliated Protozoa Peritrichia attach themselves to the sand grains, but utilize paticles suspended in the filtering water (Lloyd, 1973). Vorticella are abundant in the upper layers, but the Spirotrichia and Rotifera are evenly distributed throughout the bed depth. The Vorticella increases rapidly in the first few days of the filter run and causes a great reduction of bacteria during that period in the filtrate. During higher rates of filtration the Vorticella and Spirotrichia redistribute themselves to cope with the higher rate, and penetrate a few centimetres into the bed, rather than all accumulating on the bed surface. Rhizopeda especially the subclass Amoebina are abundant in the slow sand filter. These are known for bacterial predation and perhaps have a significant function during purification in filtration (Windle Taylor, 1967 - 68).

3.4 Effect of Storage

Storage of raw water started for the sake of water quantity, but now with the benefits during storage coming increasingly to light, it may be equally attractive to justify storage based solely on quality considerations. Ridley (1964) has done pioneering work on the study of thermal stratification

in Thames Valley reservoirs. He described thermal density layering as important in terms of filtration and disinfection, as only 30 feet deep water is isothermal for most of the time, while a depth of 52½ feet ensures a temperature difference sufficient to produce a stable three-layered density stratification consisting of epilimnion, thermocline and hypolimnion. The use of jet type inlets and offshore outlets was advanced for inducing internal circulation in standing reservoirs to control thermal stagnation. Steel (1964) pin pointed the remarkable rapidity of events occurring during thermal stratification, and argued a case for monitering facilities capable of determinations at time intervals as small as five minutes.

Storage has been described as a significant step for the treatment of water (Holden 1970). The hygienic advantages were summarised by Houston (1909). He described the devitalisation of pathogenic bacteria and reduction of excremental organisms, as the main virtue of storage, and went to the extent of calling adequatley stored water a safe water. In the modern context though, this appears to be an overstatement, but it also indicates the large increase in the level of pollution of surface waters since then. It is generally agreed that 10 days storage can reduce the coliform organisms by 75 to 99 per cent, the greatest reduction occurring during spring and least during winter. In addition the settlement of considerable amount of particulate matter takes place whatever the duration of storage. Some of the physical, chemical and bacteriological changes that take place when river Thames water is stored for periods ranging from 14 to 120 days are shown by Holden (1970) on page 331, and are also clearly presented in the Metropolitan Water Board reports, covering several decades.

Ridley (et al 1956) have explained the influence of reservoir design on the actual retention time; for example, a short distance between the inlet and the outlet may allow undirectional flow, but in other cases the design may include arrangements for inducing two directional rotation of the water mass. Storage provides a very dilute nutrient medium for some bacteria which grow under those condictions, and in warm weather and in the presence of decaying plant material, coliforms and some of the Pseudomonas group find agreeable conditions to grow (Burman, 1961). Storage reduces colour, ammoniacal nitrogen and oxygen absorbed from permanganate. During profuse algal growths over long storage, there may be reduction in temporary hardness and nitrate content. Filtration and coagulation improve, in the absence of algae in influent water. Storage acts as a buffer to avoid sudden deterioration of influent water during floods or intermittent introduction of pesticidal pollution.

As pointed out in Section 3.2, spores of Cl. perfringens survive the

usual chlorine doses. Therefore, the best treatment is to remove them in earlier treatments as much as possible including storage of surface waters. Storage of water for 3 to 4 weeks causes complete destruction of V. cholera, though chlorination is fully effective if carried out properly (Holden 1970). Howston (1910) reported startling success in removing pathogens through storage. He found that a storage of five to nine weeks achieved 99.9% pathogen destruction. However, poliovirus is notorious for withstanding long periods of storage, extending up to several months. Recently an extensive study on the survival of viruses in water was carried out by Poynter (1968) using plaque mehtod. In the case of poliovirus 3, he estimated that at 15 - 16 ^{o}C, the initial concentration of 20,000 PFU/ 100 ml was reduced to less than 50 PFU/ 100 ml after 15 days, and at 22 ^{o}C to less than 10 PFU after 11 days.

It appears that even from virus inactivation point of view, a storage of 2 to 3 weeks is extremely valuable.

At Walton reservoirs of the Metropolitan Water Board, London, 17 per cent of the gull population was found to be Salmonella carriers. Fifteen different species of Salmonella were isolated, many of which were detected in the washings from rapid gravity and slow sand filters at the relative sites (Mandle Taylor 1966). Such external factors affect the reservoir water quality adversely. Calcareous sources enriched by sewage or agricultural drainage, assist tremendously in algae production, which in turn support a vast number of invertebrate and vertebrate animals. Other disadvantages of storage reservoirs are during the period of summer stagnation. In this respect Ridley (1964) has reported, a concentration of blue green algal of over 400,000 cells/ml in the top 6 metres of eutropic impoundment, and excessive concentrations of hydrogen sulphide and ammoniacal nitrogen in the lowest layers.

The overall advantages of storage far outweigh some of these temporary problems. Quality of outflows from impoundments, due to density layering, is significant for waterworks. Control of thermal density layering is important while designing impoundments. Partial or complete destratification is now possible by incurring small costs (Ridley et al 1966).

CHAPTER IV

PREVIOUS STUDIES OF CLARIFICATION KINETICS

Deep bed filters, especially the rapid sand filters, are used to clarify suspensions of water. During run the pressure drop increases due to clogging of the bed. Two fundamental operators in terms of clarification and pressure drop have therefore been considered for developing the mathematical models. These start with the conditions that the filter is initially clean and the two parameters are time-dependent.

4.1 Depth Clarification

Mathematical models are developed to find out suspension concentration and pressure drop at any time ts and depth of the filter Dm. The clarification is measured by the change in suspension concentration S, which dependson the quantity of deposits per unit filter volume σ (specific deposit) and the distance in the filter from the inlet surface Dm, and the elapsed time of filtration ts. The physical parameters and operating variables used are, inlet concentration So, filtration approach velocity Vf, gram size D, initial porosity fo.

Unisize Media

Even though now there is enough understanding of the transport mechanisms in the filter pores and the surface chemistry of filtration systems, it was pointed out by Ives (1973) that there is still insufficient understanding of the nature of suspensions, and the physics of the removal of suspension by filtration. For filter clarification, an empirical coefficient λ has been used to measure the interaction between a uniform suspension and a uniform filter medium. The mathematical models are based on the simplified case of a homogeneous, nonflocculating suspension filtering at a constant rate through an isotropic uniformly permeable bed of sand, under laminar flow conditions. The assumptions can be represented in the following mathematical form:

$$-\frac{\delta S}{\delta Dm} = \lambda S \qquad 4.1.1.$$

Equation 4.1.1. was first proposed by Iwasaki (1937) in relation to slow sand filtration. In the thirties even the slow sand filter was considered, by some, in terms of physical clarification, and the impurities in solution and the organic suspension were not given any significant importance. Iwasaki formulated initially another basic equation for the mass balance of suspension particles. It is based on the simple assumption that particles removed from suspension are deposited in the filter pores. Because of the local gradients of suspension concentration and deposit concentration with respect to time and distance, Ives (1971) is critical of the simplification and has described it as misleading. It is also clear that this mass balance equation considers only the physical phenomena and does not take into account the biological phenomena encountered in the case of organic material. In differential form, the mass balance equation can be written as equation 4.1.2.

$$-\frac{\delta S}{\delta Dm} = \frac{A}{Q}\frac{\delta \sigma a}{\delta ts} \qquad 4.1.2.$$

where S is the concentration of suspension, vol/vol
Dm is the distance into filter from inlet surface
A is the inlet face area of filter
Q is the volumetric filtration rate
σa is the absolute specific deposit
ts is the elapsed time of filtration

Equation 4.2.1. was also proposed independently by Mints (1951), and was observed as having a statistical basis with λ for the probability of removal of a particle per unit depth of the filter by Litvinienyn (1963) and Hsuing and Cleasby (1968). At the run time to zero, equation 4.2.1. can be integrated to the form,

$$S = So \exp(-\lambda oDm) \qquad 4.1.3.$$

where So is the inlet concentration of suspension, and
λc is the initial value of the filter coefficient at ts = o.

Since 1937, equation 4.1.3. was the basis for most of the mathematical models for filtration, but it was Ison (1965) who proved the validity of the expression experimentally and showed also for a nonflocculating suspension that each of the size fractionsof suspension particles followed equation 4.1.3. using different values of λo for each size fraction. Normally λ is considered a mean for the whole suspension, but Mackrle and Mackrle (1959) have formulated a mathematical model based on the values of λ for heterodisperse suspensions in a series form.

Deb (1969) used the model of a coated sphere, using the refined approach of allowing for the contact points between spherical grains, thus modifying on the geometry of the deposit, and produced relationshipe more complex than (4.1.6.) He also modified the mass balance equation (4.1.2.) to a more exact form:-

$$-\frac{\delta S}{\delta Dm} = \frac{1}{Vf}\frac{\delta \sigma}{\delta ts} + \frac{(f-\sigma)}{Vf}\frac{\delta S}{\delta ts} \qquad 4.1.4.$$

where S is the suspension concentration, vol/vol
Dm is the distance into the filter.
Vf is the approach velocity.
σ is the volume of deposited particles per unit bed volume
ts is the filter run time.
f is the porosity of the bed.

Equations for constant time and the relationship of simultaneous events have also been reviewed by Horner (1968). Due to the porosity inbetween deposited particles, an experimental error occurs, as the particles occupy greater pore space than determined theoretically. To rectify this discrepancy, Camp (1964) and Mohanka (1969 a, 1969 b) introduced a bulking factor into equation 4.1.4. Ives (1973) has quoted the measured values of self porosity of particles as 60%. The effective specific deposit can be described as $\sigma = \beta\sigma a$, where β is a bulking factor, and the local instantaneous porosity can be written as,

$$f = f_o - \sigma \qquad 4.1.5.$$

For the sake of simplification, negligible term $\delta S/\delta ts$ is usually omitted from equation 4.1.4. Because of the assumption that diffusional movement is very much smaller than the advective motion, the negligible diffusional term is also omitted. Herzig et al (1970) formulated a statement including this diffusional term, which was earlier investigated by Litwiniszyn (1965) under the conditions of significant concentration gradients.

Research workers generally agree that the deposited particles bring about alteration in the characteristics of the filtration action, and therefore most of the proponents of mathematical models of filtration have accepted the fact of variation of λ during filtration. It is therefore logical that λ must be described as some function of the specific deposit σ. At the I.W.S.A. 1969 Vienna Congress, Ives (1969) formulated equation 4.1.6. which may be described as the most general of all the variously proposed functions,

$$\lambda = \lambda o \left(\frac{1 + b\sigma}{f}\right)^{y} \left(\frac{1 - \sigma}{f}\right)^{z} \left(\frac{1 - \sigma}{\sigma U}\right)^{x} \qquad 4.1.6.$$

where λo is the initial filter coefficient
b is a geometric constant for the packing of the filter gains
σ is the specific deposit
f is the porosity
y empirical exponents (spherical specific surface)
z empirical exponents (capillory specific surface)
x empirical exponents (velocity)
σU is the saturation value of specific deposit (< porosity f)

An examination of equation 4.1.6. will reveal that the equation is not based on the detailed filtration mechanisms, but is based more on the general assumptions of the important pore geometry and interstitial velocity. The first term within brackets in equation 4.1.6. is for the increase in specific surface in the filter due to the localised coatings of deposited particles on grains, indicating an increased clarification during the initial stages of filtration, but not accepted by many investigators. The second term is for the diminution of specific

surface in the filter due to accumulations of deposits in side spaces in pores. These first two terms are according to the sphere and capillory model of Mackrle et al (1965). The third term is based on the increase in mean interstitial velocity because of the reduction in pore cross section by deposits, assuming that the maximum velocity is reached when the specific deposit is σU inhibiting further depositing of particles. The third term is based on the model by Maroudas (1965).

Most of the mathematical models formulated previously can be expressed by a judicious choice of the exponents y,z and x.

Iwasaki (1937)

$$y = 1, \quad z = 0, \quad x = 0$$

$$\frac{\lambda}{\lambda o} = \frac{1 + b\sigma}{f} \qquad 4.1.7.$$

Ives (1960)

$$y = 1, \quad z = 1, \quad x = 1$$

Expansion of Ives equation 4.1.8. below equals the expansion of Ives equation 4.1.6., and is therefore a special case of the general equation 4.1.6.

$$\lambda = \lambda o + a_1\sigma - \frac{a_2\sigma^2}{f-\sigma} \qquad 4.1.8.$$

where a_1 and a_2 are the Ives filter coefficients.

Mackrle et al (1965)

$$x = 0$$

$$\frac{\lambda}{\lambda o} = \left(\frac{1 + b\sigma}{f}\right)^y \left(\frac{1 - \sigma}{f}\right)^z \qquad 4.1.9.$$

Shokhtman (1961), Beertjes, and Lerk (1967)

$$y = 0, \quad z = 1, \quad x = 0$$

$$\frac{\lambda}{\lambda o} = \frac{1 - \sigma}{f} \qquad 4.1.10.$$

Maroudas (1965)

$y = 0, \quad z = 0, \quad x = 1$

$$\frac{\lambda}{\lambda o} = \frac{1 - \sigma}{oU} \qquad 4.1.11.$$

Equation 4.1.6. does not cover the specific surface model proposed by Deb (1969), and by Hereit (1969).

Some research workers have not accepted the concepts of equations 4.1.1. and 4.1.6, and have considered the detachment mechanism to be significant. Mints (1951) has considered the counteracting effect of the variable rate of detachment on the constant rate of deposition as equation

$$-\frac{\delta S}{\delta Dm} = \lambda S - \frac{\alpha}{Vf}\sigma \qquad 4.1.12.$$

where α is the detachment coefficient. In I.W.S. A. 1959 Vienna Congress, Ives (1969) criticized the above equation (4.1.12.) on the plea that if λ is constant α should be a function of S.

Because of the now better understanding of clarification mechanisms, an interest is growing in computing the trajectories of particles in suspension as these approach a filter grain (Ives, 1973). Current research is employing more sophisticated packed bed models than the single spherical collector, making use of the trajectory calculations in aerosol filtration.

Size-graded media

It is only in experimental filters that the media is of a uniform size. In practice the sand size is graded, but for the sake of calculations, a mixed size remaining heterogeneously mixed is treated theoretically like a unisize media bed. Filter media is size graded either for structural or operational reasons, or because of high cost involved for sieving media to make it unisized. The normal filters washed by up flow fluidisation cause a size succession from finest at the top to coarsest at the bottom. In the modern multi-layer filter,

media of various sizes and densities are chosen by necessity, and the order of size strata depends upon the design.

The principles of filter transport mechanisms and the mathematical models for specific surface dictate that the filter coefficient varies as an inverse function of grain size D

$$\lambda = \text{const.}\ \bar{D}^{n_1} \qquad 4.1.13.$$

where n_1 is the exponent of grain size, depending on the dominant transport mechanism, and quoted by Ives (1973) between 1 and 3, determined empirically.

Probably, the exponents x, y and z and constant b are functions of D, which complicate the model further. Mohanka (1969) has described such analysis and computation by experimenting with a fine layer filter. Diaper and Ives (1965) have solved for a size graded filter assuming n_1 as unity and a linear variation of grain size with distance, $D = Do + jDm$. The grain size is Do when the distance into filter $Dm = 0$, and j may be positive or negative depending on the increasing or decreasing grain size in the direction of flow. The equation 4.1.14. can be used to compare analytically the processes of downflow and upflow filtration through continuously size graded media.

$$\lambda D = P1 - P2\sigma^2 \qquad 4.1.14.$$

where P1 and P2 are the Diaper Ives filter coefficient constants.

It can be ovserved that equation 4.1.14 does not form a particular case of the Ives general equation 4.1.6.

4.2. Headloss due to Clogging

As the water passes through the filter media, the flowing suspension deposits and accumulates in the grain pores which causes loss of permeability resulting in increased resistance to flow. The filter media offers some resistance even to clear water, which can be calculated by the Carman Kozeny equation 4.2.1.

$$\left(\frac{\delta H}{\delta Dm}\right) = \frac{5\upsilon Vf s^2}{gf^3} \qquad 4.2.1.$$

where $\delta H/\delta Dm$ is the hydraulic gradient
υ is the kinematic viscosity of the filtering liquid
Vf is the approach velocity of filtration
s is the specific surface (surface area of media per unit bed volume)
f is the porosity

For clean media, $s = so$ and $f = fo$; so the above equation can be modified to form equation 4.2.2.

$$\left(\frac{\delta H}{\delta Dm}\right)_o = \frac{5\upsilon Vf s^2 o}{gf^3 o} \qquad 4.2.2.$$

For a filter layer containing specific deposit σ (which varies from layer to layer with Dm, and increases with run time ts).

$$s = so\left(\frac{1 + b\sigma}{f}\right)^Y \left(\frac{1 - \sigma}{f}\right)^Z \qquad 4.2.3.$$

$$f = fo\left(\frac{1 - \sigma}{fo}\right) \qquad 4.2.4.$$

The specific surface s and the porosity f are modified and the equation 4.2.1. could be rewritten as equation 4.2.5.

$$\frac{\delta H}{\delta D_M} = \frac{5 V^{[illegible]}}{g f_o^3} \left(\frac{1 + b\sigma}{f_o}\right)^{3y} \left(\frac{1 - \sigma}{f_o}\right)^{3j-3} \quad \ldots\ldots\ldots 4.2.5$$

Ratio of the hydraulic gradient at any time of the run to the hydraulic gradient of clean filter.

$$\frac{(\delta H / \delta D_M)}{(\delta H / \delta D_M)_o} = \left(\frac{1 + b\sigma}{f_o}\right) \left(\frac{1-\sigma}{f_o}\right)^{3j-3} \quad \ldots\ldots\ldots 4.2.6$$

Considering the special case $y = j = 1$.

$$\frac{\delta H / \delta D_M}{(\delta H / \delta D_M)_o} = \frac{(1 + b\sigma/f_o)^2}{(1 + \sigma/f_o)} \quad \ldots\ldots\ldots 4.2.7$$

Expanding the righthand side

$$\frac{\delta H / \delta D_M}{(\delta H / \delta D_M)_o} = 1 + (2b+1)\frac{\sigma}{f_o} + (b+1)^2 \left(\frac{\sigma}{f_o}\right)^2 + (b+1)^3 \left(\frac{\sigma}{f_o}\right)^3 \quad 4.2.8$$

By approximation the headloss per unit depth is proportional to the local specific deposit, especially when $\sigma \ll f_o$ This relationship was formulated by Horner (1968) and Herzig et al (1970) proved the relationship to be true for some other mathematical models. Mints (1966) had also used it for several empirical formulations.

By integrating through the filter depth, when the filtrate concentration is small compared with that of the inflow (less than 5%), the linear relation between total headloss and the run time is given by equation 4.2.9

$$H = Ho + \text{const. } ts \quad \text{---------- } 4.2.9$$

where Ho is the initial total headloss through the filter media. Mints had summarised Equation 4.2.9 in the I.W.S.A.1966 Barcelona Congress.

While delivering a lecture on Captive Mechanising Infiltration, Ives (1973) talked of deposits forming a discontinuous cake at the inlet surface of the deep tied filter, which follows Boucher's Law, where rise in headloss is exponential with time.

$$hs = ks \quad \exp (Kt\ ts)$$

where hs is the headloss due to surface deposition; ks is the initial headloss at surface, usually very small; kt is the rate constant of surface headloss, ts is the elapsed time of filtration.

In water filtration it is desired to minimise hs to enable it to lengthen the filter run.

The three components of the headloss in a rapid filter, Ho the initial headloss, hd the headloss due to accumulations in the pores, and hs the surface

deposit headloss are shown in Fig. 4.2.1.

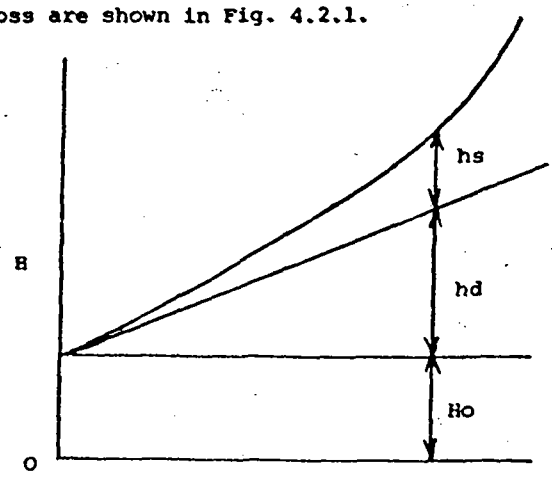


Fig. 4.2.1. Time

Headloss variation with time in a deep bed filter

In spite of the substantial development in mathematical modelling for deep bed filters, none is entirely predictive and determination of constants by experiments is necessary. Biological growth on and within the slow sand filter has not been considered specifically.

CHAPTER V

PREVIOUS STUDIES OF BIOLOGICAL OXIDATION KINETICS

5.1 Biological Oxidation Kinetics in Depth

Adolphe Kemna (1899) can be described as the father of the theory of the slow sand filtration. Kemna recognised the valuable work done by Allen Hazen in USA, and himself proposed the slogan of enquiring into the why and wherefore of a process of water purification so intimately connected with our welfare. During the middle of the last century the standard of purity of water generally recognised was the physical aspect, affecting the senses. During this first period, as per Kemna, the suspended particles were arrested on the top because they were larger than the pores or could not wind their way through the sinuous channels in the bed. The second period was characterised by a mainly chemical conception of purity, especially the organic purity. Kemna remarked that it was in the third period that the rise of biology and bacteriology connected with water supply was witnessed.

When a clean filter is started, there is no chemical or biological action. After a couple of days the dirt layer on the surface accumulates and the filter starts working also biologically and chemically. Kemna described this layer full of life, green and blue algae interweaving their filaments into a felted sheet. Diatoms with siliceous frustules and gelatinous envelopes fill up the meshes, zoogloea stick on every particle and innumerable bacteria dot the whole mass. Vegetable and bacterial life destroy the organic compounds of the influent water. The microbes instead of being destroyed, rather multiply in the surface layer and are caught in the slimy layer on the surface of grains; thus the filter acts towards them like a spider's web. This theory of spider's web was explained by Prof. Vernon Boys, with the aid of his extremely thin quartz fibres. Kemna has pointed out that open filters are better than covered ones because of the healthy effect of light on the microbes of the filter. This observation is significant in view of the suggestions for providing covers to slow

sand filters for control of algal blooms. Kemna quoted the work of Dr O. Strohmeyer of the Hamburg Waterworks Laboratory, who showed green algae extremely energetic against microbes, sometimes achieving complete disinfection in less than a day. This was explained by the nascent state of oxygen or the ozone given out by the plants; a view that would hardly be supported today. Most pathogenic bacteria are adapted to parasitic life, are not at home in ordinary water and suffer competitively with the essentially aquatic forms.

In the I.W.S.A. 1955 London Congress, Van de Vloed brought the question of slow or rapid filters in the open and compared the two on their merits. After intense application of rapid filters during the first half of this century, it was in this Congress that the sagging confidence in slow sand filters was restored and the versatility of the slow sand filters in terms of its biological purification was recognised. Van de Vloed emphasised the energy in pure water known as the Brownian movement, and the energy on clean grain surface in terms of large surface area, the electro osmosis, capillary force, the negative electrokinetic potential on the sand grain, the electrical double layer, chemical affinity and the absorption. Deep bed filtration is the best process for removing particles smaller than the pore size (35 microns). These particles are microorganisms, substances in the colloidal state (between 0.2 micron and 5 nanometer), or in solution (smaller than 5 nm). He felt that the river sand was weak in surface energy as it absorbs iron, aluminium and manganese, but not sufficient to attain a completely reversed zeta potential. The different aspects of surface energy introduced by Vloed were not probed in depth and the clear demarcations were felt wanting.

Van de Vloed was explicit in bringing forth the biological factors. He felt that when the slow sand filter is commissioned, the biological process starts with the grains on the top by providing a brownish red coat on the surface, which consists of partly decomposed organic matter, iron, manganese, aluminium and silica which favours absorption of negative organic unicells in colloidal systems in a two-week old filter, in which the change on the grain surfaces has turned positive. He also noted that the better absorption of anions out of solutions causerformation of more carbonic acid through biodegradation. After about 2 – 3 weeks, due to absorption of anions, a higher concentration of inorganic salts mainly phosphates will result. At this moment a surface skin of algae sets in depending on the light intensity and temperature. This filter skin, popularly called the "zoogleal film" in USA, was first called "schmutzdecke" by Piefke in 1880. Van de Vloed called it the "autotrophe zone" and

described it as consisting of organisms brought by the influent water and of the local forms in the superficial layers of the filter, the commonest being sessile algae, diatoms mostly, together with less or more number of protozoa, a few larger animals such as the chironomus and a variety of bacteria. Vloed did not favour the use of the term schmutzdecke which means "dirt-layer", especially for the secondary slow sand filters, because of the richness of life and paucity of dirt there. The sole exception is the chitinous remains of arthropods and their insoluble substances. Autotrophe zone was described by Vloed as the upper most layer of sand inhabited principally by photosynthetic algae, rather than the traditional connotation of the word schmutzdecke which is a gelatenous bacterial film.

Slow sand filters owe much to the autotrophe zone and Van de Vloed outlined its two principal effects. Firstly, the straining effect due to the interstices between the cellulose threads of the chlorophycae and the siliceous bodies of the diatoms being smaller than the finest sand used. Secondly, the metabolic action of algae results in the consumption of carbon dioxide and the available nitrogen and phosphates from the water and the release of oxygen which is helpful in oxidising the suspended and dissolved organic impurities. Immediately below the autotrophe zone is the heterotrophe zone which was described excellently by Pearsall, Gardiner and Greenshields (1946). Heterotrophe zone houses aerobic bateria which degrade organic impurities to carbon dioxide and simple organic salts like nitrites, nitrates and phosphates. The numerical balance of the microflora and fauna of this zone continually tends to bring about an equilibrium according to the character of the organic impurities to be degraded. According to Piefke the depth of the heterotrophe zone does not exceed 30 cm, but according to Vloed, the deepest layer termed as the "universal oxidation zone" also oxidises the organic matter through contact catalysis on the surface of the grain.

In the S.W.T.E. 1967 symposium, Ridley (1967) made the observation that the presence of unicellular algae throughout the filter run causes the headloss to rise steadily, and the gelatenous matrix formation adds to the inconvenience in filter cleaning. Normally diatoms replace unicellular algae, and diatoms' shapes and sizes are ideal for plugging sand pores resulting in rapid headloss buildup. Due to photosynthesis, if the filamentous algae are overproductive, it causes production of oxygen bubbles, which may carry the mat along with the surface sand to float to the top of influent water. Thus exposed portions of the bed increase permeability locally but causing deterioration of filtrate quality. Another difficulty listed by Ridley due

to filamentous algae in the autotrophe zone is their ability to seal the bed surface, following the death and disintegration of these large algae with attendant tastes and odours. As the length of run in the slow sand filter is long, normally ten weeks, several tons of living and dead matter is retained. Ridley expressed fear in the potential risk of taste and odour in filtrates, and the possibility of complexes, such as muco-poly saccharides, which may affect industrial processes.

Ridley saw the slow sand filter tank as a complex ecosystem and compared its physical conditions to a shallow pond with a permeable floor, in which the primary production of organic matter by algae is enough to support wide variety of life in the form of bacteria, protozoa, rotifera, crustacea, nematoda, annelida and even larvae of insects. The species of predominant algae proliferating on sand bed as described in detail by Ridley have been described in section 3.2.

Huisman has described well the biological purification in the slow sand filter in a recently published document (Huisman, 1974). He writes that the purification of influent water begins when it enters the filter tank. The slow movement of the influent water over the sand allows larger particles to settle and the smaller ones coalesce and settle. The planktonic algae which are so abundant in the filter tank consume carbon dioxide, nitrates, phosphates and other nutrients from the water to form cell material and oxygen. Gelatinous schmutzdecke consisting mainly of filamentous algae, diatoms and bacteria, entraps particles of mineral and organic matter, living and dead algae, parasites, and a proportion of other impurities, and digests and breaks them down. After passing through the schmutzdecke the water enters the sand bed and leaves it after a few hours. It is here that some important purification processes take place. Even though there is some straining effect especially in the top layer, the very small particles like colloids, bacteria and viruses are much smaller than the pore size, but are transported, absorbed and held on the grain surface as explained in detail in section 4.1. During the ripening period the sand grains attain a sticky slimy coating, which in many respects is similar to the schmutzdecke except for its larger particles and algae. This organic coating on the sand grains is a teeming mass of bacteria, bacteriophages, predatory organisms such as rotifers and protozoa, all feeding upon the retained impurities or upon each other, breaking down the organic matter converting it into cell material and inorganic inoffensive materials, carried away in the now mineralised filtrate. This biological capability of the filter diminishes with depth because of declining availability of

organic impurities and the dissolved oxygen level.

In the beginning the schmutzdecke was considered to be a delicate layer of organic matter and bacteria and the filtrate quality was understood to be dependant on it, thus avoiding higher filtration rates to keep the schmutzdecke intact. The recent understanding of the schmutzdecke portrays it as mainly an algal layer, dominated by filamentous algae, sometime after its ripening, which plays a limited role in the total purification process. Generally the schmutzdecke plays an important role for the filter, but it can be an undesirable layer by clogging the filter creating rapid headlosses, and degrading the filtrate quality in taste and odour by leaching out metabolic products.

5.2 Analogy of Nitrification

The heterotrophic bacteria which are present in the depth of a slow sand filter or are associated with the BOD test, obtain their energy requirements through the biochemical absorption of oxygen and by using organic matter both as an energy source and as a source of carbon for growth. The nitrifying bacteria use ammonia and nitrite mainly for energy and carbon dioxide for growth. To oxidise 1 g (as N) of ammonia to nitrite, Nitrosomonas require about 3.22 g of molecular oxygen, and to further oxidise 1 g (as N) of nitrite to nitrate, Nitrobacter need only 1.11 g of oxygen. Water Pollution Research Laboratory (March 1971) has given the approximately net chemical equations as below.

$$5\ CO_2 + 55\ NH_4^+ + 76\ O_2 \longrightarrow C_5H_7NO_2 + 54\ NO_2^- + 52\ H_2O + 109\ H^+$$

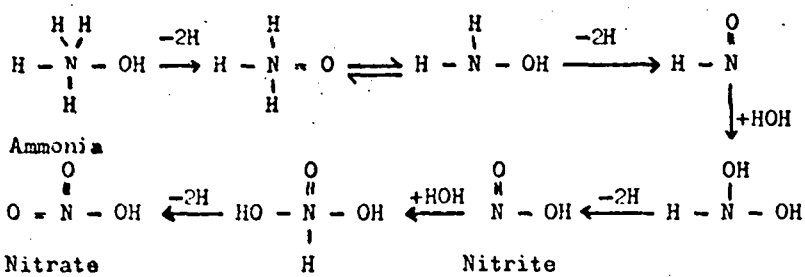
(Nitrosomonas cells)

$$5\ CO_2 + 400\ NO_2^- + 195\ O_2 + NH_3 + 2\ H_2O \longrightarrow C_5H_7NO_2 + 400\ NO_3^-$$

(Nitrobacter cells)

The rate of oxygen consumption is proportional to the concentration of heterotrophic and/or nitrifying bacteria present. Heterotrophic bacteria can quickly double in two hours time at 20°C. Therefore substantial bacterial growth occurs if there is biodegradable organic matter. Nitrifying bacteria multiply rather slowly, the doubling time being roughly one day even under favourable conditions. For a given concentration of Nitrosomonas, the rate of nitrification is mostly independent of the ammonia content till about mg/l. The rate of nitrification slows down if the ammonia concentration is less than 3 mg/l, and is about one half of the maximum with about 0.5.1 mg/l of ammonia.

The autotrophic bacteria in the schmutzdecke derive their energy from the oxidation of inorganic compounds. Little is known about the energy reactions of the heterotrophic bacteria, and even less is known about the autotrophic bacteria. The exact energy system of the autotrophic bacteria appears to be yet unknown (McKinney, 1962). The nitrifying bacteria with the ability of converting ammonia to nitrates do it in two phases. In phase 1 the Nitrosomonas bacteria convert ammonia to nitrite. In second phase the Nitrobacter bacteria take the nitrites and oxidise them to nitrates.



In phase I, the 3 DPN molecules reduced yield considerable energy to the Nitroso- bacteria. In phase II as only one DPN molecule is produced and then reduced, the energy yield is low and requires the Nitro- Bacteria to process three times as much substrate as the Nitroso to obtain the same energy and this also explains the rapid conversion of nitrite to nitrate in mixed populations. The demand for energy prevents a large nitrite buildup. The DPN is regenerated by dissolved oxygen in the same way as heterotrophe bacteria in the depth of the filter. The above reaction is also incidentally a very good example of microorganisms in oxidation systems not oxidizing organic matter by the direct addition of oxygen, but by the indirect scheme of hydrogen removal and addition of water.

Like all other microbes, nitrogen oxidising bacteria are also very sensitive to temperature and the temperature below $4^{o}C$ retards metabolism and thus ammoniacal nitrogen appears in the filtrate. Chlorine reacts with ammonia or the prevalent ammonium ion to form chloramines as monochloramine or dichlormmine or trichlora mine,

$$NH_3 + HOCl \rightleftharpoons NH_2Cl + H_2O$$

Ammonia — monochloramine

$$NH_2Cl + HOCl \rightleftharpoons NHCl_2 + H_2O$$

or

$$NH_3 + 2HOcl \rightleftharpoons NHCl_2 + 2H_2O$$

dichloramine

$$NHCl_2 + HOCl \rightleftharpoons NCl_3 + H_2O$$

$$NH_3 + 3HOCl \rightleftharpoons NCl_3 + 3H_2O$$

trichloramine

Nitrogen trichloramine is a principal eye irritant in chlorinated bathing waters. Also the disinfection power of chloramines, measured in terms of contact time is less than chlorine.

5.3 Virus Removal in Slow Sand Filters

Since early sixties a consciousness arose that treated water supplies to consumers should not only be free from objectionable bacteria, but also from viruses, and the time honoured practice of considering the bacterial safety of water based on coliform removal, is beginning to be considered not wholly satisfactory. This awareness brings slow sand filters into sharper focus, as some big claims have been made, at times, for its capacity to deal with virus.

It is now agreed that surface sources in populated areas are mostly polluted by enterovirus, as also shown by Poynter (1968) that the sewage effluents contain enterovirus when tested the year round. Other reports also confirm the presence of enterovirus in varying degrees in river Seine (France), rivers Flow and Vauchere (Switzerland), river Ruhr (Germany), and rivers Thames and Lee in England (Poynter, 1968).

Robeck et al (1962) found that complete virus removal was achieved when the water was filtered at ground water movement rate (.05 m/h) through a 0.6 m column of sand of 0.18 mm, de. The percentage of virus removal decreased with increase in flow rate, until at the rapid filtration rates used in primary filters, most of the virus passed through. Use of demineralised water instead of any natural river or stored water was questioned by Poynter (1967) and considered responsible for not very satisfactory virus removal when filtered at the normal slow sand filter rates.

Some very interesting tests were conducted at Kempton Park by the virology unit of the Metropolitan Water Board in the middle of 1970 on the removal of virus through slow sand filtration. A tank containing up to 1.5 cu m of the Staines Aqueduct water was inoculated with 100 to 1,000 plague forming units per millilitre (PFU/ml) of attenuated poliovirus 1. This suspension was pumped to the top of the experimental filters consisting of 2 identical miniature cylindrical perspex columns 88 mm diameter (Area approximately .09 m^2) with sand shaded from the light. By returning the overflow to the tank a constant inoculum was available above the filters thus improving the maintenance of steady state. Two filters were run in parallel containing sand depths of 600 mm and 300 mm respectively. The main flow rate was 0.2m/h, but 0.1m/h and 0.4m/h were also used. Filters were

cleaned as necessary. The samples were taken from the storage tank and from the influent and effluent of the filter columns.

The results showed that throughout the course of these experiments there was a marked decline in the numbers of viruses present in the inoculated water of the storage tank, which was most noticeable at higher temperatures but also during cold weather. During mid-May when a marked increase in temperature of the aqueduct water occurred, from 7°C to 15°C and eventually to 21°C, the rate of loss was such that no viruses were detectable after 24 hours. During June and July inactivation rates ranged from 69 per cent to 99 per cent. The decrease in virus number can be attributed to biological activity in water. No marked differences were recorded in the rate of virus loss in the water on top of the filter as opposed to the water in the supply tank, which suggests that most of the effect of the filters occurs in the sand phase.

The results were of preliminary nature and filters were operated under particular experimental conditions, but it was claimed that using stored river water as normally supplied to Thames Valley filtration stations and with the addition of virus at the rate of about 100 PFU/ml, operating under as normal standard conditions as possible with a filtration rate of 0.2 m/h, and a 600 mm depth of sand, a virus removal rate of approximately 99.9 per cent or more was continuously achieved at various temperatures below 20°C, which happened on the very first day and was maintained at a more or less constant rate thereafter.

The temperature of the filters varied from 5 to 25°C. The better virus removal at higher temperature may be explained due to the enormous increase in the number of protozoa who acted as predators to the virus. For mesophilic organisms the optimum temperature is 35° C, and the rate of microbial growth doubles with every 10°C increase in temperature upto the limiting temperature (McKinney, 1962).

Regarding depth of sand, a comparison of these filters running in parallel, both using the same supply, showed that for every virus particle passing through 600 mm of sand four passed through 300 mm of sand. This however still represents 99.6 per cent removal or more. From the above findings it is clear that depth of sand in slow sand filters plays a very important role in removing the virus.

Preliminary trials for the effect of flow rate showed only 75 per cent removal with a 50 per cent increase in the rate of filtration. As a conjecture, the same degree of virus removal may be possible at enhanced rate of filtration by proportionally increasing the sand depth.

There is evidence of a lag in the virus appearance in the filter effluent. Some were obtained even 48 hours after virus inoculation ceased.

A tentative figure of an impressive 1,000 fold reduction in virus numbers at a flow rate of 0.2m/h is thus obtained for filter efficiency.

According to McKinney (1962) over 99.99 per cent of the bacgeria in the raw water are removed by a well operating slow sand filter, which amounts to a 10,000 fold reduction.

Sterile sand filtration experiments showed that absorption cannot account for most of the virus removal by slow sand filters.

CHAPTER VI

PREVIOUS STUDIES ON UPRATING

6.1 Switzerland

Schalenkamp (1971)

Schalenkamp conducted a useful investigation on the possibility of operating slow sand filters rapidly and studying the physical and biological results at St. Gallen and Zurich. In Zurich, slow sand filters are covered to rationalize land use by installing them under tennis and football areas. It was reported that for a waterworks of 250,000 m^3/day capacity in Zurich, land costs not important, a treatment process consisting of primary rapid filters (max. vel. 6m/h) active carbon (max. vel. 20 m/h) and secondary slow filter (vel. 0.625 m/h) cost practically the same as one with a primary rapid filter (max. vel. 6 m/h) and secondary rapid filter with active carbon layer (max. vel. 5 m/h). At both the places, the removal of phytoplankton (>and <20μm) without the application of flocculants and active carbon was better with primary rapid and secondary slow filtration than with double rapid filtration. Bacteriological purification wise it was shown that the results in a rapidly operated (0.625 - 0.875 m/h) slow filter were outstanding, though they did not meet Swiss standards; that of rapid filters were considerably far off those figures. It was claimed that normal slow filters (Normal Langsam Filter, NLF) with a velocity up to 0.312 m/h could be always operated successfully, but that they could also be operated rapidly with a velocity of 0.625m - 0.875 m/hr (Schnell Langsam Filter, SLF).

Experimental Results in St. Gallen Works

The experiments were conducted from July 1965 to January 1967. The NLF was operated continuously with a velocity of 0.312 m/hr, and SLF at 0.334 m/hr for first 8 hours, at 0.625 m/hr for the next 8 hours and at 0.875 m/hr for the rest of 8 hours. The samples were always taken at the end of 24 hour period, at a velocity of 0.875 m/h.

In NLF by dosing flocculants and aids in the raw water and conversion of the rapid filter to a two layer filter with sand and anthracite, the run

time was extended from minimum 2 - 6 to maximum 6 - 9 months and the works were modified to accommodate 2.5 m headloss. Headloss rose from an initial 50 cm to the final 100 cm in a year. In the case of SLF the first three runs lasted for 3, 2 and 2½ months respectively, and the cleaning was effected by scraping off a 1 to 1.5 cm sand layer. During the first run, the headloss rose from initial 115 cm to 195 cm before cleaning, and the initial headloss for the 2nd and 3rd runs was 125 and 135 cm respectively. During the fourth run a deeper scraping of 2.5 cm thick brought the initial headloss to 120 cm resulting in a longer length of the run for over 4 months. For the fifth run, a still thicker top layer (4 cm) removal lengthened the run to 5½ months and the still lower initial headloss of 110 cm reaching a maximum of 185 cm. A fear was expressed that the biological purification aspect would be completely lost if the filtration rate exceeded 0.875 m/h in SLF.

The clarification by both the filters in respect of zooplankton, phytoplankton, and the suspended matter is reproduced below,

Phytoplankton (cells $> 20\mu m$)

Average 7,500 cells/l in rapid filters
43/l NLF
101/l SLF

Phytoplankton ($< 20\mu m$)

60,000 cells/l rapid
2,988/l NLF
4,311/l SLF

Zooplankton

580 cells/l rapid
3/l NLF
4/l SLF

Suspended matter

0.33 mg/l rapid
0.11 mg/l NLF
0.14 mg/l SLF

Expectedly, the physical clarification action of NLF is somewhat better than that of SLF.

For biological purification, numbers of bacteria and coliforms, O_2, CO_2, BOD_5 and the permanganate value were determined as follows,

Bacteria on PC - Agar at 20 °C, 5 days,

Average 5,100/ml rapid filter
46/ml NLF
107,'ml SLF

Bacteria on PC - Agar at 30 °C 5 days

600/ml rapid filter
36/ml NLF
62/ml SLF

Coliforms Endo - Agar 37 °C

100/100 ml rapid
0/100 ml NLF
0/100 ml SLF

Coliforms Tergital - 7 Agar 44 °C

55/100 ml rapid
0/100 ml NLF
0/100 ml SLF

Dissolved Oxygen

Because of the differing sampling techniques, the results were not reliable and were abandoned. The loss of D.O. in NLF and SLF was reported to be 0.46 mg/l and 0.42 mg/l.

Free CO_2

Average 0.26 mg/l NLF
0.27 mg/l SLF Added

BOD_5

0.32 mg/l NLF
0.26 mg/l SLF Reduction

PV

0.44 mg/l NLF
0.11 mg/l SLF

Considering the trials as a whole it may be concluded that the SLF with a velocity of 0.875 m/hr was certainly still very satisfactory but nevertheless filtered somewhat less well than the NLF at 0.30 m/hr.

Experimental Results from Zurich Waterworks

Since 1868, Zurich waterworks has been treating Zurich lake water by slow sand filters. The trials lasted for one year. The NLF operated continuously at 0.312 m/h. The SLF was operated at a mean filtration rate of 0.461 m/h, filtering daily at 0.633 m/h for 9 hours, at 0.475 m/h for the next 10 hours, and at 0.175 m/h for the final 5 hours, the initial headloss of 54 cm rising to 236 cm in 9 months. In NLF the headloss during the same period rose from initial 28 to 110 cm.

The physical clarification by the two filters with respect to phytoplankton and detrilus is reproduced below,

Phytoplankton (cells $> 20\mu$ m)
4190 or 2780 cells/l rapid filters
0 and 0 cells/l NLF and SLF

Phytoplankton (cells $< 20\mu$m)
68,660 or 101,710 cells/l rapid filters
14,380 cells/l NLF
10,260 cells/l SLF

Detritus (Particles $> 20\mu$m)
17,970 and 16,300 particles/ml rapid filter before NLF and SLF
16,600 particles/ml NLF
15,600 particles/ml SLF

Detritus (Particles $< 20\mu$m)
27,700 and 25,640 particles/ml rapid filter before NLF and SLF
26,580 particles/ml NLF
24,300 particles/ml SLF

Better removal of small phytoplankton for SLF is in contrast to the results at St. Gallen, but the almost zero efficiency of either filter for removal of detritus particles is disturbing and casts some doubt on the operation of these experiments.

The results of the biological purification of the two sets of filters in respect of Bacteria coliforms, oxygen content, PV, COD, TOC and COD/TOC ratio had been reported as follows,

Bacteria on PC - Agar 20° 5 days

223 and 157/ml rapid filter

56/ml NLF

41/ml SLF

Coliforms on Endo - Agar 37°

8 and 9/100 ml rapid filters of NLF and SLF

0.6/100 ml NLF

1.0/100 ml SLF

Total bacteria on Ando - Agar 37°

23/100 ml rapid filters

5/100 ml NLF

5/100 ml SLF

Oxygen

0.3 mg/l taken up in NLF and SLF, but results reported unreliable because of differing sampling techniques.

PV	NLF	0.4 mg/l	Reduction in both cases
	SLF	0.7 mg/l	
COD	NLF	0.28 mg/l	Reduction in both cases
	SLF	0.26 mg/l	
TOC	NLF	0.07 mg/l	Reduction in both cases
	SLF	0.04 mg/l	
COD/TOC	NLF	0.1 mg/l	
	SLF	0.16 mg/l	

Interestingly the purification in SLF is marginally better than in NLF.

It was concluded from bacteria and plankton removal point of view, that the slow sand filter is not a surface but a depth filter.

Schalenkamp has not tried to throw light on the expected cumulative effect of clogging. At St. Gallen, the rapidly rising initial headloss could be remedied by scraping 4 cm of layer instead of 1.5 cm. The modified NLF able to withstand 2.5 m headloss is a welcome feature to double the length of the run, but its cumulative effect on the depth of silt penetration needs to be investigated. The same effect needs investigation in the case of Zurich, where it was possible to see only one full run.

Bertschinger (1889)

As a result of new interest in the slow sand filter, an old work by Bertschinger was discussed in Zurich in the late sixties (quoted in Schalenkamp, 1971). Bertschinger carried out tests on five filtration rates, 1.0, 3.8-5, 6.8-8.6, 9.8-13.4 and 20 m/day, in respect of the chemical and bacteriological cleaning action and concluded that,

"Filtration velocity is (at least over the range 3 and 13.4 m/day) without effect on these results, i.e. the filtered water gives the same chemical results and the same bacterial counts whether the filtration proceeds at higher or lower velocities".

It is difficult to say how relevant his bacterial counts would be, as the water microbiology was not much advanced by 1889. But there certainly appears room for improving filtration rate, by conditioning the influent water, over the conventional figure 0.1 m/h (2 gals/sft/h). In this respect Vlood (1955) was positive and generalised that velocities over 0.2 m/h were impracticable. But in view of the modifications to slow filters, as at Zurich to enable it to withstand a headloss of 2.5 m; and advances of conditioning the influent water by prefilters, this opinion of impracticability seems untenable.

6.2 Germany

Schmidt (1972)

It has been reported in a general meeting of the Institution of Gas and Water Works in Geneva, that capacities could be raised from 400 to 1100 - 1200 m^3/m^2 of filtered water per filtering cycle by the use of an intermittent filtration technique. The technique was applied for several years on the slow sand filters in Dortmund, for preventing algal blooms. Once in 24 hours the filter is put out of operation and drained, and then restarted again. This on-off technique successfully checked excessive algal growths in the filter tanks thus lengthening the filter run three-fold. Also it raised the level of oxygen saturation in the filtrate from 20-60% in the normal filter, to almost 100% saturation in the intermittently operated prefilter-slow filter system.

Rechenberg (1965)

At Dortmund Waterworks a study on the possibility of uprating slow sand filters, showed that by doubling the rate of filtration, the

permanganate consumption of filtrate increased by 12%. This showed that even though there was less oxidation of impurities on uprating, yet in proportional terms there is scope for higher filtration rates.

6.3 Netherlands

Huisman et al (1974)

Huisman while describing the effect of filtration on the delivered water quality, has mentioned the research carried out at Amsterdam Waterworks. Three covered slow sand filters were operated for a full year at the constant filtration rates of 0.1, 0.25, and 0.45 m/h. The results indicated no marked difference in the effluent quality. It has been summed up that the effluent quality depended largely on the grain size of the filtering medium but not on filtration rate. So according to Huisman, constant filtrate quality could be obtained at enhanced filtration rate, by the change in design of media characteristics. The limitations of media characteristics in terms of magnitude, for the optimum filtration rate were not described.

For turbid waters it was opined that pretreatment could be financially attractive if it allowed a slow sand filtration rate of 0.1 m/h to be increased by about 20%, or a rate of 0.2 m/h by roughly 60%.

In connection with the study at Amsterdam, it is felt that, the results on uprating may not be generalised, unless the detailed biological effect was studied.

6.4 Belgium

Kemna (1900)

The favourite prospective improvement of intermittent slow sand filtration, seems to have been experimented at Antwerp Waterworks, long ago without actually calling it so. Kemna experimented this technique not for lengthening the filter run but for doing away with filter cleaning. The top layer of the slow sand filter was allowed to dry after running down the water. The aim was to restore a high efficiency of purification by utilising the residual spores and remaining bacteria. With the drying and consequent breaking of the top layer the permeability was thought to be ensured, but on two occasions the headloss increased to 100 cm in four days,

even though the filtration rate was 1/3rd and 1/5th of the normal. The bacterial purification was unsatisfactory (120 colonies/ml, after 3 days) and there was no saving in time. The experiments were considered a decided failure and therefore abandoned.

It seems the experiments were unsuccessful because these were tried as a substitute to surface scraping. There appears to be promise in the technique for lengthening of the run, (see Schmidt in Section 6.2), if ultimately cleaned by scraping; especially in circumstances of high algal blooms.

6.5 India

Kardile (1970)

Some interesting observations were made on slow sand filters and semi-rapid filters, in the state of Maharashtra; where about 5000 villages were reported having a potable water source farther than a mile (defined as the difficult area). The Central Public Health Engineering Organisation of the Government of India, favours slow sand filters for the rural areas where surface water source is available. Some semi-rapid filters were also constructed during the sixties. The prevailing design norms have been reproduced in Table 6.5.1 including those for the rapid filters for easy comparisons.

The semi-rapid filters for treating the surface water are a compromise between a rapid and a slow sand filter, where pretreatment is included as for a rapid filter, but the washing and controls are similar to a slow sand filter. It was intended to filter at 1 m/h, with partial backwash and 7.5 cm to 15 cm surface scraping. It was observed that only one out of the seven semi-rapid filters was able to provide partial backwash, others resorting to surface scraping only. Due to the reported deficiency in pretreatment, settleable floc formation was unsatisfactory, resulting in the microfloc going to the filters. The only backwashed semi-rapid filter, was backwashed at a meagre velocity of 1.5 m/h. The whole bed was choked with silt and floc with 5 cm of mud on the top, reducing the actual filtration rate to 0.5 m/h. In the other semi-rapid filters with no backwash arrangement the condition of the bed was even worse and 7.5 cm to 15 cm scraping was not enough to prepare the bed, Most of the sand was removed, washed and relaid every time, which in effect made a smaller depth of 23 cm to 45 cm more convenient to work with. With a rather coarse sand of 'de' between 0.5 and 0.7 mm, and 'U' between 2 and 3, the higher allowable

loss of head of 1.2 m caused clogging of the bed right to the bottom.

The three slow sand filters constructed prior to 1900, used a storage reservoir as the raw water source. Subsequently, because of high turbidity of between 500 to 200 mg/l during rainy and summer seasons, two of the three works were provided with pretreatment. The alum was mixed before the settling tanks but there was no flocculation arrangement, which resulted in the microflocs passing to the filter beds. The bed depths were as low as 10 cm to 30 cm with sand 'de' of 0.4 to 0.5 mm and 'U' between 2.5 and 4.5, which resulted in below acceptable levels of turbidity and bacteria. The silt content in the beds was about 25%, causing clogging to the bottom and making normal scraping ineffective, which needed opening up of the beds for effecting the required filtrate. At the 3rd slow sand filter with no pretreatment the beds became anaerobic causing undesirable taste and odour in the filtrate. It was concluded that there was no hidden constructional defect. The speed of mineralisation process was considered primarily responsible for making the slow sand filter to flow.

Kardile expressed no clear opinion as to the admissibility of coagulation as a pretreatment for the slow sand filter. The claim that the speed of mineralisation is a primary factor in causing the slow sand filter to flow is obscure. It could only be true for the breakdown of suspended organic impurities when deposited in the pores. In fact dissolved organics contribute largely to growth of bacteria and biological activity within the filter affecting mineralisation but resulting primarily in clogging the filter.

The principal reasons for the poor performance were located in the high level of turbidity in the raw water and the inadequate pretreatment. Doubt was expressed on the large scale adoption of slow sand filters for the rural areas.

It is felt that the report, though an extensive and useful document, has not quoted any figures on the turbidity and bacteria in the effluent or even the influent. A deeper search into the design aspect of the slow sand filters could have been useful. The low performance appears to be due to three reasons: the high influent turbidity, the coarse sized sand, and the rate of filtration. Definitely, the 'de' as big as 0.3, 0.4 and 0.5 mm with 'U' almost 4 is too coarse to be used for a slow sand filter. Adoption of a filtration rate of 0.13 m/h for the slow sand filters seems to be over ambitious under these circumstances. Failure to provide a storage reservoir on the works, which would also serve as a settling tank is another reason in keeping the turbidity level too high. Use of finer sand, filtering at lower rates, using low turbidity settled influent should be able to change the doubt into surety for the adoption of slow filters.

Table 6.5.1 Design Norms for Different Filters

(Adopted from Kardile 1970)

	Particulars	Rapid Sand	Semi Rapid	Slow Sand
1	Type of raw water	Surface water with high turbidity	Surface water with high turbidity	Clean water with organic and bacterial pollution
2	Pretreatment with coagulation	Necessary	Necessary	Not necessary
3	Normal rate of filtration met/hr	5	1	0.1
4	Loss of head allowed in the filter, m	1.8	1.2	0.6
5	Sand depths in cm	75 to 90	75 to 90	90 to 120
6	Sand size, de mm	0.4 to 0.6	0.5 to 0.7	0.2 to 0.4
	U	Not greater than 1.75	Not greater than 2	2 to 2.5
7	Washing process	Backwash	15 cm sand scraping and partial backwash	Surface scraping of sand
8	Generally adopted for capacities	Greater than 4.54 mld	Less than 4.54 mld	Less than 4.54 mld

6.6 Metropolitan Water Board*, London

Glimpses of some inspiring fundamental research, for improving the rate of filtration, either in the existing filtration works or by the structural modifications, or by incorporating the changes in design; can be seen at the Board's filtration stations at Walton, Hampton and Kempton Park, and the laboratories at the headquarters. The more important operational parameters studied recently are increased filtration rates, sand characteristics, covering and prefiltration ozonation.

Windle Taylor (1971 - 73)

A pair of experimental slow sand filters, receiving rapid sand filtrate, with in situ washing and ozone dosing arrangements, constructed two decades ago on the Walton works premises, was used extensively for the increased filtration rates studies. Chemical, bacteriological and microbiological investigations showed that filters could be operated till 0.5 m/h without any deterioration in the effluent quality. However, when filtered at 0.625 m/h, there was deterioration only in one parameter of some increase in ammoniacal nitrogen. The sand depth was at its minimum of 0.3 m, and it was suggested to reconsider the minimum bed depth for such fast filtration rates. The filters were started at 1m/day on the 1st day and increased to 5m/day by day 5. The results proved satisfactory not only during summer but also during winter when the stored water quality was poorer. With respect to the distribution of silt and organic debris in the sand columns there was no noticeable difference between the slow and the fast rates. A more precise silt test is under development. One important finding was that there was cumulative initial headloss for the fast run filter which reduced the run length and necessitated deeper cleaning.

Following the success with these experimental filters, full sized slow sand filters at Hampton Works (bed 45) showed equally encouraging results when operated at 0.5 m/h. Coliform counts were higher for the test bed 45 but still lower than the controlled. Ammonia and alluminised nitrogens were slightly higher. To be able to save time, bed 45 was started at 1-3m/day on the 1st day and 6-12m/day on the second day. This

* From 1 April 1974 Metropolitan Water Division, Thames Water Authority

modification caused no apparent deterioration in the physical, chemical, biological or bacteriological parameters of the effluent. It was suggested that newly cleaned beds could be returned to service in summer at higher rates than originally thought. At Hampton the special hydraulic situation allows the headloss to rise up to 3 m, which can allow filtration up to 0.5 m/h, which is not practicable at most of the other slow sand waterworks in the Thames Valley.

For long term high rate filtration, slow filters must be modified to take a headloss of about 3 m. It was concluded that for short periods higher filtration rates up to 0.5 m/h appeared acceptable, even though long term implications were obscure. Other directions for research were proposed especially the penetration of silt, organics and invertebrates into the sand depths. Alternative methods for cleaning in terms of backwashing and in situ mechanical skimming were being considered.

Regarding the proposed structural modification to increase the headloss capability to 3 m, it is felt that to achieve the higher filtration, even though the increased rate of flow and length of run due to the greater pressure will increase the filter clogging, yet the rate of flow will not be so damaging to the bed permeability as the lengthening of the run. To lengthen the filter run under a head of 3 m or so should encourage the fine silt to penetrate the depth of the bed resulting in cumulative initial headloss, thus causing surface scraping to be ineffective.

Ridley (1967)

While explaining the important advances achieved by the Metropolitan Water Board, Ridley reported that the problem of flow restriction in slow sand filtration due to algal clogging was in effect solved in 1923, by the introduction of first rapid gravity sand filter as a primary filter. The use of primary rapid filters, doubled the rate of secondary slow sand filters at one stroke.

Even though the precise figure for the improvement of filtrate output was questioned by West (1967), there is no doubt that the introduction of double filtration can be considered, the major break through so far, for uprating the slow sand filters. It incidentally also could solve the problem of high turbidity and algal blooms in raw water, which are so often encountered. Most of the research for uprating the slow sand filters is even these days based on the concept of utilising a conditioned influent.

McDonald (1973)

At an Institute of Water Engineers meeting, while delivering an enthusiastic lecture, McDonald spoke of improving results with the use of polyelectrlytes as filter and, at the filtration rate of 0.5 m/h, and went to the extent of championing 0.25 m/h filtration rate to be established officially for design purposes. He saw enormous economic advantages in using mechanical skimmers and cleaning machines and claimed 25% more output by making inexpensive alterations. He also proposed backwashing of slow sand filters, but he did not specify the technique to be used.

Turner (1974)

At another Institute of Water Engineers meeting, Turner described the difficulties to optimise the 26 hectare Coppermills site for converting into a modern 490 mld slow sand filtration works. He described them as full scale experiments lasting over twelve months, filtering successfully at 0.2 m/h. He was confident of the possibility of stepping up the filtration rate to 0.25 m/h.

6.7 Implication of Covering

Metropolitan Water Board, London

Recently (Windle Taylor 1971 -73, 69 - 70) bed shading investigations were carried out on the Walton experimental filters, and on the full-sized beds by covering with black polythene sheeting. Covering had checked algal growths resulting in saving labour for the disposal of large masses of filamentous algae, but it did not help in lengthening runs in any significant measure. Thin polythene sheeting was not suitable for permanent covering, and the high cost of suitably covering large areas of filters did not seem to justify advantages in terms of heat retention and the filtrate quality. Greater possibility of pollution by birds putting nests under the shading was envisaged.

Covering the pilot filters from run No. 4 onwards to run No..11 did not bring out any significant improvement with respect to the headloss or the turbidity removal when studied along with other investigations.

The expected advantages by covering in terms of reduced algal blooms, and avoidance of raw water quality deterioration by windborne contamination, do not match the high cost of putting permanent structure on the slow sand filters. These advantages may prove decisive, only if the covering

is considered to prevent deterioration of filtrate quality due to very cold climate, or to prevent the expense of ice removal during heavy frosting.

CHAPTER VII

THE PROBLEM

The study reported in previous chapters has brought forth several outstanding features of the slow sand filter. The slow sand filter is a very uncomplicated and compact contrivance for purifying the water. The process has a good scientific basis and by making use of its biological purifying capability it could produce the very best filtrate, and is seen to be capable of withstanding the impruities encountered in well-controlled rivers and streams in modern industrialised society. Incidentally, when considered on its own, it is hardly any drain on resources, which may be of considerable significance in some places. Also, with the added significance of virus in the water supply cycle, the slow sand filter can be considered an extremely effective barrier for the enterovirus to penetrate. Another important aspect that has emerged is that in spite of the versatility of the slow sand filtration, there is very little fundamental research carried out, for understanding its kinetics and for making mathematical models to improve its utilisation.

This state of affairs has been explained by Hinsman that some people consider slow sand filtration not sophisticated enough and too expensive. Ridley and Schalenkamp have shown that if land cost were not significant, or if the land could be put to alternative uses as in Zurich, or if the works form a part of the green belt in the overall scheme of city and regional planning, then the cost of slow sand filtration is favourable or even economical. The deterioration in the quality of surface waters, which may be dealt with by the biological purification of the slow sand filter, causes renewed interest in exploring the complex mechanisms therein. In the rural communities of developing countries, the greatest need is not of sophistication or the saving on land, but reliability and simplicity of operation. To be able to assign a major role to these filters for the treatment of public water supplies in the developing and the industrialised countries, it is imperative that disadvantages associated with the slow sand filter be considered more seriously.

As already discussed, the high cost of construction and the large requirements of land areas, principally emanate from the adoption of low rates of filtration. Therefore any study directed to upgrade the status of the slow sand filter must be in that direction.

Thus the problem is, how much can a slow filter be uprated before meeting problems of -

i) Insufficient clarification-

ii) Inefficient cleaning due to silt penetration-

iii) Insufficient biological oxidation.

While substantial research data and information, on the various aspects of rapid filtration including the development of conceptual models for removal of suspended matter and mathematical models for the headloss development and removal of suspended impurities is now available, very little investigations have been carried out to contribute towards the understanding of biological kinetics in the slow sand filter, or towards the building up of mathematical models for the biodegradation or headloss in slow sand filters. There is also need of finding out the extent of application of the existing concepts and models developed primarily for the rapid filter, to slow sand filtration.

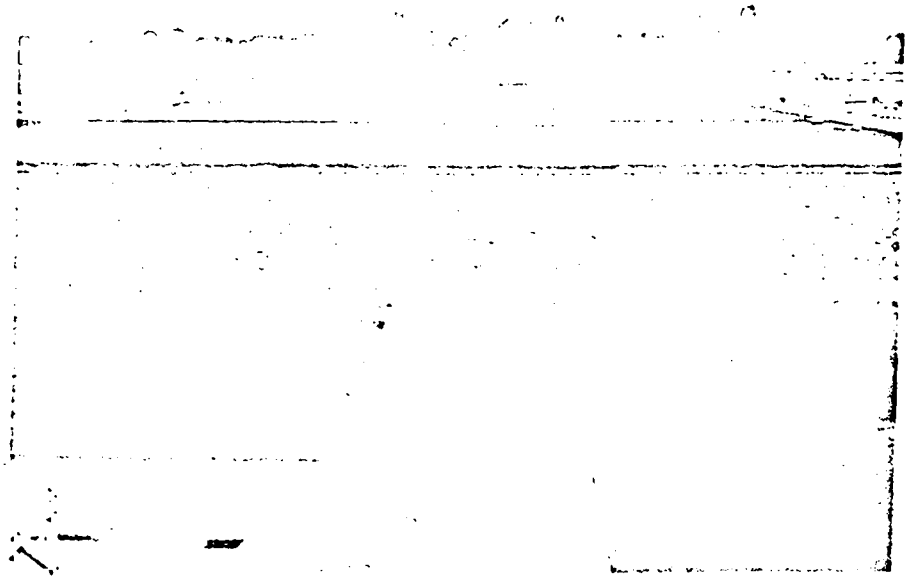
The scope of the present research is outlined in section I.I.

CHAPTER VIII

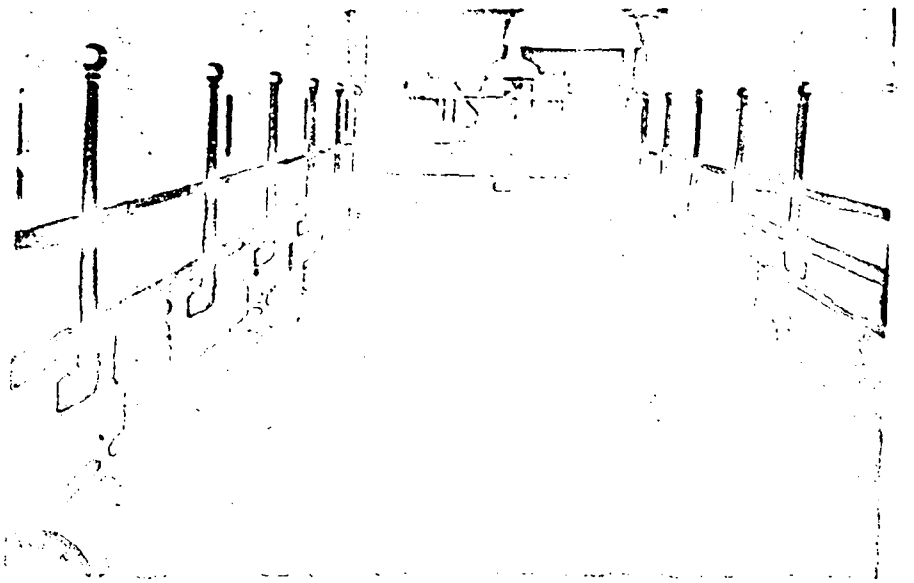
EXPERIMENTAL APPARATUS, PROCEDURE AND DIFFICULTIES

The experiment was designed to test the biodegradability of a low concentration of organic material in solution, and the pattern of headloss and turbidity removal, within the slow sand filter; and to investigate these aspects with respect to the possibility of operating it. To be able to meet this requirement a set of two adjacent slow sand filters, with inlet and outlet connections, on Walton Water Works of Thames Water Authority (previously Metropolitan Water Board of London) was chosen and used as pilot filters, to observe the processes through both beds simultaneously. Further, these were considered essential:
(1) Reproducible organic matter concentration and media gradation, (2) conditions to produce a controlled flow rate, (3) an accurate method of sample withdrawal and headloss measurement within the depth of the filters, (4) reproducible filter runs, (5) approved methods and instruments to determine low turbidity and concentration of organic substance.

Concentrated phenol solution was pumped through a micrometer pump and injected into the inlet pipe of the test (east) filter which received raw water from the primary filters of the main works. The higher filtration rate (compared with 0.13 m/h used by the M.W.B. normally) resulted in proportional reduction of detention time over and within the filter bed. Manometer tapping points cum phenol sampling points had been located on the filter wall, in the control room to allow the observation of headloss and phenol concentration at different filter depths and run times. Tests were conducted with a uniform filtration velocity of 0.2m/h. A more detailed description of the apparatus, the equipment, the phenol solution, the media, the schedule and procedure for the experiment and the observations and difficulties encountered follows in subsequent sections.

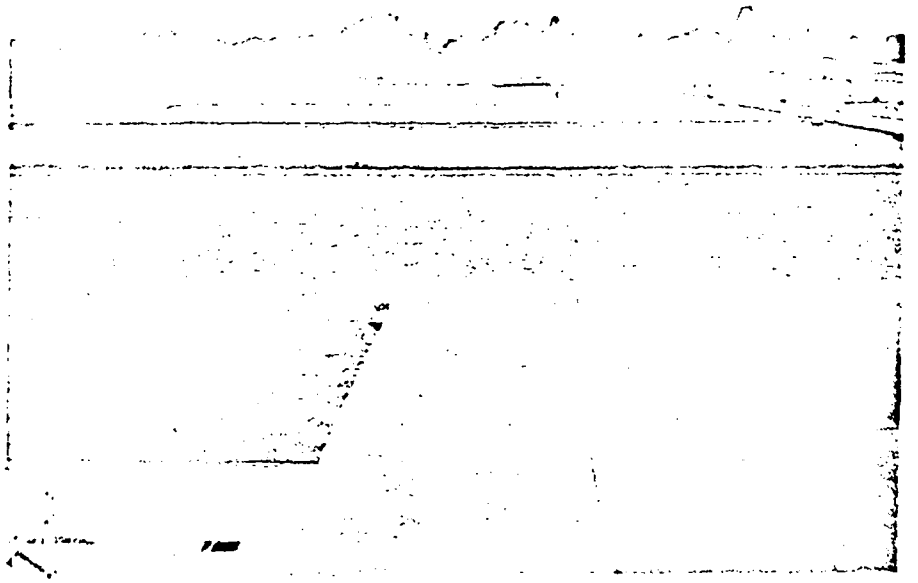


Yelton Water Works, General View

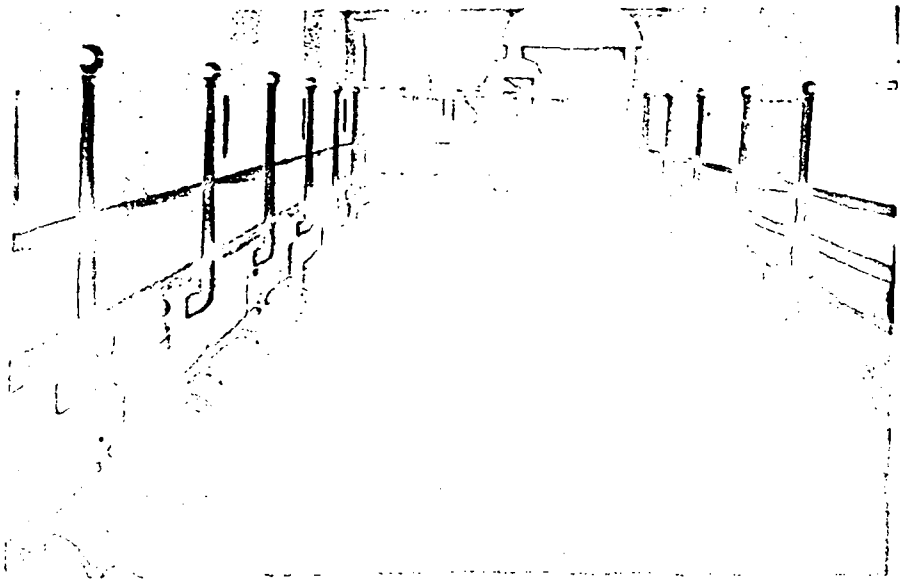


Primary Filters

Photo 8.1.1



Walton Water Works, General View



Primary Filters

Photo 8.1.1

8.1 Apparatus and Equipment

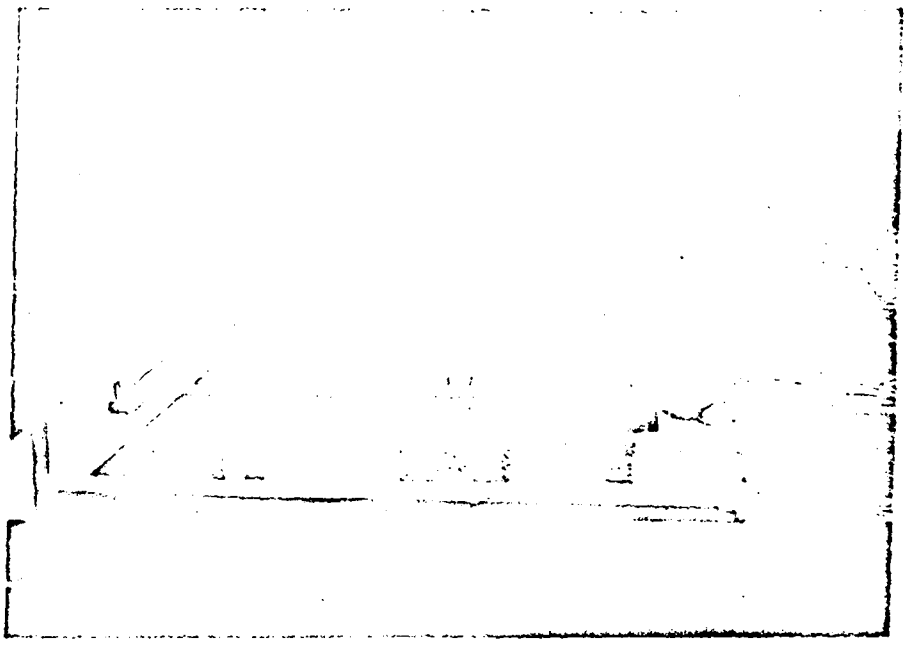
The flow diagram of the experimental filters is shown in fig. 8.1.3. The pilot filter layout and details are shown in figs. 8.1.4 and 8.1.6, and the general position of pilot filters with respect to rest of the works in fig. 8.1.5, photo 8.1.1. and 8.1.2. The control room arrangement in photo 8.1.2 and the details of inlet and outlet pipes and the sample valves in fig. 8.1.7 and 8.1.10. Photo 8.1.9 shows details of the sample taps and the phenol solution dosing device. In the analytical work mainly two instruments, a Unicam Spectrophotometer and a Hach Turbidimeter (photo 8.1.11) were used. The investigations for relating the Hach Turbidimeter with EEL Nephelometer were carried out at the Water Examination Laboratory of the Thames Water Authority.

Raw water for the pilot filters was brought from the primary filter house of the main water works, and pumped through a low lift pump (fig. 8.1.5).

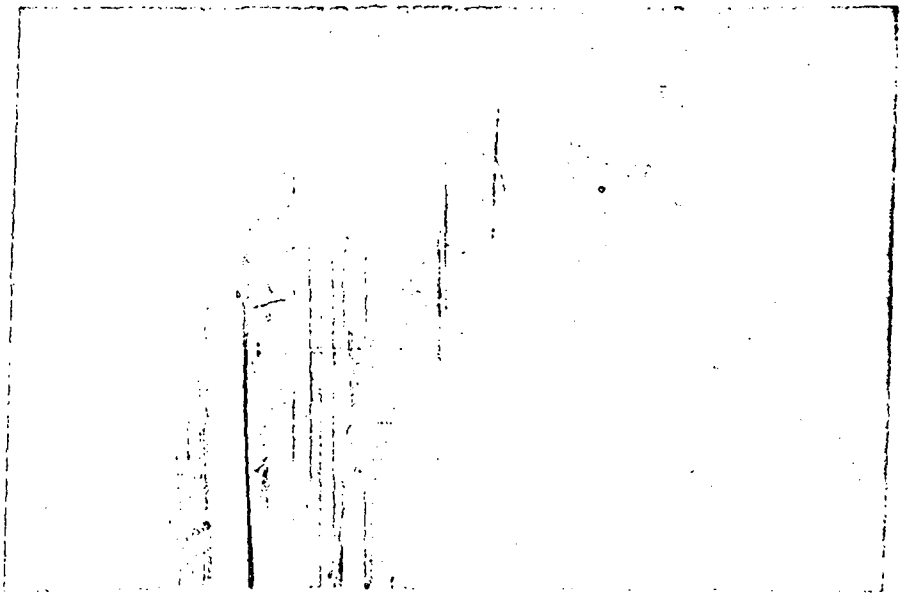
8.1.1 The Filters

A set of two filters, at Walton Water Works used by the Thames Water Authority for research purposes, was chosen, to modify and use for the purpose. The two filters are adjacent to each other, one was used as the pilot and the other operated as control. Each measuring 10' 6" (3.20m) long, 6' 0" (1.82m) wide, and 7' 11" (2.41m) mean deep. The walls on three sides are of mass concrete, 2' 6" (0.76m) thick, with a 1' 0" (0.3m) thick concrete dividing wall. Each filter has two observation glass panels 2' 0" (0.61m) wide, in the side and back walls. To minimise disturbance due to incoming water, an 8 gallon (36 litre) tank has been made in the wall below the ball valves.

A common inlet pipe (2" G.I.) rises through the control room to the top of the filters and distributes the water through a tee and ball valves into the two filters. The

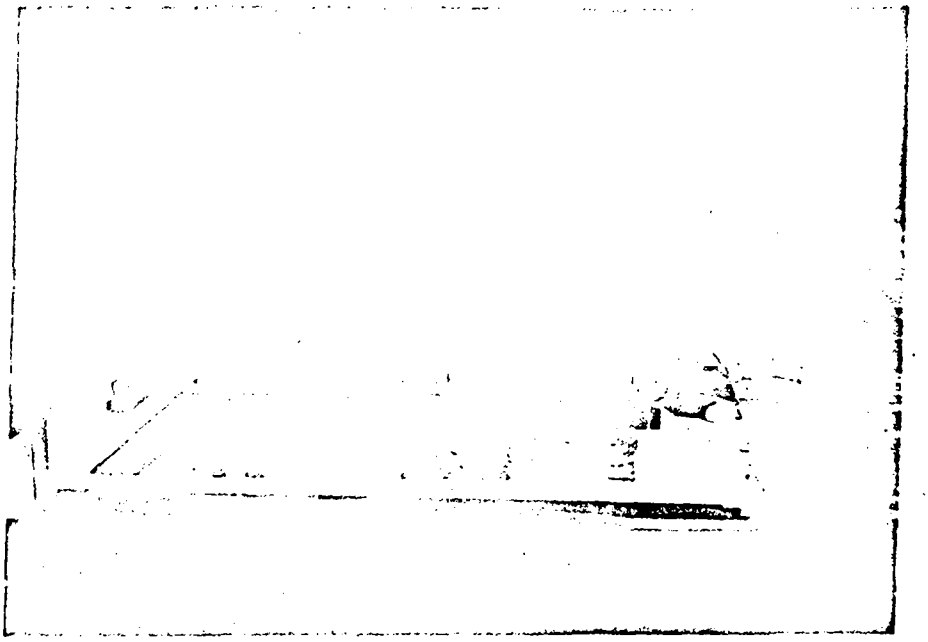


Pilot Filters, General View

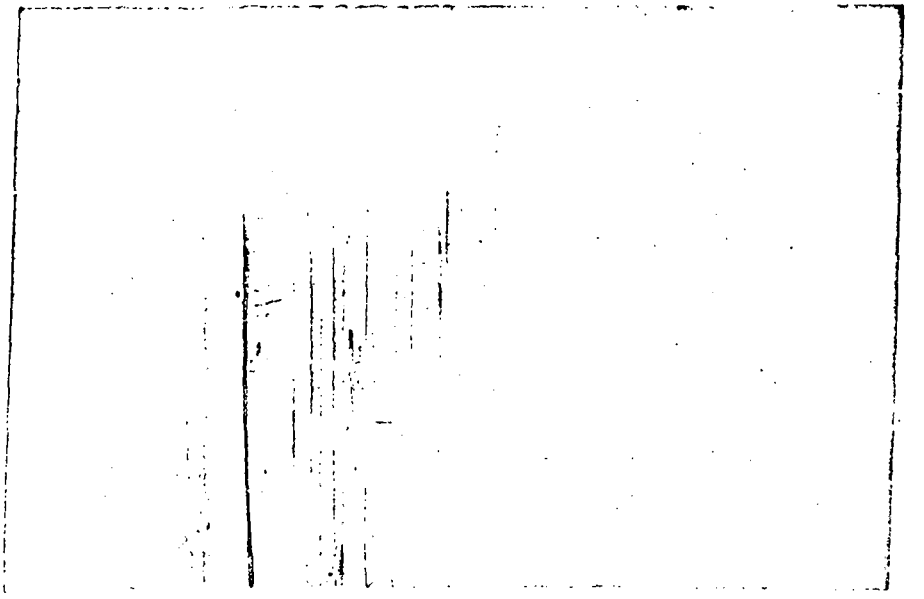


Control Room for Pilot Filters

Photo 8.1.2



Pilot Filters, General View



Control Room for Pilot Filters

Photo 8.1.2

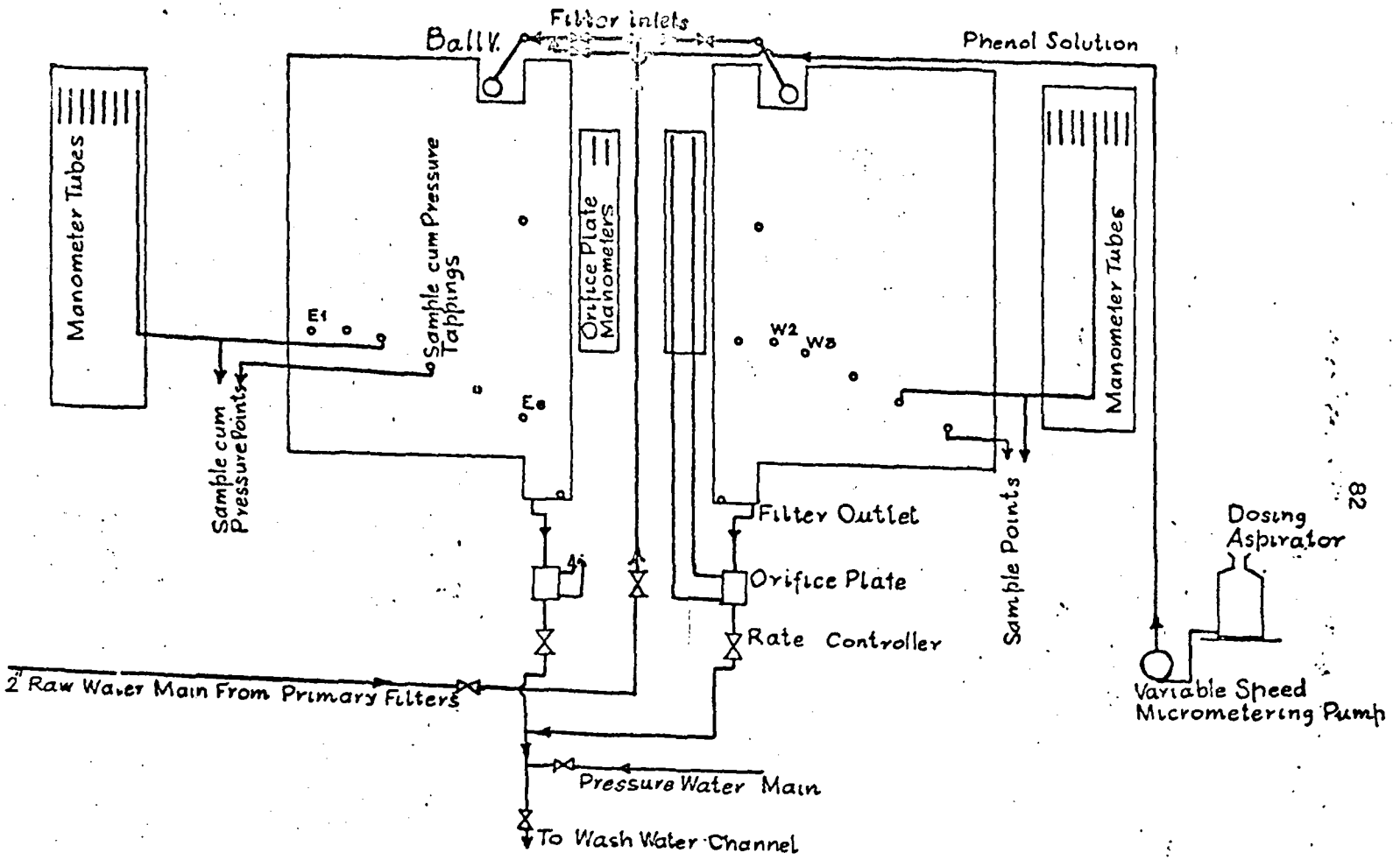


FIGURE 8.1.3

FLOW DIAGRAM OF EXPERIMENTAL SETUP

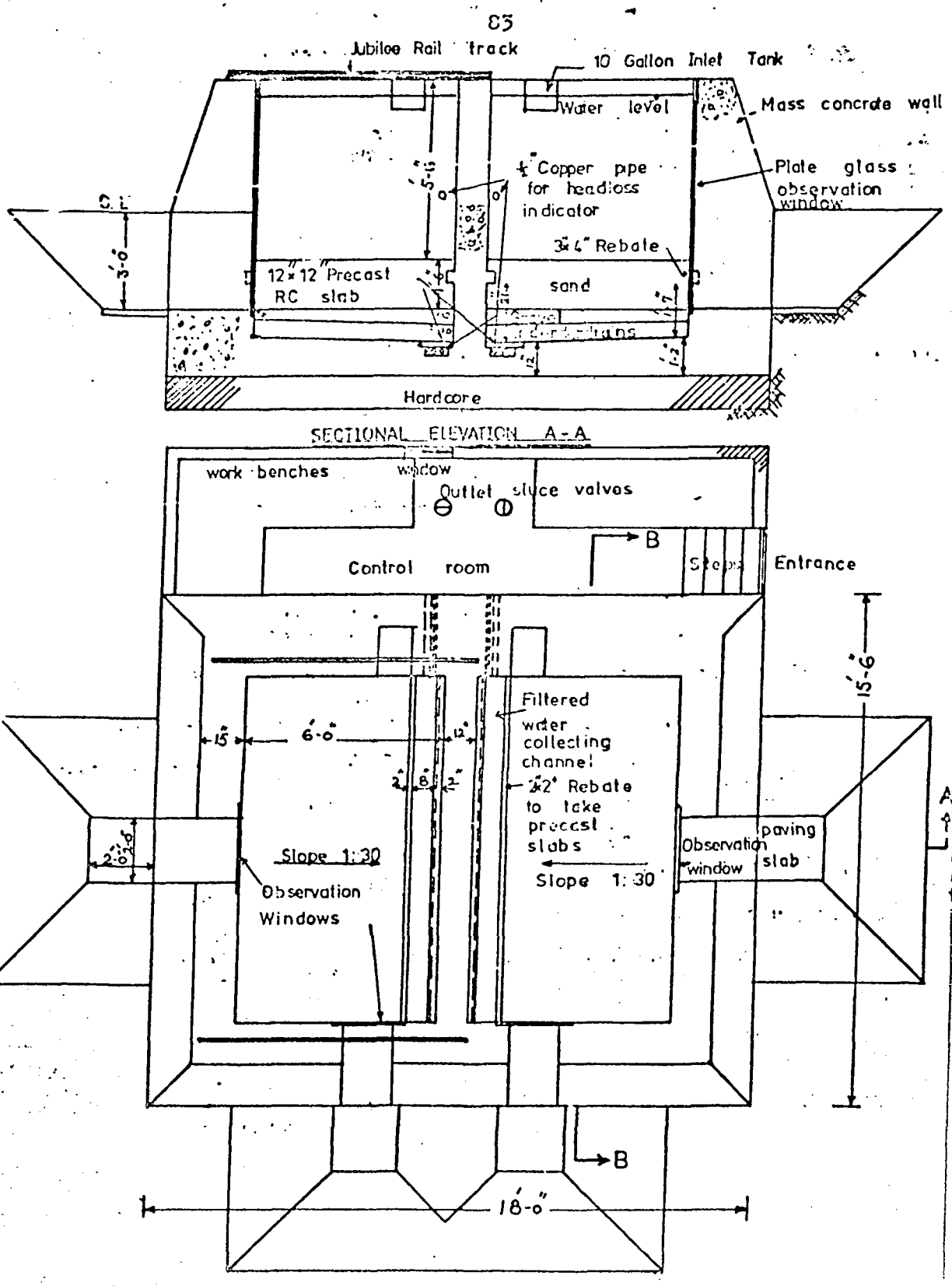
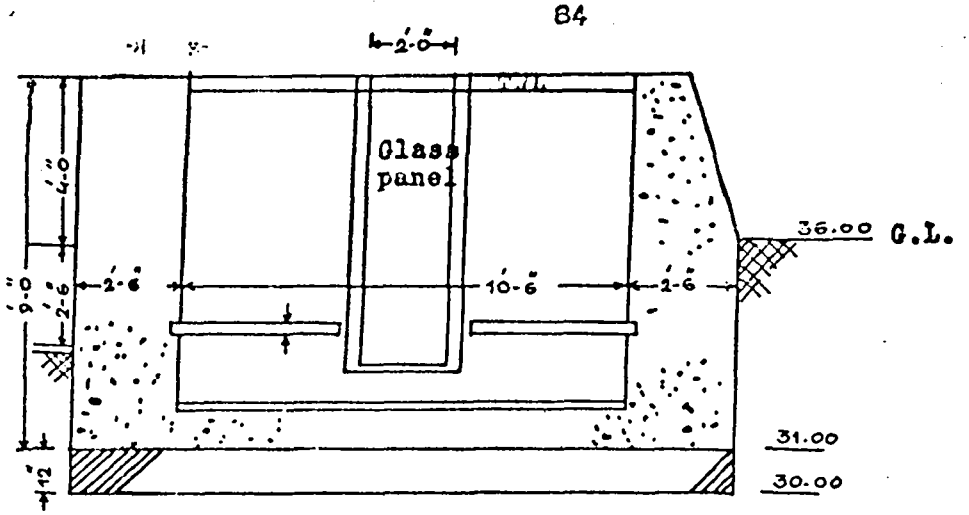


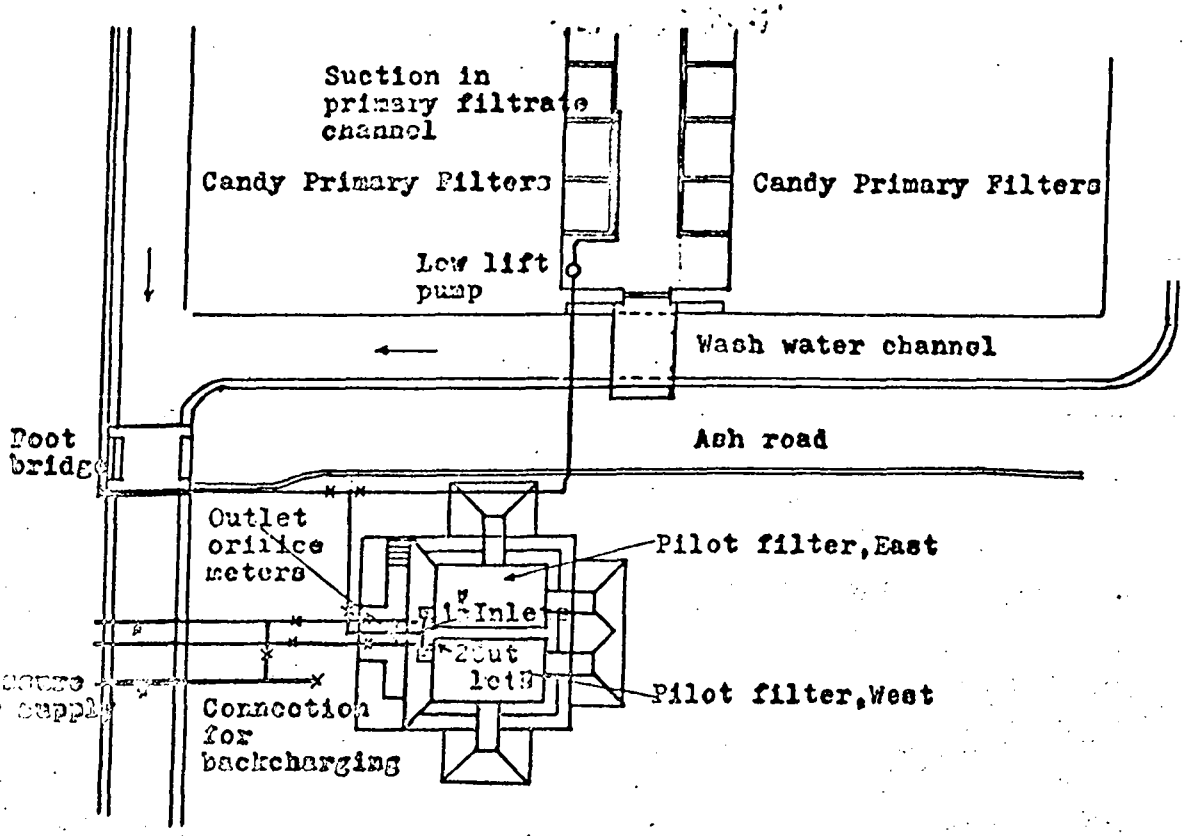
FIGURE 8,1,4

LAYOUT OF PILOT FILTERS



SECTIONAL ELEVATION B-B

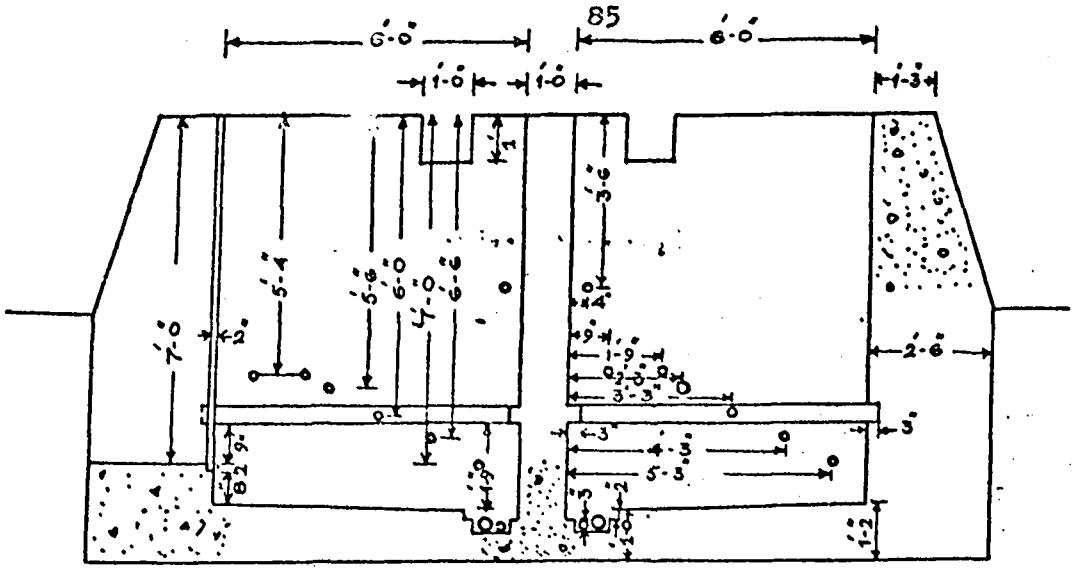
(Sand etc.removed)



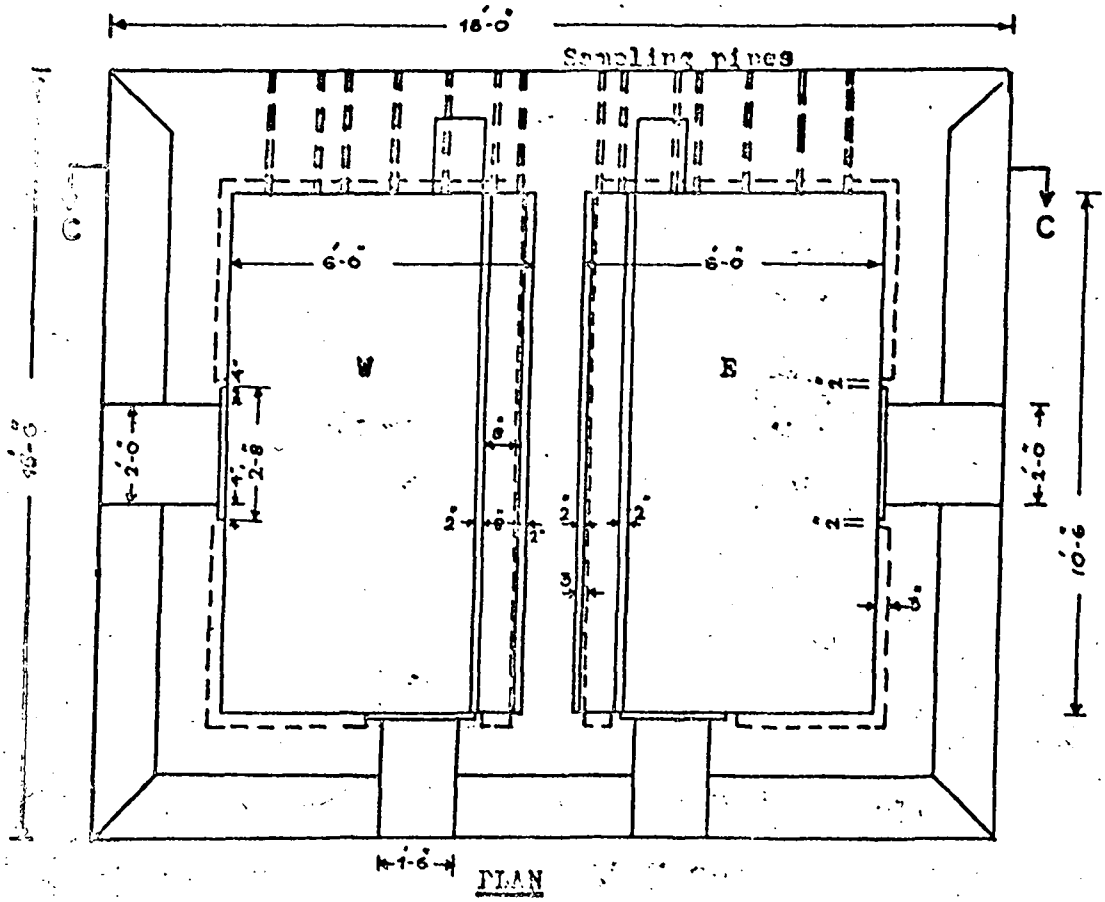
SITE PLAN

FIGURE 8.1.5.

Site plan of pilot filters



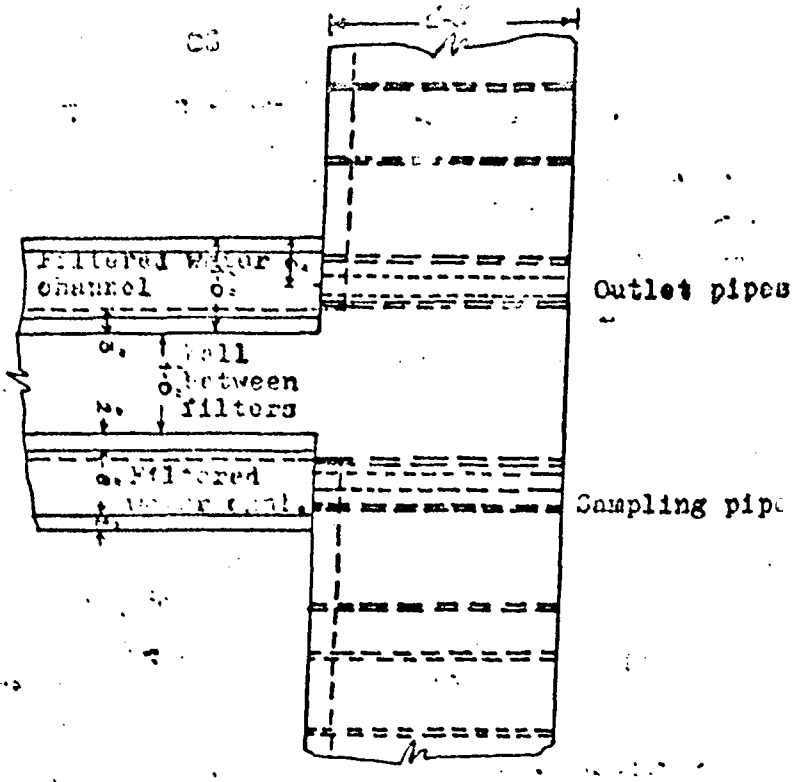
SECTION C-C



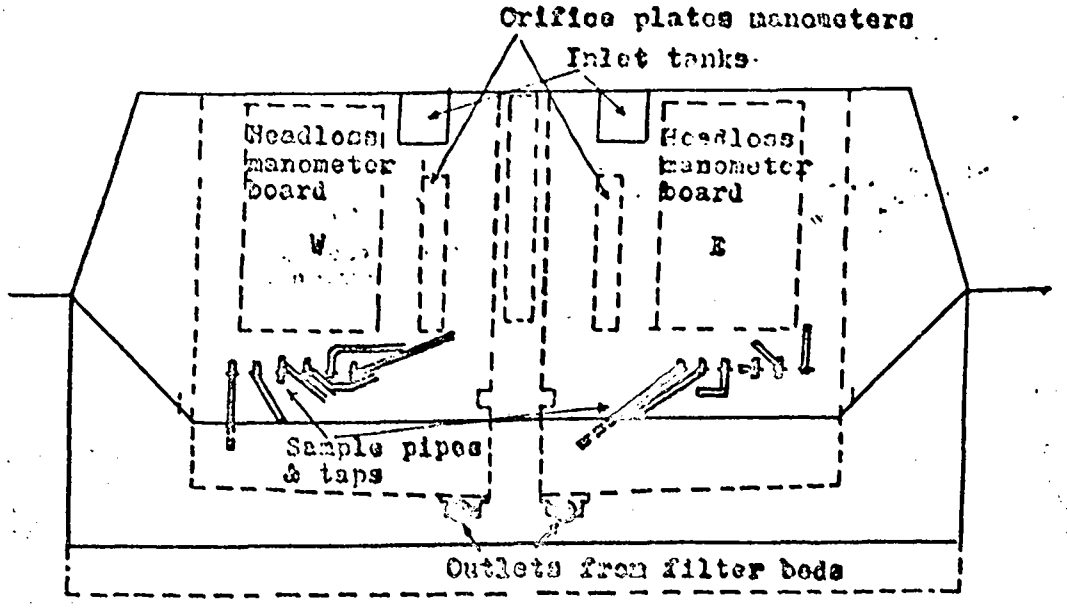
PLAN

FIGURE 8.1.6.

Layout of sampling pipes



DETAIL OF FILTERED WATER CHANNEL, PIPES, ETC.



ELEVATION E-E

FIGURE 8.1.7.

underdrainage channel (1' 0" x 0 3") terminates into the outlet pipe (2" G.I.) fitted with orifice plates and the control valve, to be able to regulate the flow of filtrate and the recharge water. The total headloss pipes are fitted 3' 6" (1.06m) below the top, and in the filtered water drainage channel. The filter floor has a slope of 1:30 towards the drainage channel. Staggered sample cum pressure pipes are led through the north wall into the control room, spaced 6" (15 cm) vertically, spread over full filter width, in the lower 4' 6" (1.37m) of the filter. The pilot filters are constructed half dug in ground in the vicinity of primary filters, from where they receive raw water. All these details are shown in figs. 3.1.4, 3.1.6, 3.1.7 and 3.1.10.

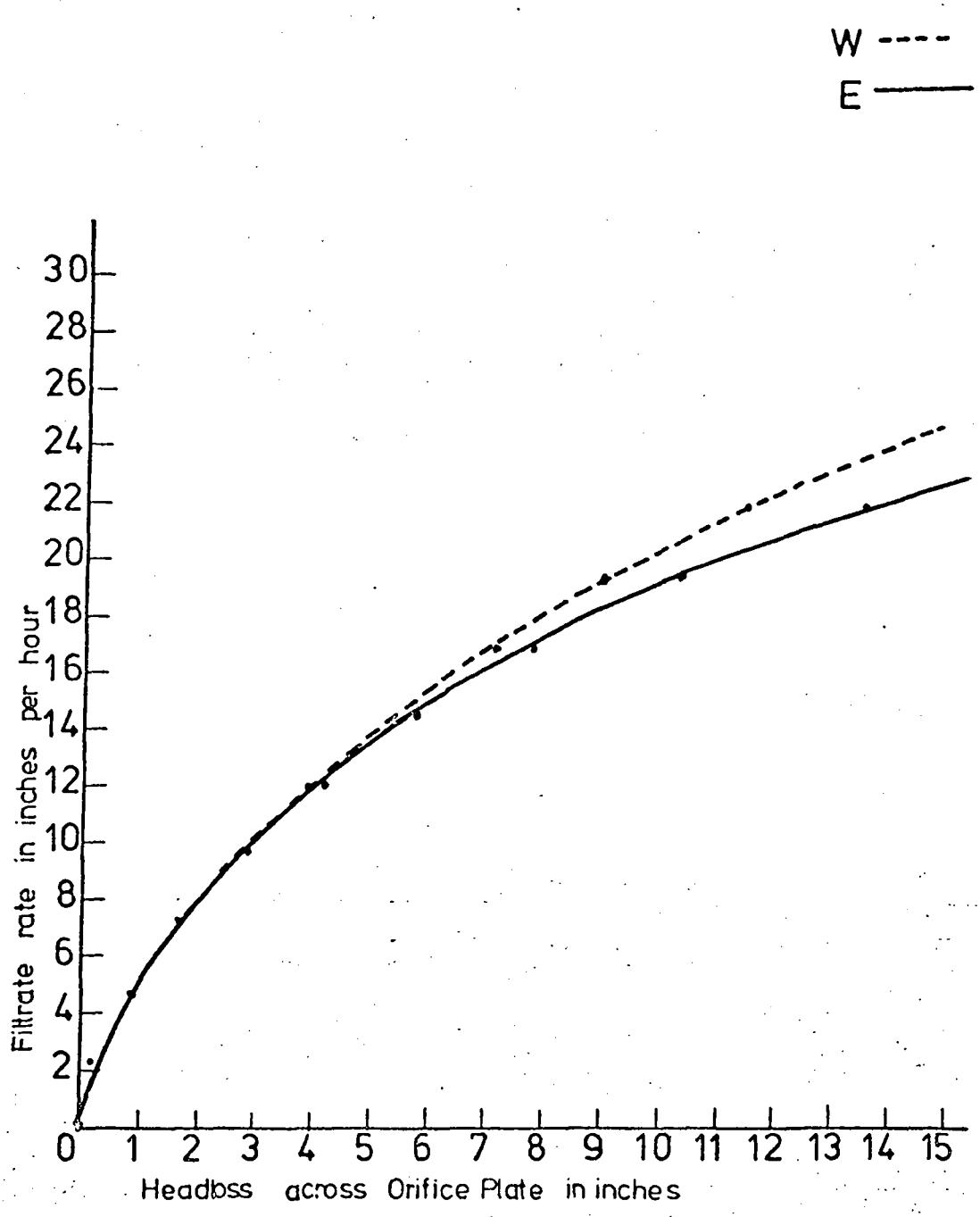
In view of the importance of wall effect (Rose, 1945) the pilot filter size was considered satisfactory enough with respect to the media therein or the actual size of slow sand filters in use. The free board of 6" (15 cm) was only just sufficient to take care of fluctuations in water level.

3.1.2 Flow Measurement and Control Equipment

Filtrate from each filter unit passed through the orifice plates to the flow control equipment and then to waste in the wash water channel or alternatively into slow sand filter no. 1 of the main water works.

The flow was measured with orifice plate type capable of measuring from almost zero to 22 ins/hr (0.56 m/h) of flow rate (of filtration), as depicted by the calibration curve in graph 8.1.8.

As in the full scale filter, the use of a rate controller assisted the maintenance of a constant flow through the filter. It was only once or twice a week that the manual adjustment of the rate controller was necessary to



GRAPH 8.1.8

Calibration Curve - Filtration rate V/S Headloss on Orifice Plate

maintain constant flow regardless of the headloss in the filter. The position of rate controller has been shown in fig. 8.1.10. The inlet water was controlled by a ball valve based on the throttling action, which depended on the level of water in the filter.

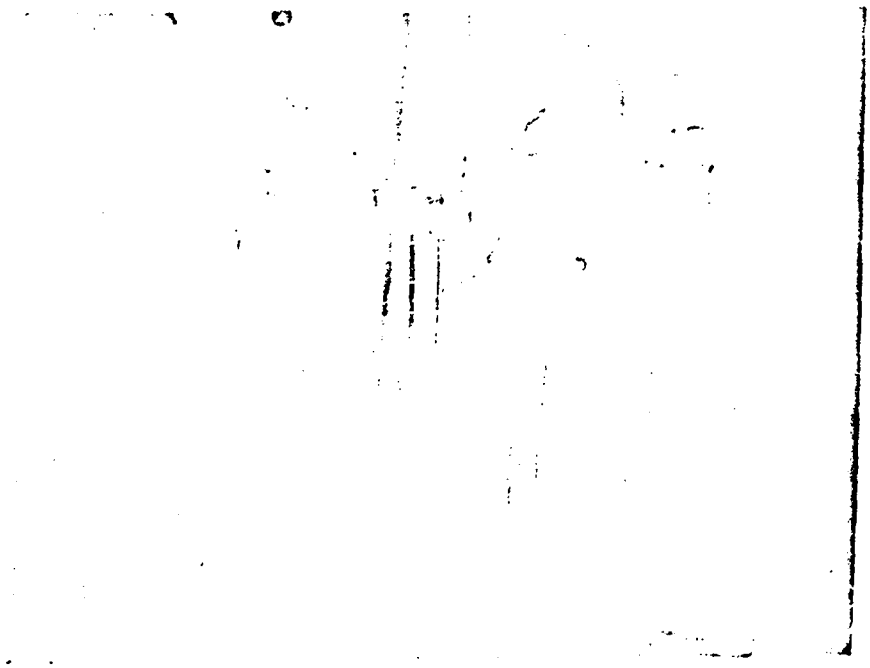
The apparatus worked satisfactorily, except that the rate controller on the west control filter sometimes gave trouble in fine adjustment, as it was also sensitive to heavy vibrations and manual control.

8.1.3 Headloss Equipment

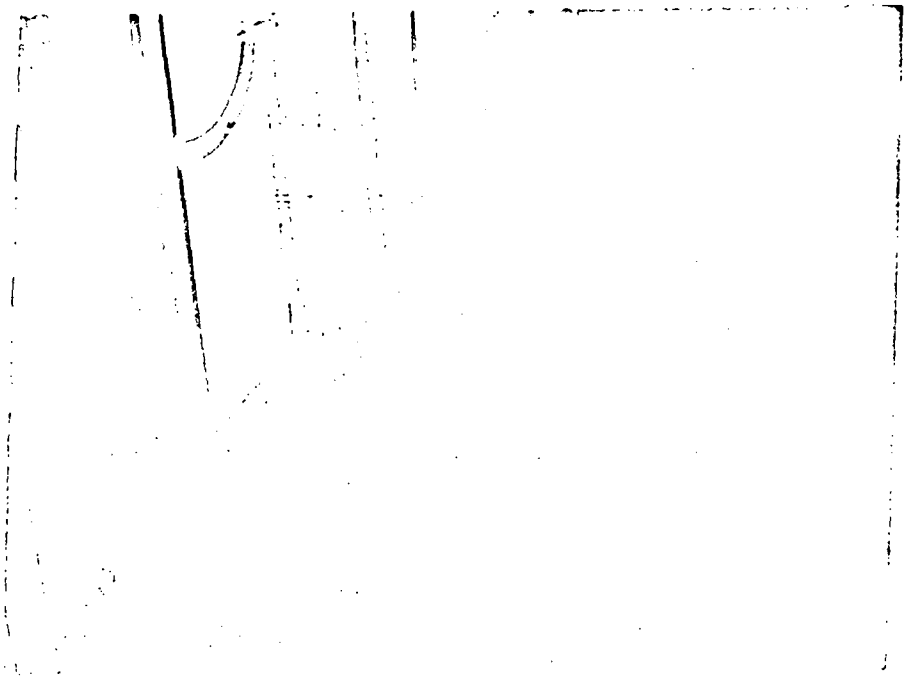
The arrangement of headloss equipment was made by designing and fabricating a separate manometer board 70" (175 cm) high for each filter. After initial difficulties it was enclosed in a metal frome covered with perspex sheet sealed with black tape to minimise moisture penetration and fungus growth which occurred earlier. The manometer board was installed right above the sampling taps, with eight transparent 1/4" (6 mm) dia. Polythene tubes to connect six sampling and two headloss probes. In the sample tap connectors tee junctions were made and connected to the manometer. Thus the complete profile of the headloss throughout the vertical section of the filter was visible. If the profile looked erratic at any stage, especially at the start of the run, the respective manometer tube was operated to clear airlocks by unclamping and flowing water through it for a few minutes. A close up view of connections is shown in photo 8.1.9 and the headloss equipment in photo 8.1.2 and fig. 8.1.7.

8.1.4 Dosing Pump

A Micrometering Pump Series II (Metering Pumps Limited, 83 New Broadway, Ealing, London, W.5, England) with composite

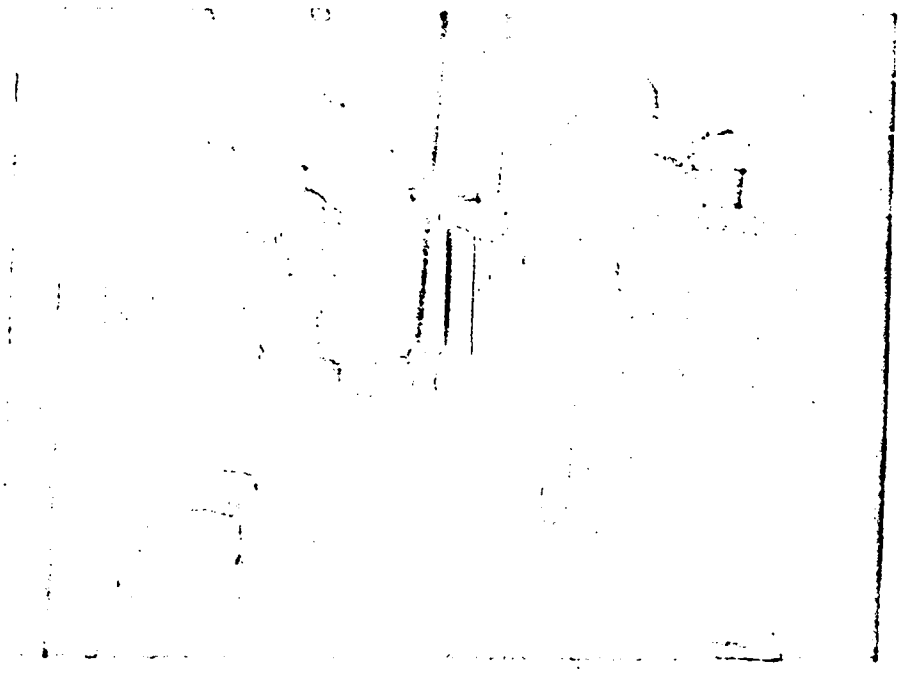


Cooling Device

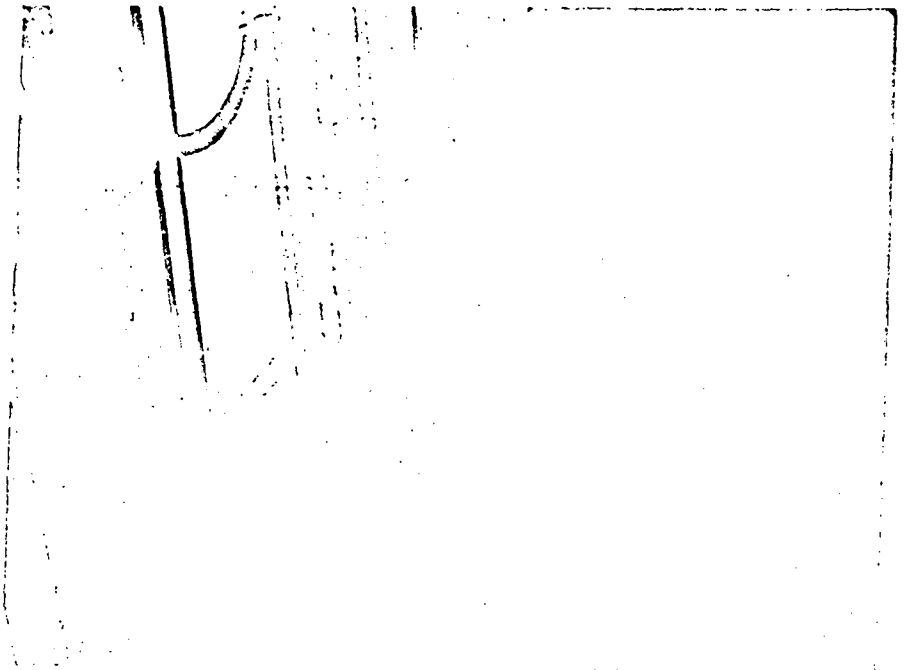


Close up of Sample Taps and Hose Connections

Photo E.1.9



Dosing Device



Close up of Sample Taps and Heating Connections

Photo 8.1.9

motor was used for dosing the phenol solution to the influent of the east filter (photo 3.1.9). To eliminate priming, and to help pump work efficiently, a flooded and short line suction, and to ensure positive seating of valves, a delivery pressure of five feet had been provided. Since the volume of solution dosage 15 ml per hour was small, an additional mechanism, known as the capsule reduction unit was used, which reduced the S.P.M. from 100 to 20 and the pump capacity from 230 to 45 ml per hour. Under appropriate conditions, a calibration curve was prepared with the help of a burette, and was found to be within 2% variation. Thought was given to the highly corrosive nature of concentrated phenol solution on the pump head, but considering the contact material of stainless steel (18/8/3 grade) and ceramic, in the standard head, its replacement with nickel or monel metal or high density polythene was considered not necessary.

3.1.5 Dosing Device

Concentrated 80% phenol solution was stored in two 10 litre capacity glass aspirator bottles connected through a 1/4" (6 mm) dia. polythene tube cross. The other two hands being jointed to a 1/2" bore glass burette for calibration, and to the inlet of the micrometring pump as shown in photo 8.1.9. The concentrated phenol solution was pumped through the micrometring pump, and injected into the 2" G.I. inlet pipe carrying water from the primary filters, at a point just before the ball valve for the east filter, as shown in fig. 8.1.3.

3.1.6 Sampling Device

Headless cum sampling probes made of 1/2" G.I. pipe having holes of 1/8" (3 mm) dia. throughout the length projected 6 ft (1.85 m) into the bed (figs. 8.1.10 and 8.1.6).

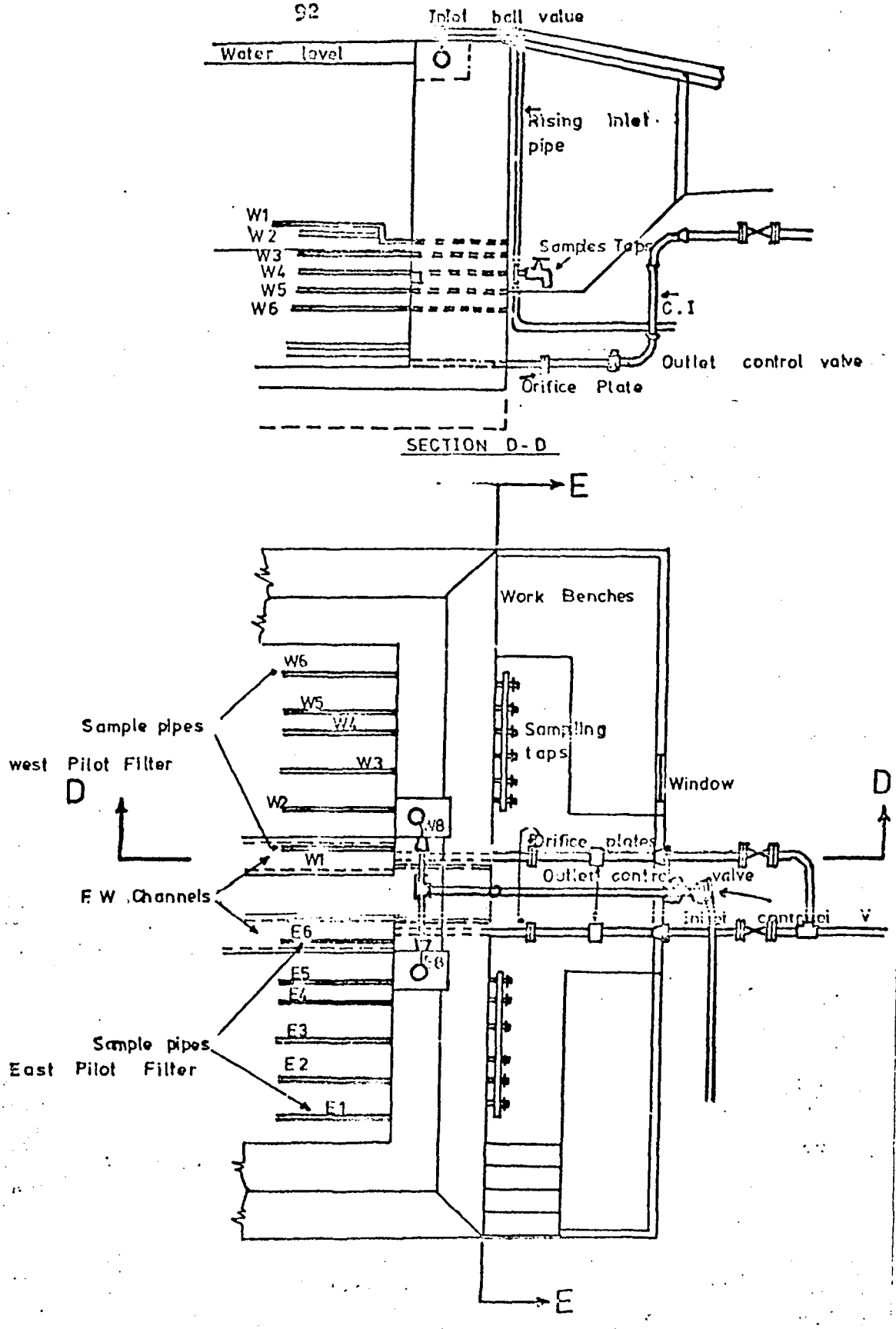


FIGURE 8.1.10 PLAN
Details of Pipework in Control Room

By this means the area of withdrawal was kept sufficiently high yielding enough water in the sampling tap. To be able to provide natural conditions, without any undesirable biological growth around the probes, the holes were not covered with a wire gauze as is sometimes done.

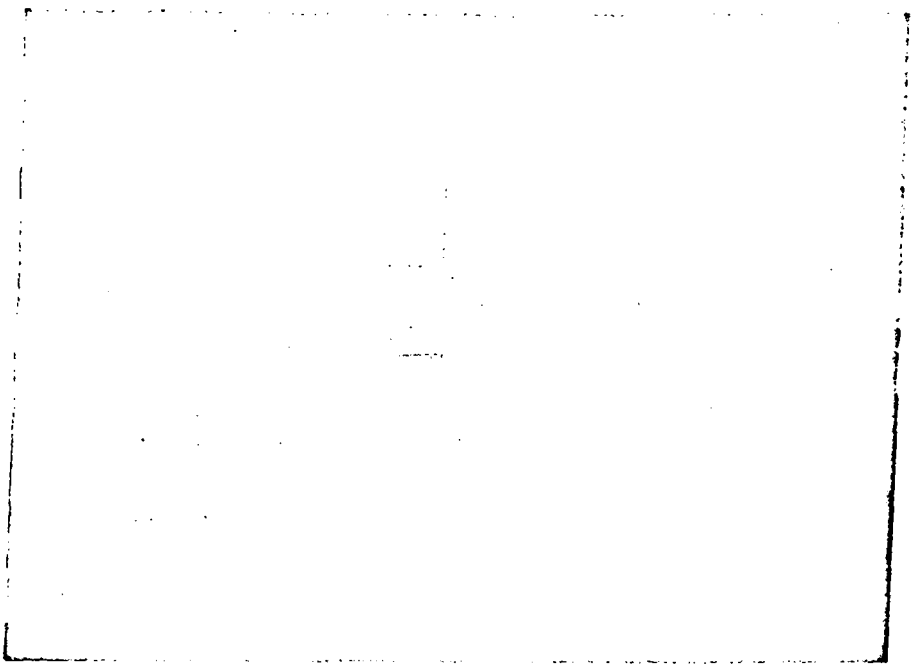
In the control room (beside the north filter wall) sample pipes were connected with brass taps of 3/16" (4.5mm) internal dia. fitted into a manifold, which could allow withdrawal independently and at a designed slow rate as shown in fig. 8.1.7 and photo 8.1.9.

The sampling equipment included 250 cc polystrene wide mouth tall bottles of water tight screwtop, and 500 cc glass bottles with dust proof polythene covers. PVC covered bar racks were used for transporting the bottles.

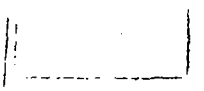
8.1.7 Spectrophotometer (Phenol Concentrations)

The spectrophotometer used was a 'Pye Unicam SP500 Series 2' (Pye Unicam Limited, Cambridge, England), for the measurement of residual phenol in samples of filtered water, drawn from different depths of the pilot filter. The instrument has been designed to carry out single beam absorptiometric measurements within the wavelength range of 186 - 1000 nm. Glass cells (OS Type 3) were considered satisfactory for use with the samples, as these are suitable for all wavelengths above 340 nm. Normal precautions of warming and desiccating were taken in ensuring the stability and reliability of the operation of the spectrophotometer. The instrument is shown in photo (8.1.11). Each time concentration measurements were taken, the instrument was standardised by the following procedure:-

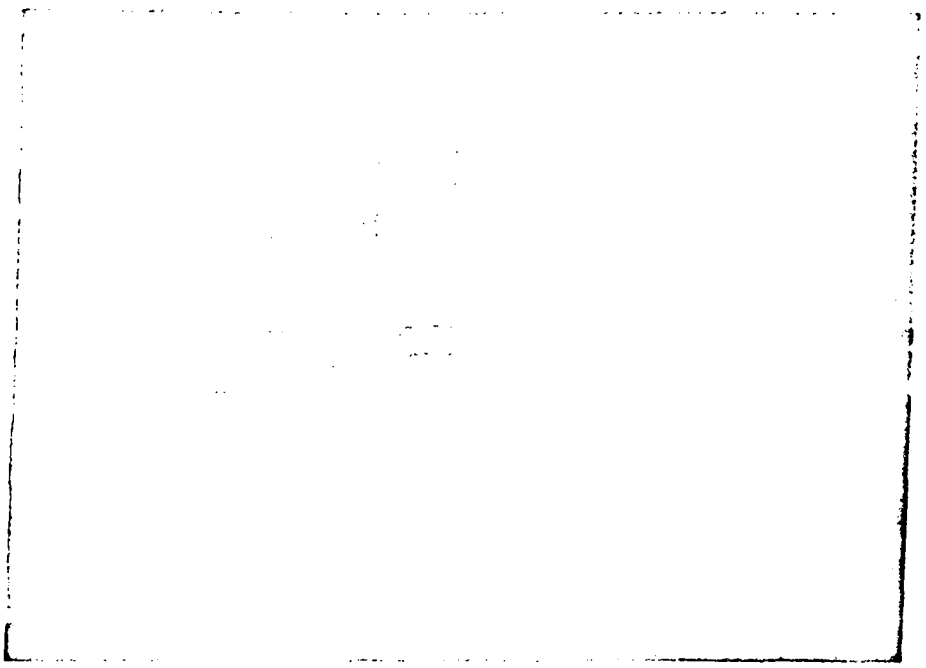
The mains and tungston lamp switches were turned on, and filter slide position 1 (no filter) selected. These being appropriate for a wavelength of 460 nm or 510 nm, for



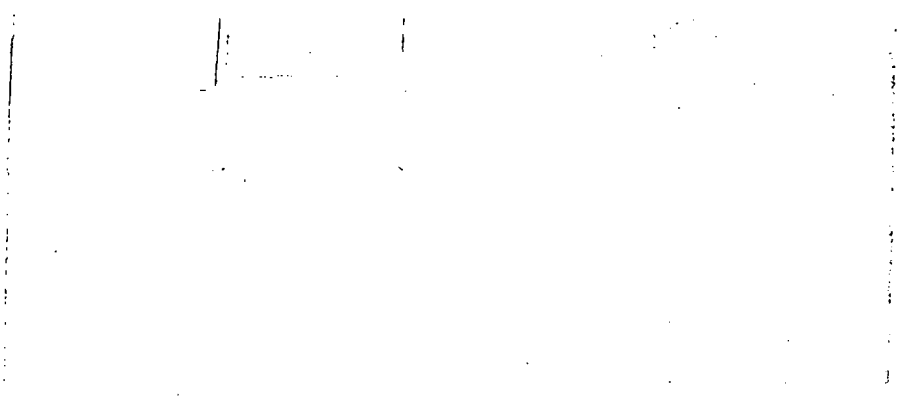
Unicam Spectrophotometer



Hach Turbidimeter

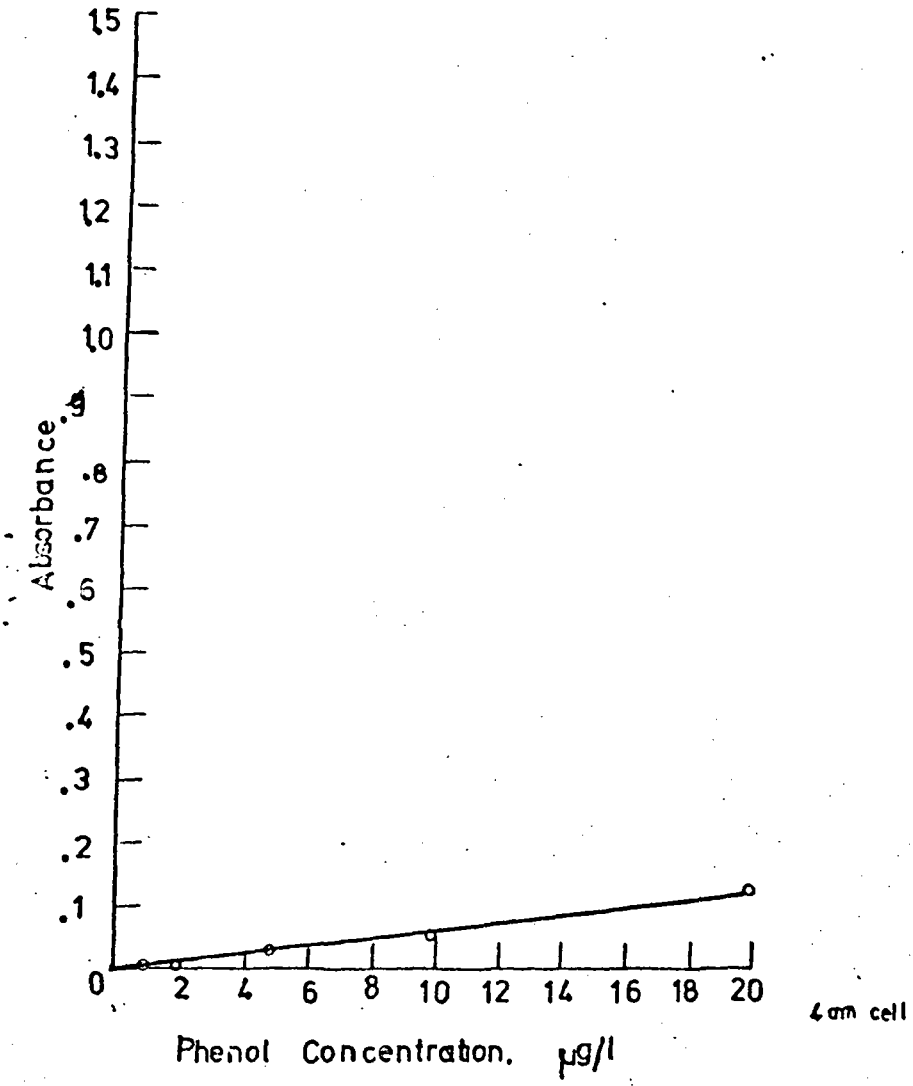


Unicam Spectrophotometer



Hach Turbidimeter

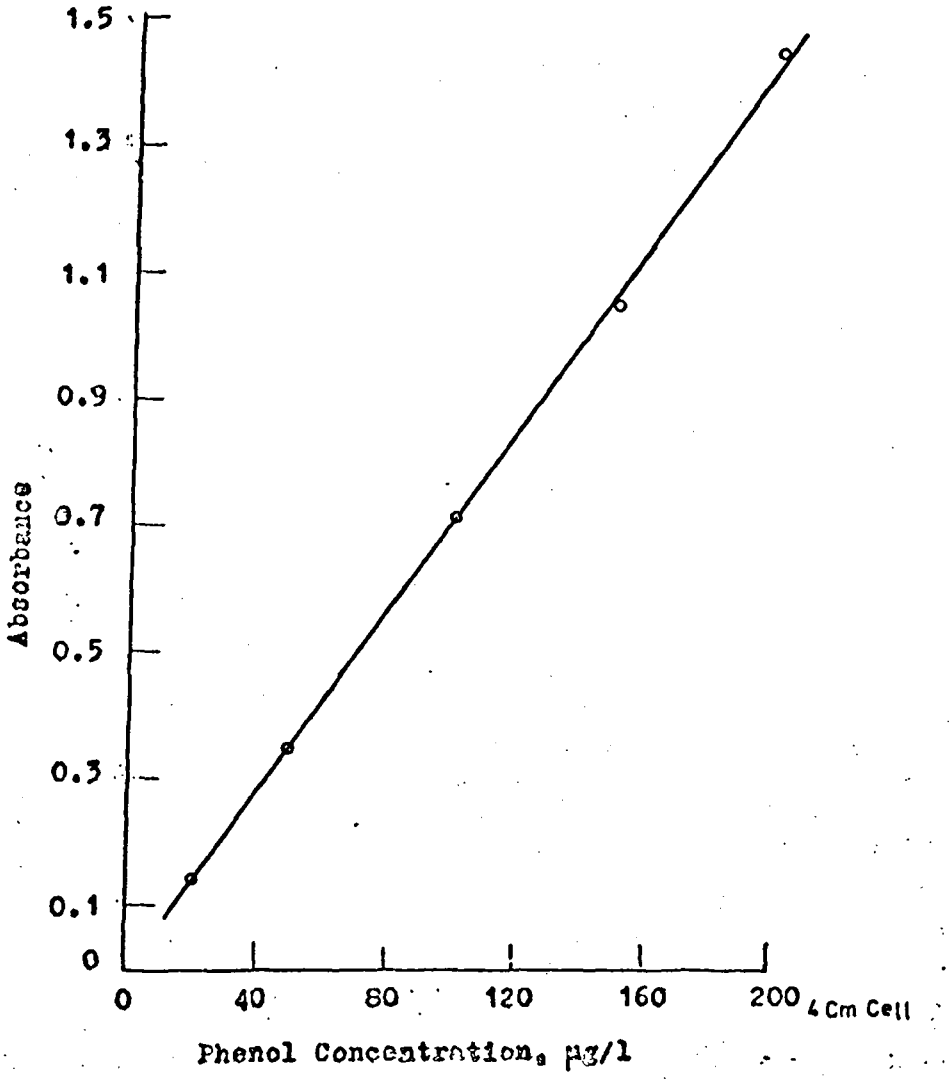
Photo 8.1.11



GRAPH (Figure) 8.1.12

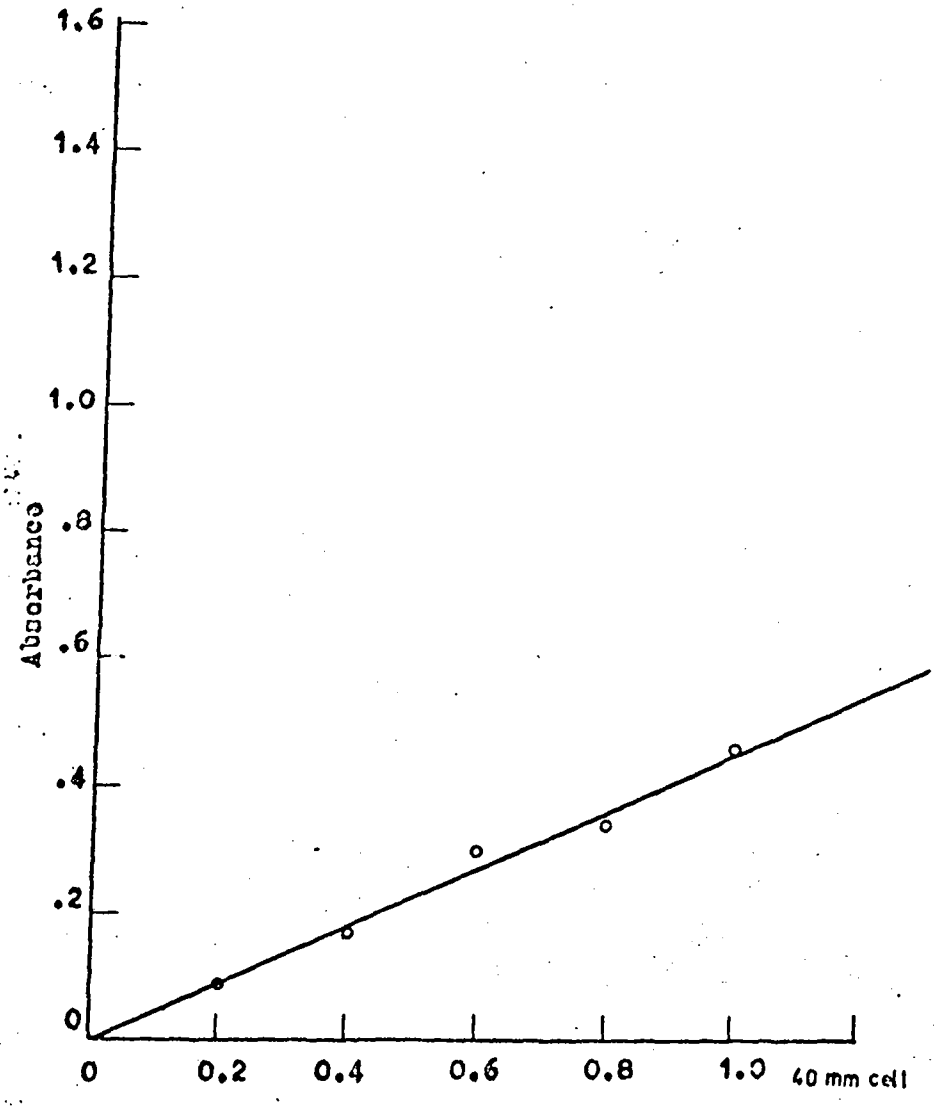
SPectrophotometer Calibration Curve
Phenol Concentration (µg/l) V/S Absorbance

(200 ml sample extracted into 25 ml chloroform and measured at 460 nm.)



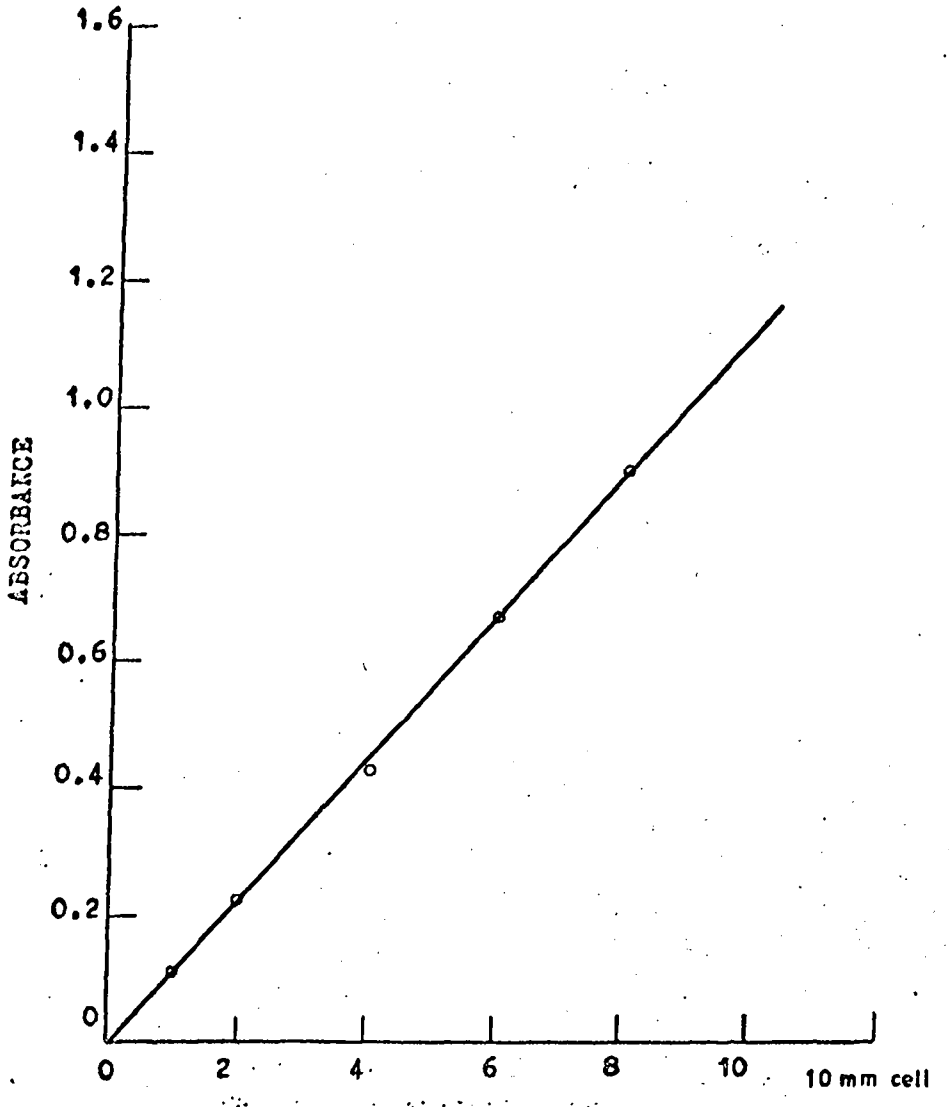
GRAPH 8.1.13

Spectrophotometer Calibration Curve of Phenol Concentration (µg/l) plotted against Absorbance.
(200 ml sample extracted into 25 ml chloroform and measured at 460 nm.)



GRAPH 8.1.14

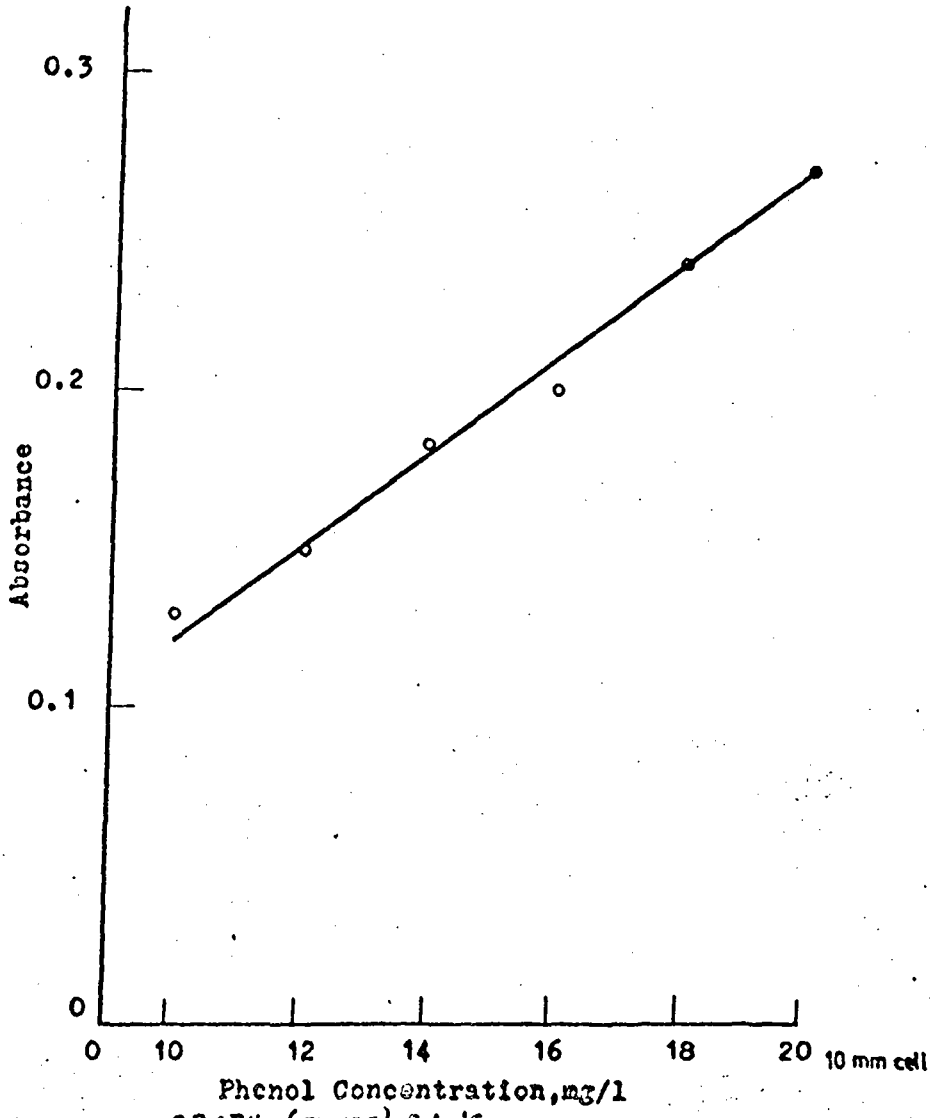
Spectrophotometer Calibration Curve of Phenol Concentration (mg/l) plotted against Absorbance.
(50 ml sample used and measured at 510 nm.)



GRAPH 8.1.15

Calibration Curve of Phenol Concentration (mg/l) plotted against Absorbance.

(50 ml sample used and measured at 510 nm)



GRAPH (FIGURE) 0.4.16

Spectrophotometer Calibration Curve of Phenol Concentration (mg/l) plotted against Absorbance. {50 ml sample processed, and final colour diluted to tenth (10 ml final colour+90 ml distilled water) and measured at 510 nm.}

chloroform solutions, wavelength control was set at 460 nm., and for aqueous solutions at 510 nm., giving maximum deflection with the colour developed by phenol (Taras et al. ed. 1971) in the respective solutions. Cells of appropriate size were used with blank and sample solutions, taking care in maintaining them clean and locating properly in the instrument. The mode was switched to 'direct read out', and zero control adjusted to 0% transmittance, ∞ absorbance, with the blank in the light path and the zero shutter pulled out, the slitwidth control was adjusted to 100% transmittance (zero absorbance). These two end positions were checked once or twice, and then the sample was moved into the light path and absorbance read. Thus one by one all the samples were moved into the light path and their absorbances recorded. The two end positions were checked again before closing. Using the calbration curve drawn already, the absorbances were translated to phenol concentrations. The calibration curve had been drawn by determining the absorption caused by solutions of known concentrations. Five typical calibration curves are illustrated in graphs 8.1.12 - 8.1.16, depicting different ranges and different media, in which each point is the average of six readings.

8.1.8 Turbidimetry

A 'Hach Laboratory Turbidimeter' working on the nephelometric principle, model 2100A (Hach Chemical Company, P.O. Box 907, Ames, Iowa, U.S.A.), of high sensitivity was used, which could measure turbidity down to 0.01 JTU was used for the water samples drawn from different depths of the pilot filters. To be able to take turbidity readings immediately after sampling, the instrument was kept on site. As the instrument is affected by even finger prints on the cells while using its finest range, due care was taken in keeping the cells clean. The instrument is shown in photo 8.1.11.

Calibration and Operation:- The calibration of the Turbidimeter is made in Jackson Turbidity Units (JTU), based on a formazin solution, now regarded as the best known turbidity standard.

The precision of calibration was checked in the laboratory by the following procedure :- 5.000 gram of reagent grade hydrazine sulphate, $(NH_2)_2H_2SO_4$, was dissolved in about 400 ml of double distilled water, and in another volumetric flask 50.000 grams of pure hexamethylenetetramine, $(CH_2)_6N_4$, was dissolved in 400 ml of double distilled water. The flasks were warmed on a flame for good dissolution of the reagents. Then the contents of one were poured into the other and the solution made up to one litre mark with the distilled water, and allowed to stand for 48 hours at about 30°C, to allow the suspension to develop. The resulting stock suspension had a concentration of 4,000 JTU. Solutions of 1000, 500, 100, 50, 10, 5, 1, 0.5, 0.1 and 0.01 JTU concentrations were prepared by diluting 250, 125, 25, 12.5, 2.5, 1.25, 0.25, 0.125, 0.025 and 0.0025 ml of adequately mixed stock suspension to one litre with distilled water. This corresponds with the procedure in Standard Methods (Taras et al. ed. 1971) except that the concentration of the stock solution there has been kept at 400 JTU. These produce one Formazin Turbidity Unit (JTU) equal to one JTU. The diluted samples thus prepared were read in the instrument and a calibration curve drawn based on average of four readings. The resulting calibration curve as shown in graph 3.1.17 fitted well with the theoretical one. The JTU markings on the instrument panel were thus dependable and accurate and no correction was considered necessary on that account. The only correction applied was to readings in the finest range of 0-0.2, due to stray light, and a correction subtraction of 0.04 JTU was applied to all readings in that range. Every time the instrument was used, it was standardised as follows:-

After turning the power switch on and allowing for warming, the instrument was standardised at 70 JTU, using a glass encased standard rod provided with the instrument. It was also standardised before a new set of samples, or every half hour to eliminate drift errors. After mixing the samples adequately, by gently inverting the sample-containing bottle thrice, it was transferred to the sample cell and read on the instrument for turbidity, after covering the cell with light

shield, and taking due care in maintaining the cell surface clean and dry. If the sample showed fine air bubbles when held in front of a light beam, then it was allowed to stand for about five minutes for the air bubbles to rise past the photomultiplier tube, before noting the reading. Whilst waiting for the next batch of samples, the instrument was still kept on, but the cell holder lid was closed without the cell.

Comparison with EEL Nazometer:-

An effort was made to establish a relationship between the Hach Turbidimeter and the EEL Nazometer used by the Water Examination Department of the Thames Water Authority (previously Metropolitan Water Board of London). A wide fluctuation of readings was noticed between the two instruments, and no linear relationship, over a long range, was possible between the two, as also evidenced by graphs 8.1.18 and 8.1.24. It was therefore decided to ignore any relationship, for readings in the finer range of below 0.2 JTU. Over the major part of the coarser range, a multiplying factor of 1.6 could be established based on the statistical and graphical means of a large amount of data collected by readings on both instruments from the same samples. The graphical mean has been obtained by means of visual line of best fit. The disparity of readings was traced to the Silica Scale Units (in mg/l) based on Fullers Earth Standard in the case of EEL Nazometer. According to German Standards Method, Kieselgur Units or Silica Units (1 mg SiO_2 per litre distilled water = 1 ppm) are similar to Jackson Turbidity Units. Also, according to Standard Methods Formazin Turbidity Units are similar to JTU. However, Knight (1950) has found different turbidities, when testing different samples of earth. Difficulty has also been expressed (Eden, 1965) in comparing turbidity measurements obtained with different instruments. Considering the importance of size shape and refractive index of a suspension, the possibility of correctly correlating turbidity with the weight concentration of suspended matter is remote. It is therefore accepted that owing to differing optical systems, the results obtained with different types of secondary instruments will frequently not

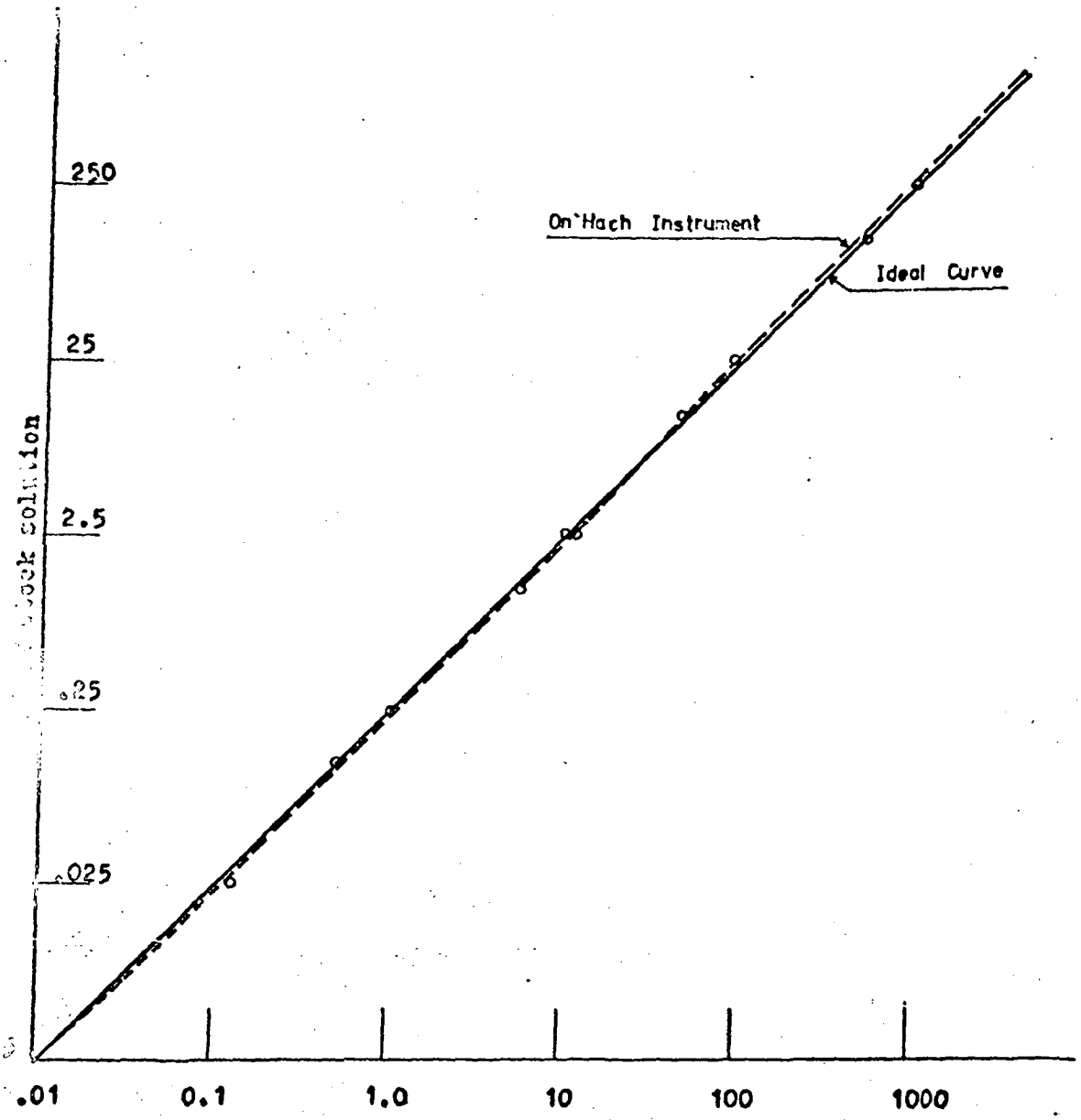
check closely, even though they are precalibrated against the candle turbidimeter (Taras et al. od. 1971).

As the comparison between Hach Turbidimeter and readings on EEL Nazometer had not been carried out before, it was thought appropriate to carry out the study over a wide range of turbidity and samples. At the conclusion of the study it was clear, that results must be studied in blocks to be meaningful, and therefore several categories of water were analysed and interpreted in suitable turbidity ranges covering filtered water, primary filtrate, stored reservoir water and the river water.

Turbidity data on filtered water (tables 8.1.1, 8.1.2 and 8.1.4) reveals that 22% of all filtered water samples read a 0 turbidity and 73% read 0.1 turbidity on the Nazometer. Only 3% read a turbidity of 0.2 and still less had a turbidity of 0.3 or more. On the Hach Turbidimeter, there was not a single sample reading zero turbidity. The average reading on the Hach was 0.13 and 0.16 against the above turbidities respectively. The difference between these two ranges on Hach is so little that it shows the limitation of EEL Nazometer in its ability to differentiate between 0 and 0.1. Looking to the great discrepancy between 0 on Nazometer and 0.13 on Hach on the one hand, and the gross inability of the Nazometer to differentiate between 0 and 0.1 on the other, it was decided to ignore all readings below 0.2 on the Nazometer. It can also be concluded that every 0 reading on Nazometer is actually 0.08, or that only 20% of all zero readings are in fact approaching zero.

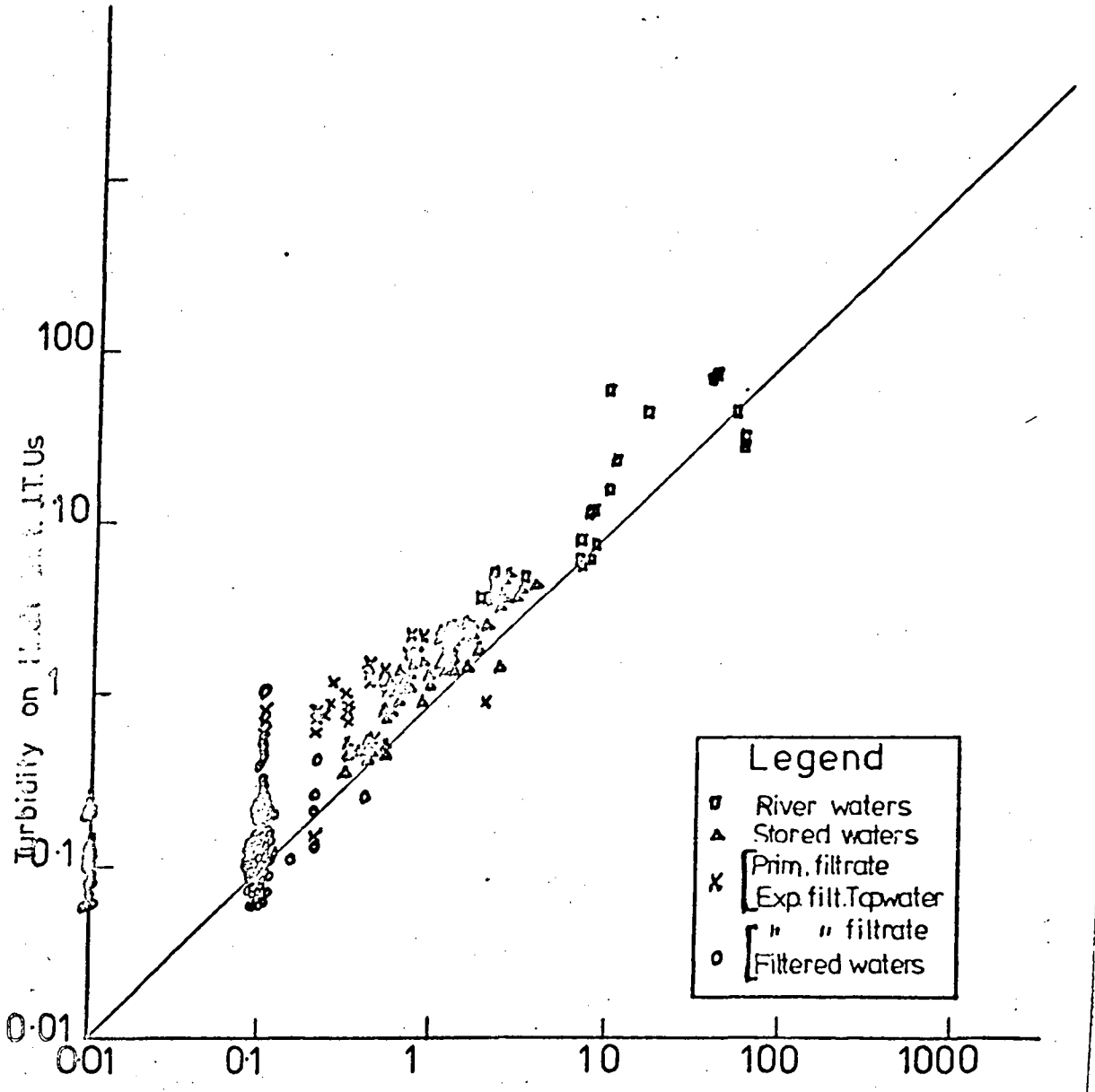
Primary filtrate samples as indicated in tables 8.1.6, 8.1.7, and graph 8.1.22, gave a multiplication factor of 2.9 indicating a larger variation. But stored water and river water samples again give a multiplication factor of 1.6 as indicated in tables 8.1.8, 8.1.9, 8.1.10, 8.1.11 and graphs 8.1.23 and 8.1.24. Interestingly, the special water samples (table 8.1.12, graph 8.1.25) whose turbidity is in the range of primary filtrate, also has a multiplication factor nearer to that range.

The whole comparison has been summed up in table 8.1.13 and graphs 8.1.18 and 8.1.26. The curve in graph 8.1.26 has divided the whole study into four ranges or zones. It is concluded that readings on BEL Nazometer should be ignored below 0.1; multiplied by 1.6, between 0.1 and 0.2 in second zone and beyond 1.0 in fourth zone; and multiplied by 3 between 0.2 and 1.0 in the third zone; to get the corresponding Nach readings.



GRAPH 8.1.17

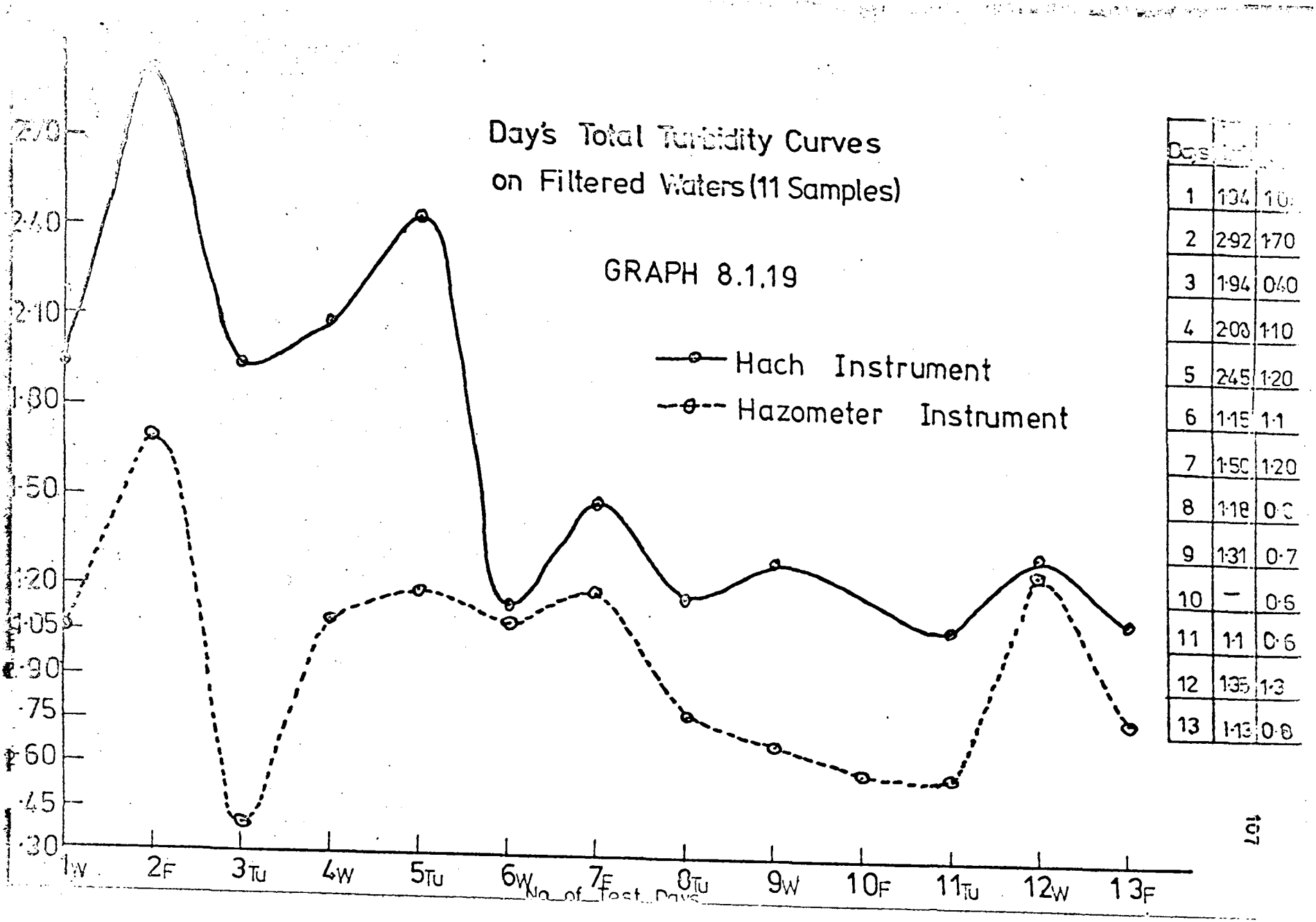
Calibration of Hach Instrument on Formazin solution.



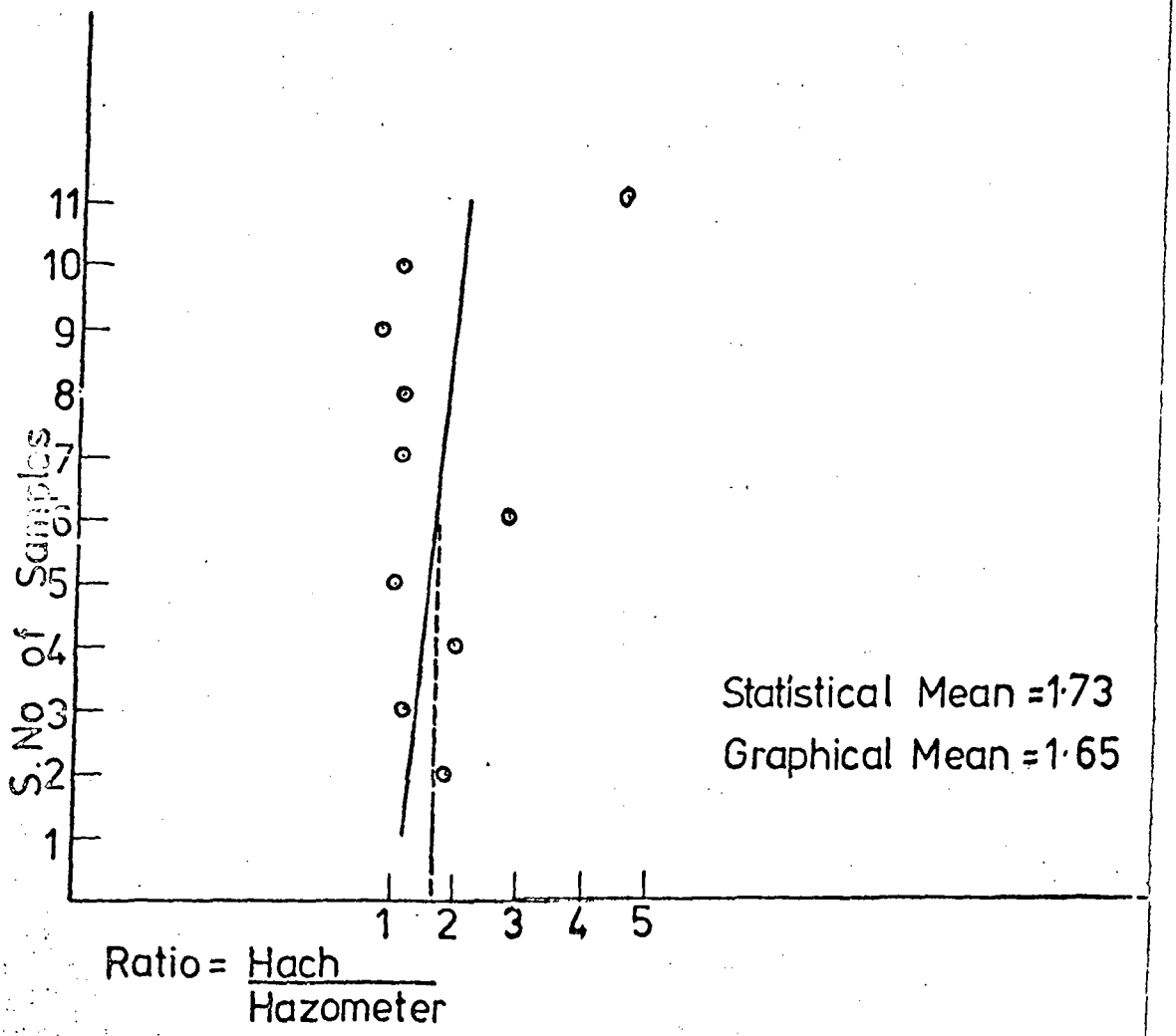
GRAPH 8,1,18

Hazometer V/S Hach-Turbidity

Mass (readings) curve



Days		
1	1·34	1·0
2	2·92	1·70
3	1·94	0·40
4	2·00	1·10
5	2·45	1·20
6	1·15	1·1
7	1·50	1·20
8	1·18	0·0
9	1·31	0·7
10	—	0·6
11	1·1	0·6
12	1·35	1·3
13	1·13	0·8



Relationship between Hach and Hazometer readings
Filtered Water Samples 9/2/72

GRAPH 8,1,20

TABLE 8.1.1

Filtered Water Turbidity, as read on Hach Turbidimeter and EEL Hazometer.

Date	9.2.72		11.2.72		15.2.72		16.2.72		22.2.72		23.2.72	
Source	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo
1 Ashford 1					0.12	0			0.18	0		
Commons 3	0.21	0					0.20	0.1				
4			0.41	0.1							0.10	0.1
2 Surbiton	0.19	0.1	0.19	0.1	0.20	0	0.20	0.1	0.28	0	0.14	0.1
3 Walton	0.12	0.1	0.26	0.4	0.09	0.1	0.20	0.1	0.15	0	0.08	0.1
4 Kempton	0.20	0.1	0.24	0.1	0.11	0	0.14	0.1	0.13	0.1	0.12	0.1
5 Barn Elms	0.10	0.1	0.24	0.1	0.21	0.1	0.09	0.1	0.55	0.4	0.12	0.1
6 Hampton	0.28	0.1	0.48	0.3	0.13	0	1.06	0.1	0.13	0	0.06	0.1
7 Hanworth	0.11	0.1	0.16	0.1	0.20	0	0.14	0.1	0.23	0.1	0.10	0.1
8 Lee Bridge	0.11	0.15	0.33	0.1	0.31	0.1	0.29	0.1	0.27	0.1	0.12	0.1
9 Hornsey	0.07	0.1	0.11	0.1	0.24	0	0.20	0.1	0.13	0.1	0.07	0.1
10 Stoke Newington	0.10	0.1	0.09	0.1	0.06	0	0.11	0.1	0.20	0	0.10	0.1
11 Copper Mills	0.45	0.1	0.41	0.2	0.27	0.1	0.45	0.1	0.20	0.1	0.14	0.1

TABLE 8.1.2

Filtered Water Turbidity, as read on Hach Turbidimeter and HEL Hazometer.

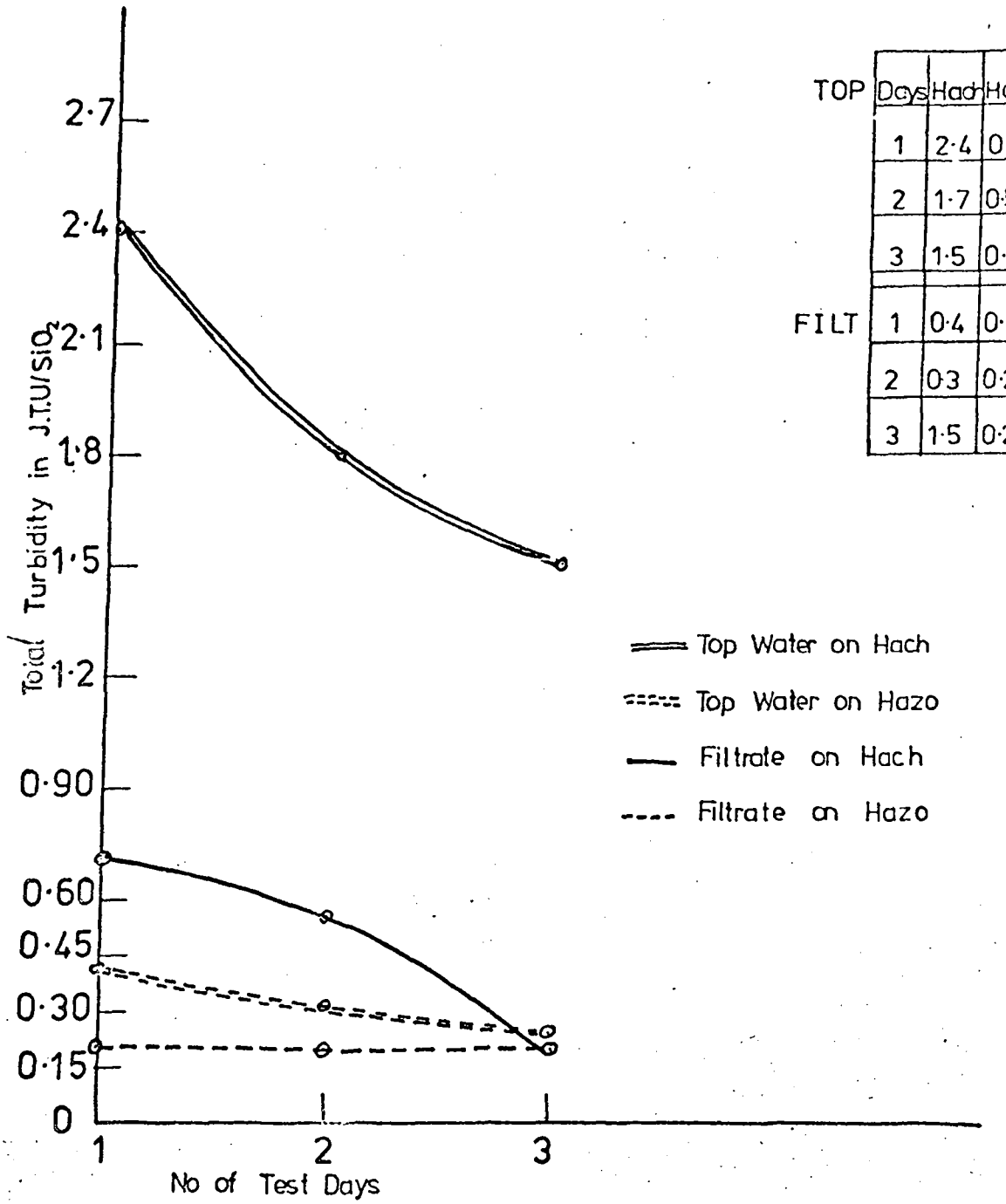
Date	25.2.72		29.2.72		1.3.72		7.3.72		8.3.72		10.3.72	
Source	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo
1 Ashford 1												
Commons 3	0.09	0.1										
4			0.10	0	0.13	0.1	0.08	0	0.07	0.1	0.13	0.1
2 Surbiton	0.13	0.1	0.12	0.1	0.21	0	0.11	0.1	0.14	0.1	0.08	0
3 Kilton	0.15	0.1	0.11	0	0.13	0	0.11	0.1	0.15	0.1	0.09	0.1
4 Kempton	0.11	0.1	0.10	0	0.14	0.1	0.07	0	0.08	0.1	0.11	0
5 Barn Elms	0.13	0.1	0.14	0	0.09	0	0.12	0.1	0.12	0.1	0.10	0.1
6 Hampton	0.11	0.1	0.10	0.1	0.08	0	0.11	0.1	0.26	0.2	0.07	0.1
7 Hanworth	0.13	0.1	0.10	0.1	0.09	0.1	0.13	0.1	0.15	0.2	0.08	0.1
8 Lee Bridge	0.14	0.1	0.14	0.1	0.09	0.1	0.11	0.1	0.14	0.1	0.13	0.1
9 Hornsey	0.13	0.1	0.06	0.1	0.07	0.1	0.06	0	0.07	0.1	0.09	0.1
10 Stoke Newington	0.12	0.1	0.07	0.1	0.06	0.1	0.06	0	0.06	0.1	0.08	0
11 Copper Mills	0.21	0.2	0.14	0.1	0.22	0.1	0.14	0	0.11	0.1	0.14	0.1

TABLE 8.1.3

Filtered Water Turbidity, Relationship between readings on Hach Turbidimeter and PDL Hazometer.

Date	Av. ratio Hach/ Hazo	Av. reading on Hach when Hazo = 0	Av. reading on Hach when Hazo = 0.1	Av. reading on Hach when Hazo = 0.2	Av. reading on Hach when Hazo = 0.3(or 0.
9.2.72	1.8	0.21	0.17	-	-
11.2.72	1.7	-	0.22	0.41	1.1 x Hazo
15.2.72	4.8	0.16	0.22	-	-
16.2.72	1.9	-	0.38	-	-
22.2.72	2.0	0.19	0.22	-	1.4 x Hazo
23.2.72	1.0	-	0.10	-	-
25.2.72	1.2	-	0.13	0.21	-
29.2.72	1.5	0.10	0.11	-	-
1.3.72	1.9	0.13	0.11	-	-
7.3.72	1.8	0.08	0.12	-	-
8.3.72	1.0	-	0.10	0.21	-
10.3.72	1.4	0.09	0.11	-	-
Statistical Mean	1.7	0.13	0.16	0.28	1.2 x Hazo

Note: Statistical Mean is based on total number of samples and not on (sampling) days.



	Days	Hach	Haz
TOP	1	2·4	0·7
	2	1·7	0·5
	3	1·5	0·2
FILT	1	0·4	0·2
	2	0·3	0·2
	3	1·5	0·2

Days Total Turbidity Curves
Top and Filtrate Waters (2 Samples)
Walton Experimental Filters
GRAPH 8,1,21

Walton Experimental Filters Turbidity, as read on Hach Turbidimeter and EEL Hazometer.

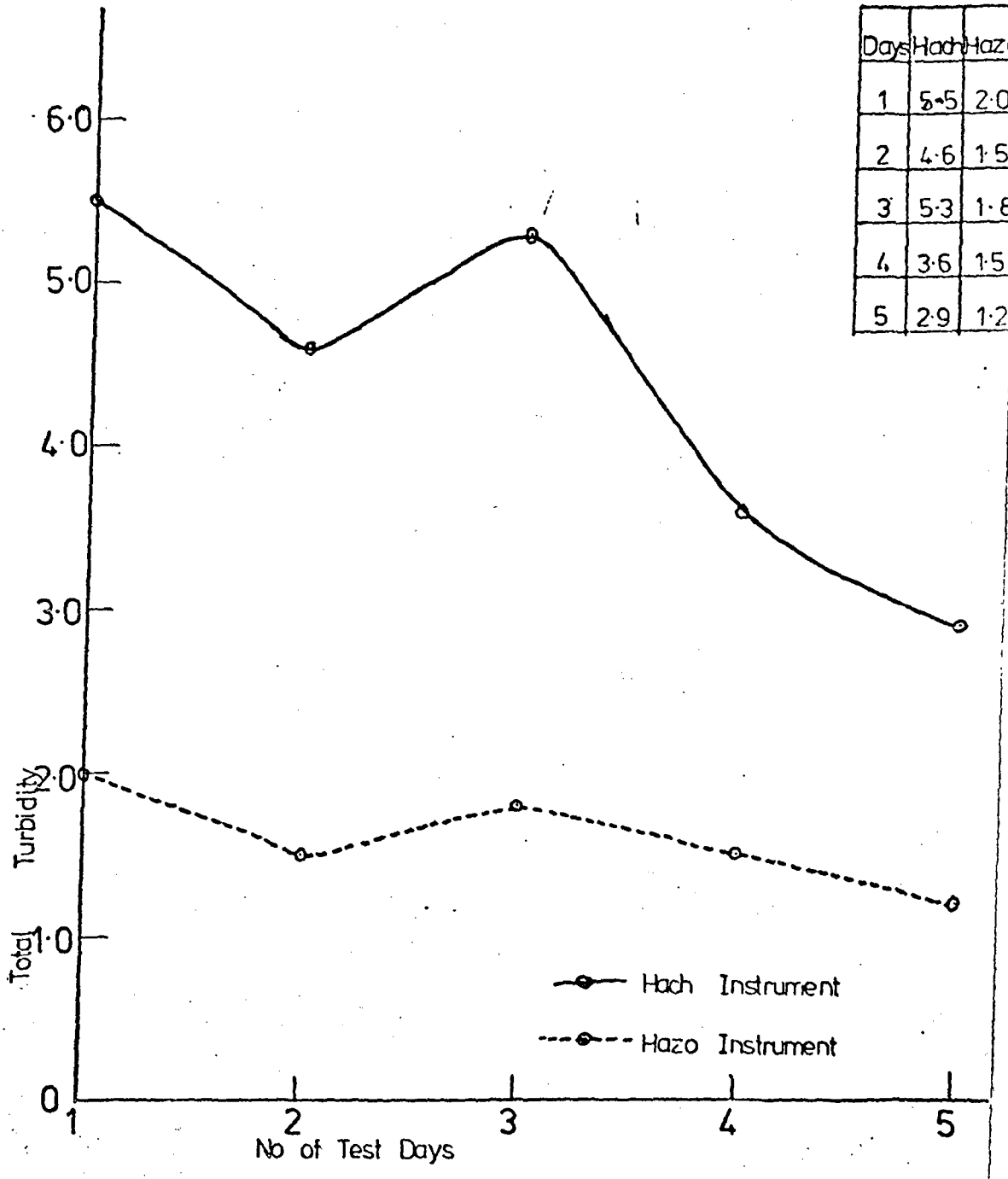
Date	21.2.72		28.2.72		6.3.72	
Source of Sample	Hach	Hazo	Hach	Hazo	Hach	Hazo
1 East Filter, top water	1.2	0.25	0.87	0.25	0.7	0.1
2 West Filter, top water	1.2	0.45	0.82	0.30	0.77	0.1
3 East Filter, filtrate	0.20	0.1	0.15	0.1	0.13	0.1
4 West Filter, filtrate	0.20	0.1	0.15	0.1	0.11	0.1

TABLE 8.1.5

Walton Experimental Filters Turbidity, relationship between readings on Hach Turbidimeter and EEL Hazometer.

Source	Ratio = (readings on) Hach/Hazo			
	21.2.72	28.2.72	6.3.72	Cumulative Average
1 East, top water	4.8	3.5	7.0	5.1
2 West, top water	2.8	2.7	7.7	4.4
3 East, filtrate	2.0	1.5	1.3	1.6
4 West, filtrate	2.0	1.5	1.1	1.5
Statistical Mean, top water	3.8	3.1	7.4	4.8
Statistical Mean, filtrate	2.0	1.5	1.2	1.6

Days	Hach	Hazo
1	5·5	2·0
2	4·6	1·5
3	5·3	1·8
4	3·6	1·5
5	2·9	1·2



Days Total Turbidity Curves
on Primary Filtrate Waters (5 Samples)

GRAPH 8,1,22

TABLE 8.1.6

Primary Filtrate Turbidity, as read on Hach Turbidimeter and EEL Hazometer.

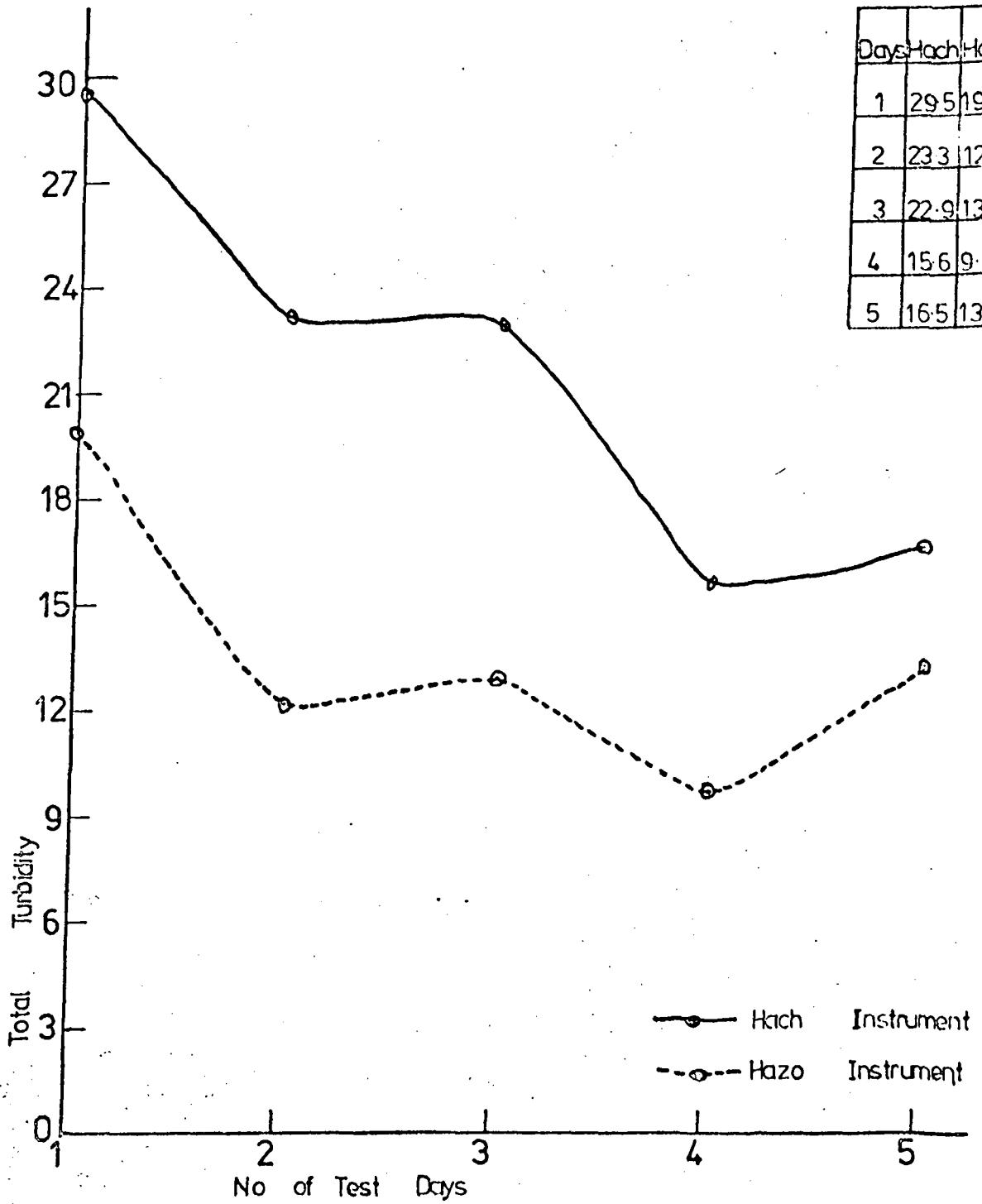
Date / Source of Sample	8.2.72		15.2.72		22.2.72		29.2.72		7.3.72	
	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo
1 Hampton	1.7	0.7	1.3	0.4	1.4	0.5	1.2	0.4	0.83	0.3
2 Walton	0.58	0.2	0.8	0.2	1.0	0.3	0.8	0.2	0.73	0.3
3 Kempton Park	1.5	0.4	0.15	0.2	0.74	0.2	0.5	0.4	0.55	0.1
4 Stoke Newington	1.7	0.7	2.3	0.7	2.2	0.8	1.1	0.5	0.80	0.5
5 Copper Mill	1.5	0.8	-	-	-	-	-	-	0.80	1.9

TABLE 8.1.7

Primary Filtrate Turbidity, relationship between readings on Hach Turbidimeter and EEL Hazometer.

Source	Ratio = (readings on) Hach/Hazo					
	8.2.72	15.2.72	22.2.72	29.2.72	7.3.72	Cumulative Average
1 Hampton	2.4	3.2	2.8	3.0	2.8	2.8
2 Walton	2.9	4.0	3.1	4.0	2.4	3.3
3 Kempton Park	3.7	0.75	3.7	1.2	5.5	3.0
4 Stoke Newington	2.4	3.3	2.8	2.2	1.6	2.5
5 Copper Mill	1.9	-	-	-	0.4	1.2
Statistical Mean	2.7	2.8	3.1	2.6	3.2	2.9

Days	Hach	Hazo
1	29·5	19·9
2	23·3	12·2
3	22·9	13·0
4	15·6	9·8
5	16·5	13·?



Days Total Turbidity Curves on Stored Waters (12 Samples)

GRAPH 8.1.23

Stored Water Turbidity, as read on Hach Turbidimeter and H.L. Hazometer.

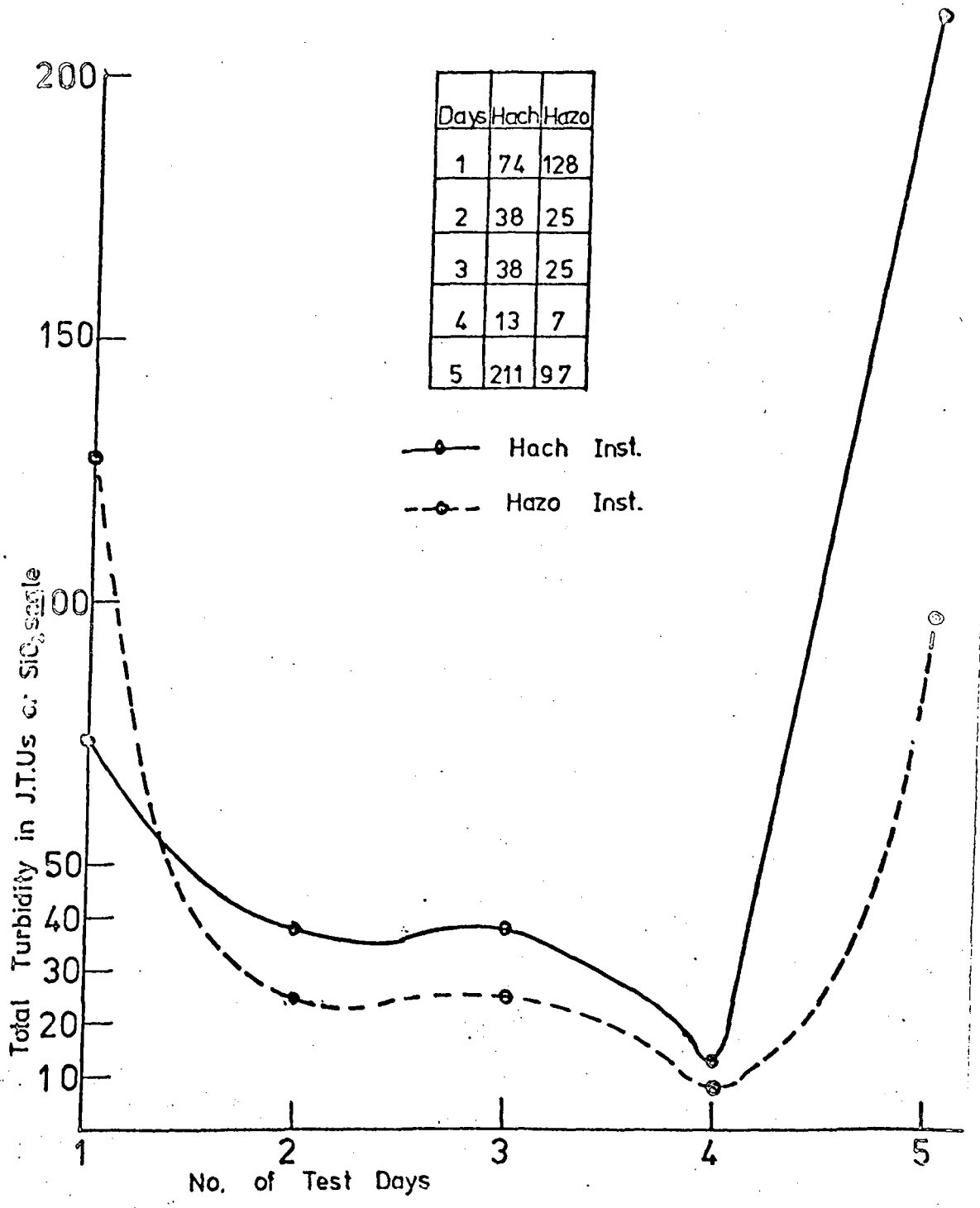
Date / Source of Sample	8.2.72		15.2.72		22.2.72		29.2.72		7.3.72	
	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo	Hach	Hazo
1 Queen Elizabeth II, inlet	4.3	3.4	2.3	1.1	3.5	2.0	2.3	1.1	2.5	1.5
2 Walton N & B, inlet	0.8	0.5	1.4	0.6	1.5	0.7	1.8	0.8	1.5	0.7
3 Lee Bridge, aquaduct	2.2	1.2	1.3	0.9	1.1	0.9	1.4	1.2	1.4	1.5
4 Stoke Newington, inlet	3.8	2.1	5.1	2.5	4.7	2.3	2.5	1.6	1.9	1.8
5 Kempton Park, inlet	4.0	2.9	2.1	1.0	1.8	1.1	0.9	0.6	1.5	1.1
6 Barn Elms, tap	1.5	0.7	1.2	0.5	1.3	0.7	1.1	0.7	0.8	0.5
7 Hanworth, St. aquaduct	3.6	2.3	2.5	1.2	2.1	1.1	1.1	0.6	1.4	0.8
8 Hampton, inlet	3.4	2.2	2.5	1.4	2.6	1.5	1.5	0.9	1.7	1.1
9 Ashford Commons	3.5	2.7	2.2	1.3	2.2	1.1	1.1	0.6	1.5	1.0
10 King George VI, outlet	0.45	0.3	0.35	0.3	0.51	0.4	0.51	0.4	0.42	0.4
11 Copper Mill, culvert	2.0	1.2	1.8	1.1	1.1	0.7	0.88	0.8	1.3	2.3
12 Wraysbury, Reservoir	0.42	0.4	0.5	0.3	0.5	0.5	0.53	0.5	0.47	0.5
13 Copper Mill, inlet	2.5	1.9	-	-	-	-	-	-	1.3	2.8
Average		1.7		1.0		1.1		0.8		1.2

TABLE 8.1.9

Stores Water Turbidity, relationship between readings on Hach Turbidimeter and EEL Nazometer.

Source	Ratio = (readings on) Hach/Hazo					
	8.2.72	15.2.72	22.2.72	29.2.72	7.3.72	Cumulative Average
1 Queen Elizabeth II (inlet	1.3	2.1	1.8	2.1	1.7	1.8
2 Walton K & B, inlet	1.5	2.3	2.1	2.3	2.1	2.1
3 Lee Bridge, aquaduct	1.8	1.4	1.2	1.2	0.9	1.3
4 Stoke Newington, inlet	1.8	2.0	2.0	1.6	1.1	1.7
5 Kempton Park, inlet	1.4	2.1	1.6	1.5	1.4	1.6
6 Barn Elms, tap	2.1	2.4	1.9	1.6	1.6	1.9
7 Hampstead, St.aqua	1.4	2.1	1.9	1.8	1.8	1.8
8 Hampton, inlet	1.6	1.8	1.7	1.7	1.5	1.7
9 Ashford Commons	1.3	1.7	2.0	1.8	1.5	1.7
10 King George VI, outlet	1.5	1.2	1.3	1.3	1.0	1.3
11 Copper Mill, culvert	1.7	1.6	1.6	1.1	0.7	1.3
12 Tregaskiss, reservoir	1.1	1.7	1.0	1.0	0.9	1.1
13 Copper Mill, inlet	1.3	-	-	-	0.5	0.9
Statistical Mean	1.5	1.9	1.7	1.6	1.3	1.6

Days	Hach	Hazo
1	74	128
2	38	25
3	38	25
4	13	7
5	211	97



Days Total Turbidity Curves on Raw River Waters (4 Samples)

GRAPH 8,1,24

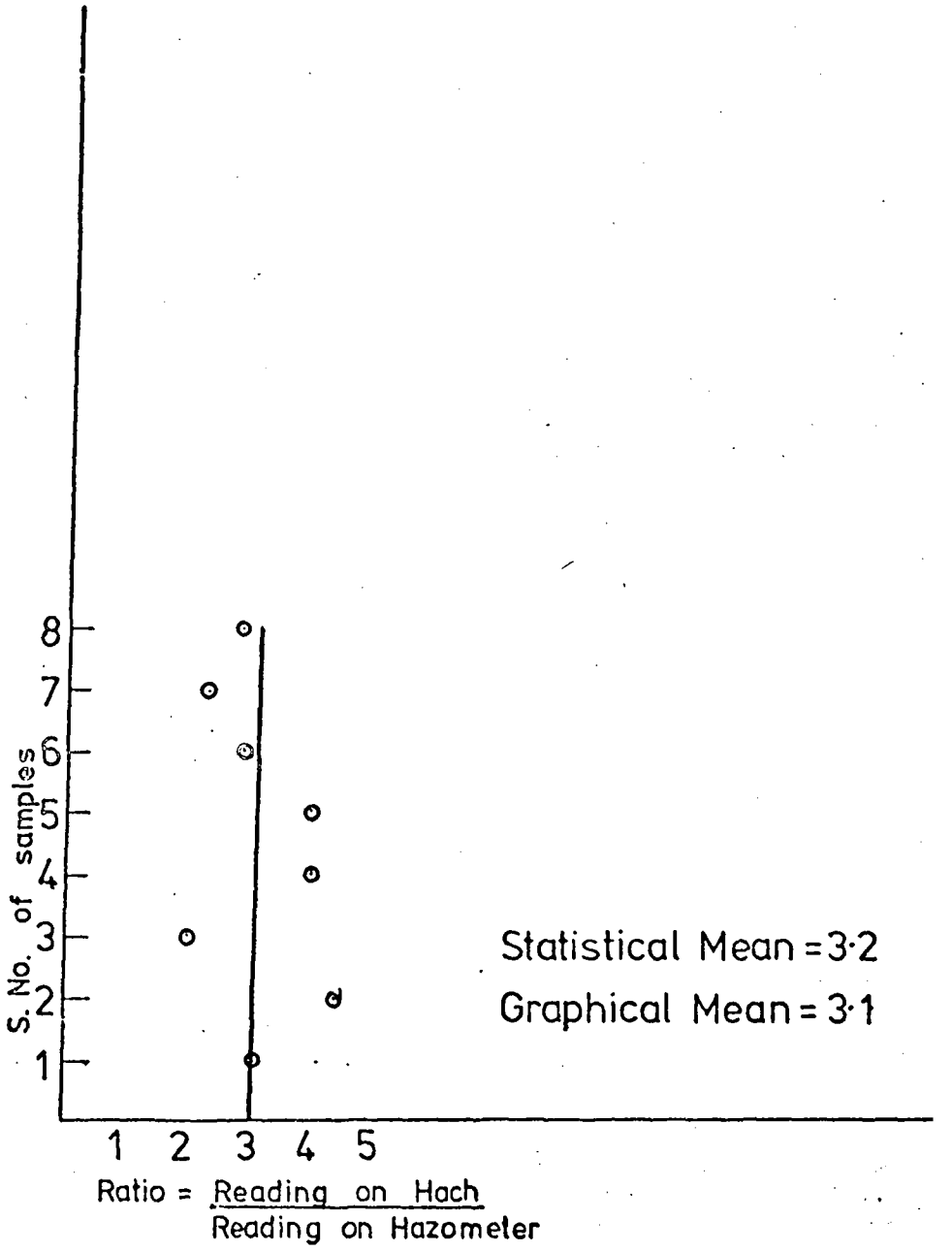
River Water Turbidity, relationship between readings on Hach Turbidimeter and EEL Hazometer.

Date / Source of Sample	9.2.72 Hach	9.2.72 Hazo	16.2.72 Hach	16.2.72 Hazo	23.2.72 Hach	23.2.72 Hazo	1.3.72 Hach	1.3.72 Hazo	8.3.72 Hach	8.3.72 Hazo
1 River Thames, Walton	32.0	57.0	12.0	7.8	12.0	7.8	4.8	3.1	73.0	37.0
2 River Thames, Laleham	28.0	56.0	13.0	9.2	16.0	9.2	-	-	71.0	35.0
3 River Lee, Chadwell	5.8	6.4	5.0	2.1	4.3	2.1	3.7	1.8	23.0	10.0
4 River Lee, Girling	7.8	8.0	8.0	6.4	6.0	6.4	4.0	2.2	44.0	15.0

TABLE 8.1.11

River Water Turbidity, relationship between readings on Hach Turbidimeter and EEL Hazometer.

Source	Ratio = (reading on) Hach/Hazo 9.2.72	16.2.72	23.2.72	1.3.72	8.3.72	Cumulative Average
1 Thames, Walton	0.6	1.5	1.5	1.6	2.0	1.4
2 Thames, Laleham	0.5	1.4	1.8	-	2.0	1.4
3 Lee, Chadwell	0.9	2.4	2.0	2.1	2.3	1.9
4 Lee, Girling	1.0	1.3	0.9	2.2	2.9	1.5
Statistical Mean	0.75	1.6	1.6	1.8	2.3	1.6



Relationship between Hach and Hazometer readings
Special Water Samples 9/2/72

GRAPH 8,1,25

TABLE 8.1.12

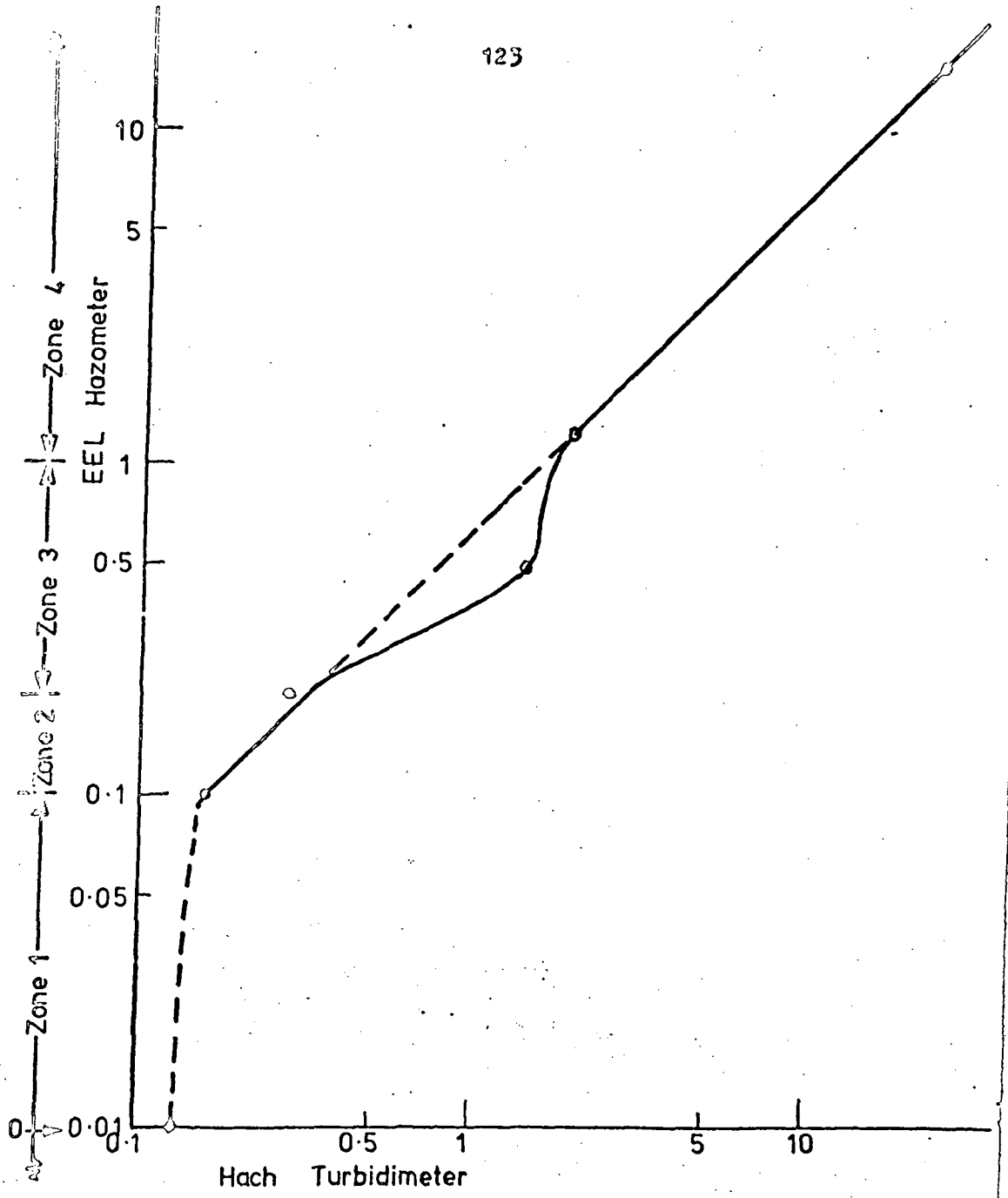
Special Samples Turbidity, data as read and relationship, Hach Turbidimeter and HDL Hazometer.

Date Source	10.2.72 Hach	Hazo	Ratio = (readings on) Hach/Hazo
1 Broxbourne, well 1	5.0	1.6	3.1
2 Broxbourne, well 2	3.5	0.8	4.4
3 Kempton, experimental, inlet	2.4	1.2	2.0
4 Kempton, experimental, outlet	0.4	0.1	4.0
5 Kempton, experimental 2, outlet	0.4	0.1	4.0
6 Richmond, contact, inlet	0.29	0.1	2.9
7 Richmond, contact, outlet	0.23	0.1	2.3
8 N. Lenth. Res. South	0.71	0.25	2.8
Statistical Mean		0.5	3.2

TABLE 8.1.13

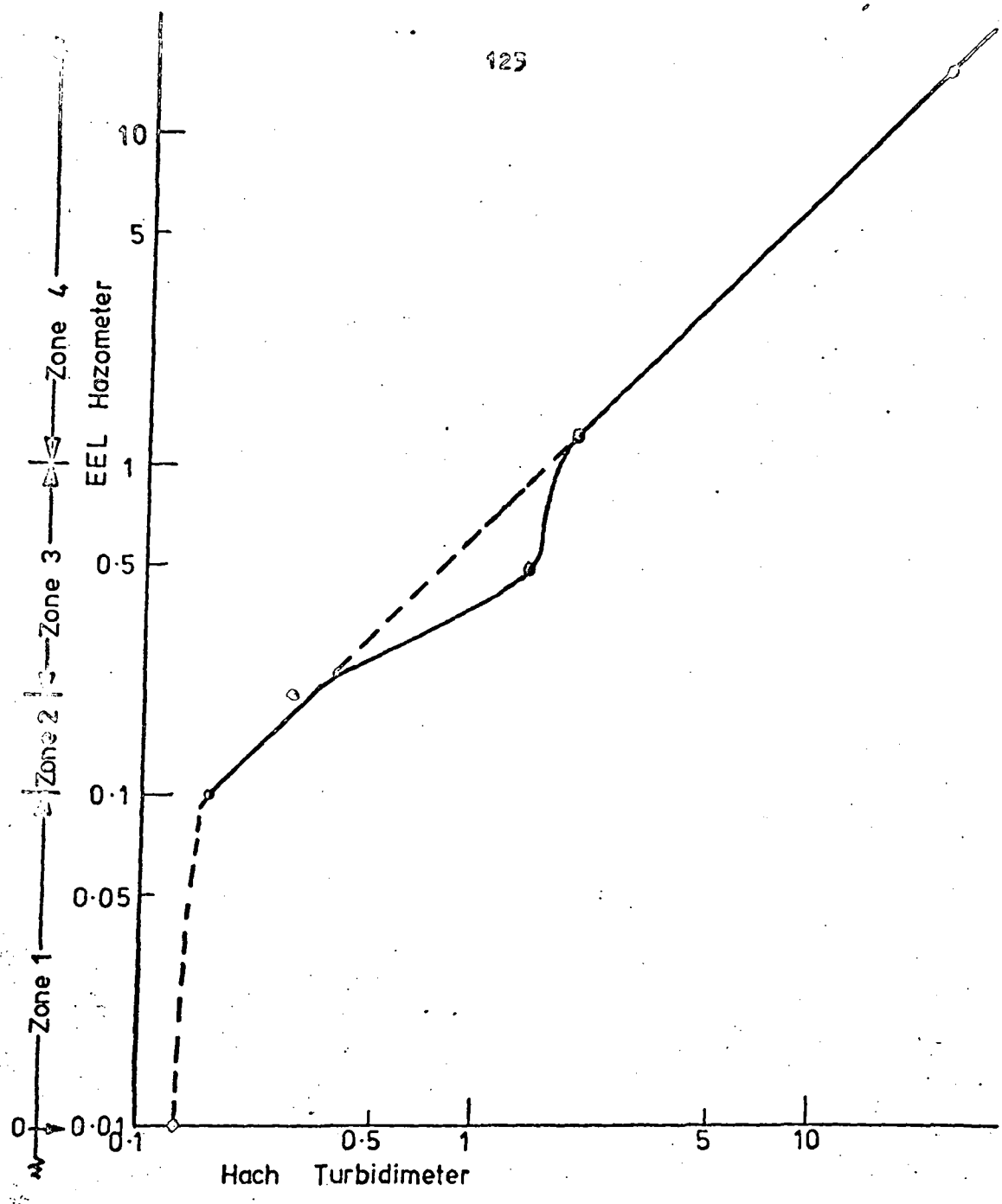
Whole Turbidity data condensed in batches, and the relationship between Hach Turbidimeter and HDL Hazometer.

	Filtered Water			Experimental Primary Filtrate				Stored raw	River	Special
Hazemeter v. Turbidity	0	0.1	0.2	0.3 Too few	0.24	0.1	0.48	1.2	14.9	0.5
Hach/Hazo ratio	1.3 ∞	1.6	1.4	1.2	4.8	1.6	2.9	1.6	1.6	3.2



GRAPH 8,1,26 (Table 8,1,13)

Curve of proposed relationship between Hach Turbidimeter and EEL Hazometer (readings in batches)



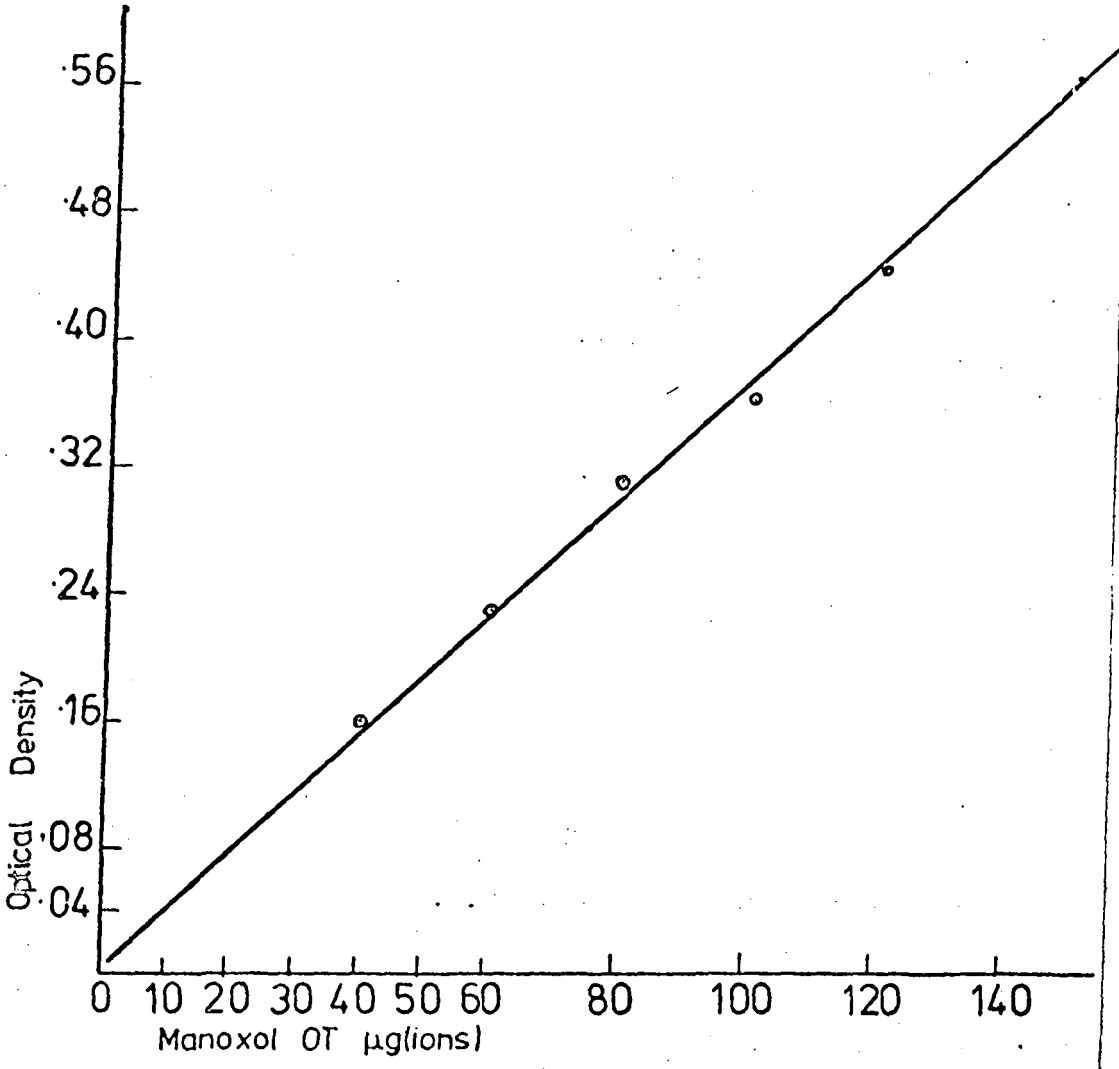
GRAPH 8,1,26 (Table 8,1,13)

Curve of proposed relationship between Hach Turbidimeter and EEL Hazometer (readings in batches)

3.2 Tracer Tests and Permeability

In previous chapters the concept has been developed that a slow sand filter is biological, and that its exact behaviour towards degrading some organic chemicals like detergents, insecticides and phenols was needed to be known, and that there was need to update it. In order to give a fair trial to above ideas, it was necessary to use a tracer substance having practical significance as far as possible.

The popularity of the use of synthetic detergents (containing surfactants) for general cleaning purposes, attracted the author's attention. The U.K. consumption of anionic surfactants increased from 17,000 tons in 1949 (W.W.S.O., September 1968) to 80,000 tons in 1971 (.W.S.O., March 1973). As early as 1954-56, it had been shown by figures that a very small but definite amount of surface active material was present even in the filtered water (Thomerton, 1956), which is still continuing (as much as 0.02 mg/l) as is evident by M.W.S.'s analytical results (Middle Taylor, 1971-73) and also reported by W.W.S.O. (5th March, 1973). It is estimated that one quarter of the population of England and Wales used river water as a source, which already contained a certain proportion of sewage effluent. It is therefore evident that a considerable proportion of the population must be ingesting traces of synthetic detergents. Out of the three main types of surface-active materials, namely anionic, nonionic and cationic, it has been estimated that some 94% of synthetic detergent products are anionic (Gardner, 1955). In the 50's and early 60's, sewage treatment plants experienced difficulties with foaming and the synthetic detergents also retarded the biological activity of secondary treatment processes. In the mid-sixties, the synthetic detergent industry almost completely switched over from hard ABS (Alkyl Benzene Sulphonate) to the more biodegradable (soft) Linear Alkylate Sulphonate (LAS) (Taras, et al. ed. 1971). The changeover seems to have brought about improvement in the otherwise deteriorating situation, as figures prove that in United Kingdom, between 1966 to 1971, concentration of anionic surfactants in sewage increased from 14.0 to 15.2 mg/l



GRAPH 8.2.1

Spectrophotometer Calibration Curve,

Ions Manoxol OT V/S Optical Density

(measured at 650nm wavelength)

(as Manoxol OT), but in sewage works final effluent decreased from 2.0 to 1.0 mg/l (H.M.S.O., 5th March, 1973). Among the Manoxol compounds (supplied by Hardman and Holden, Manox House, Coleshill Street, Manchester, England), Manoxol OT was chosen to be used as an indicator. ABS are a mixture of very many chemical compounds, compared with the known single chemical entity in Manoxol OT (Sodium dioctyl - sulphosuccinate) which could be obtained in a virtually pure state.

The method used for determining Manoxol OT concentrations was same as used by Water Pollution Research Laboratory (1965), (Procedure No. 11, Revised 1965), Hertz, England. The method is based on Longwell and Maniece (1955) and modified by Slack (1959), which uses methylene blue solution extracted in chloroform, reading on spectrophotometer at 650 nm wave length. A typical calibration curve is shown in graph 8.2.1. After some work, the limitations of concentrations determination were apparent. So many substances, organic and inorganic, normally found in waters, interfered with the determination of the surfactant componont of synthetic detergents that it was very difficult to obtain an accurate value. At best, the method gave an estimate of the concentration of anionic surfactant in the water sample. The use of Manoxol OT as a tracer was therefore abandoned in favour of Phenol.

Monohydric Phenol, C_6H_5OH, an aromatic compound and one of the simplest group of compounds appeared to be suitable and a supply was obtained (supplied by May and Baker, Dagenham, England and British Drug Houses, Poole, England). It was considered most suitable, as it was representative of similar organic chemicals, and was more reactive than the benzene hydrocarbons, biodegradable in usual sewage treatment processes, and capable of fine concentration determinations. It is important in drinking water because of taste and does not appear to have been investigated previously in this way in relation to slow sand filtration. Moreover, there is a continuing interest in phenol in drinking water, whereas detergents have lost their interest due to their biodegradability and apparent non toxicity (used for dish-washing and eating utensils). Also W.H.O. standards (W.H.O., 1970) and U.S. Public Health Service (1962), 003

very low limit 0.001 mg/l for phenol. Consequently these are important reasons to carry out experiments with phenol rather than detergents. Also N.W.B. (Windle Taylor, 1971-73) were experimenting on laboratory scale with biological degradation of phenols, so there was current interest in on-site phenol experiments.

8.2.1 Preparation of Tracer Solution.

Because of the low concentration of tracer required to be dosed and because of the convenience in dosing, phenol in aqueous solution was utilised. As the 10% or 80% solutions of phenol could not be obtained from the market, because of the worldwide oil crisis, it was decided to make the aqueous solution of phenol in the laboratory for dosing purposes. In the early stages of the experimental work, the preparation of a homogeneous suspension became highly problematic. 10%, 20%, 40% and 60% W/V solutions were tried, only to be met with failure. Aqueous phase and oily phase portions of the solutions became separated by an emulsion layer in between, after 24 hours of solution preparation. Vigorous agitation by mechanical rotors helped only little. So the concentration was carried to the point where only one of the phases was formed. In this case a solution of 5% W/V concentration produced a clear aqueous phase solution, and an 80% W/V solution produced oily phase solution, which was ultimately adopted for experimental purposes.

800 gram of monohydric phenol (C_6H_5OH, molecular weight = 94.11) were weighed in a 1 litre graduated cylinder. To this 200ml (about 25% by weight) of freshly boiled and cooled double distilled water was added. The cylinder was then placed in a bucket of hot water, and the phenol crystals were broken and agitated with a thick glass (or stainless steel) rod, to make a homogeneous solution. The contents were then brought to a 1000 ml mark by adding more distilled water, which was 67 ml (making a total of 33% of the weight

of phenol crystals). This produced a phenol solution of 800 g/l concentration, which was transfered to the dosing glass aspirators for dosing purposes. The solution was standardised at times as given in Standard Methods (Taras et al. ed. 1971).

8.2.2 Dosing of Tracer Suspension

Dosing Tank Capacity

Area of one filter = 3.20 m (10½')l x 1.82 m(6')w
= 5.82 m^2

Rate of filtration = 0.2 m(8")/h

Volume of water filtered in 24 hrs = 5.82 m^2 x 0.2m/h x 24 hrs = 27.93 m^3

Concentration of phenol in tap water = 10 mg/l

Weight of phenol crystals needed in a day = 27.93 x 10 = 279.3 gms

Phenol needed in a 2 week period = 279.3 x 14 = 3.91 kg

Using 80% W/V solution of phenol, Vol. = $\frac{3.91}{0.80}$ = 4.88 litres

Use two aspirator bottles of 10 litre capacity, to use alternately, to replenish solutions every two weeks.

Rate of Dosing

Molecular Wt. of phenol, 94.11

Intended concentration of phenol in inlet water = 10 mg/l

Concentration of phenol aqueous solution = 80% W/V

Rate of filtration = 0.2 m/h

Vol. of feed water per hour = 5.82 x 0.2 = 1.16 m^3 or 1190 lit/h

Dose of phenol solution per hour = 1190 x $\frac{10}{0.8}$ = 14.88 ml/h

Setting on pump thimble = $\frac{14.88}{45}$ = 33.06%

Similarly at inlet concentration of 5 mg/l (phenol), quantity of 80% W/V phenol sol. = 1190 x $\frac{5}{0.8}$ = 7.44 ml/h

Retention time in filter tank

Average depth of inlet water over sand bed = 5' (1.52 m)

Retention time = $\frac{1.52}{0.2}$ = 7.6 hrs

8.2.3 Media, Influent Source and Filtration Rate

Builders grade sand which is very much cheaper than the closely specified graded sand, was used. Fifteen months mature sand was retained and used for the phenol biodegradation part of the experiment. It had an effective size of 0.25 mm and a uniformity coefficient of 3.4 (compared with 2.4 used by the Thames Water Authority for normal slow sand filtration). The porosity of sand was 40%. On average 18" (0.45 m) bed of sand over 4 to 6 inches (0.1 to 0.15 m) layer of gravel rested on 6 inches (0.15 m) of under drainage system.

Primary filtrate as produced by the rapid sand primary filters at the main works was used as the influent source throughout the length of the experiment (fig. 8.1.5).

Rate of filtration used was 0.2 m/h, which is about 50% more than the usual rate of slow sand filters of the Thames Water Authority, and 100% more than the traditional slow sand filtration elsewhere.

8.2.4 Isokinetic Sampling

Calculations:- Velocity of filtration, $Vf = \frac{Q}{A} = 0.2$ m/h

Velocity through pores, $Vp = \frac{Vf}{\text{porosity}} = \frac{0.2}{0.4} = 0.5$ m/h

Velocity of sampling, Vs = Velocity through pores, Vp

$Vs = \frac{q}{a \times N}$ or $q = Vs \times a \times N$

q = sampling rate cm^3/h

a = area of hole in sample pipe (dia. = 3 mm)

N = no. of holes = 66

$q = 50 \times \left(\frac{22}{7} \times \frac{0.3^2}{4}\right) \times 66$

$= 50 \times \frac{0.29}{4} \times 66 = 233\ cm^3/h$

$= 3.88\ cm^3/min$ (@ 6 drops to 1 ml)

= 23.3 drops/min = 10 dro /25.8 secs ~ 10 dro/26 secs

Sample 466 cm^3 (in 500 ml glass bottles) in 2 hrs @ 10 drops/ 26 secs.

Time required to waste run the Sampling Taps

Total Length of sample pipe = 6' (1.82 m)
Diameter = $\frac{1}{2}$" = 12.7 mm
Vol. of pipe = $\frac{\pi d^2}{4} \times L = \frac{22}{7} \times \frac{(1.27)^2}{4} \times 182 = 231$ ml

Time needed to drain the pipe = $\frac{231}{3.88} = 59.53 \sim 60$ min.

8.3 Schedule of Experiments

It was required to record the variation of head loss, turbidity and biodegradation with organic tracer solution at an increased velocity of filtration. The usual approach velocity, and the one prevalent in British slow sand filtration practice is 3.8" (0.09 m)/h and 5" (0.13 m)/h respectively. It was therefore decided to study the variation of various parameters at uprated velocity of 0.2 m (8")/h. The tracer solution used was the simpler form of organic compound monohydric phenol, C_6H_5OH, being representative of organic compounds, whose determination at low concentrations was possible (although exacting and lengthy). Experiments were performed with an inlet concentration of 10 mg/l of phenol. As the filters were in the open, no control of temperature was exercised. The maximum day water temperature ranged from 17°C to 24°C. The complete experimental schedule is shown in table 8.3.1.

TABLE 8.3.1 - Schedule of Experiments

Run No.	Flow rate m/h	Inlet Conc. mg/l	Bed (sand) thickness ins. Test (east)	Control (west)	Length of run in days
1	0.2	2.0-10.0	19.5	21.5	18
2	0.2	10.0	19.0	21.0	7
3	0.2	10.0	18.5	20.5	16
4	0.2	0.0	18.0	20.0	44
5	0.2	5.0-10.0	17.5	19.5	25
6	0.2	0.0	17.0	19.0	23

The whole scheme of experiments was divided into five phases. Phase 1 was to acclimatize the filter organisms with organic tracer solution. The second phase was to dose at predetermined concentration. The third phase was to investigate the desorption effect of a dosed bed. The fourth phase dealt with the cumulative effect of dosing and fifth phase was again to determine the desorptive effect in a cumulative sense.

8.4 Experimental Procedure

As discussed in section 8.3, the experiments were carried out under different initial conditions of acclimatization to filter organisms. Throughout the experiment, only one concentration of phenol of 10 mg/l was tried to be maintained. The filter had already been tested in earlier runs for headloss and turbidity, without phenol, and the dosing apparatus was tested while carrying out the acclimatization run at the same time. Approach velocity in all cases was 0.2 m/h. The previous reduction capsule gear (special attachment used with the pump) of long stroke type with pumping capacity 0-150 ml/h was found to be rather too big for the small dosing flows. It was replaced by a short stroke reduction gear of 0-45 ml/h capacity after the acclimatization (cum test) run. Samples of inlet to filter and the filter depth were collected. Also the temperature of the dilute solution in the filter tank and inlet were noted. Samples were analysed for phenol concentration and pH. The sample analysis and temperature and PH readings gave satisfactory results indicating the apparatus in perfect condition for further experiments. Both filters sample tubes were marked for the various media positions.

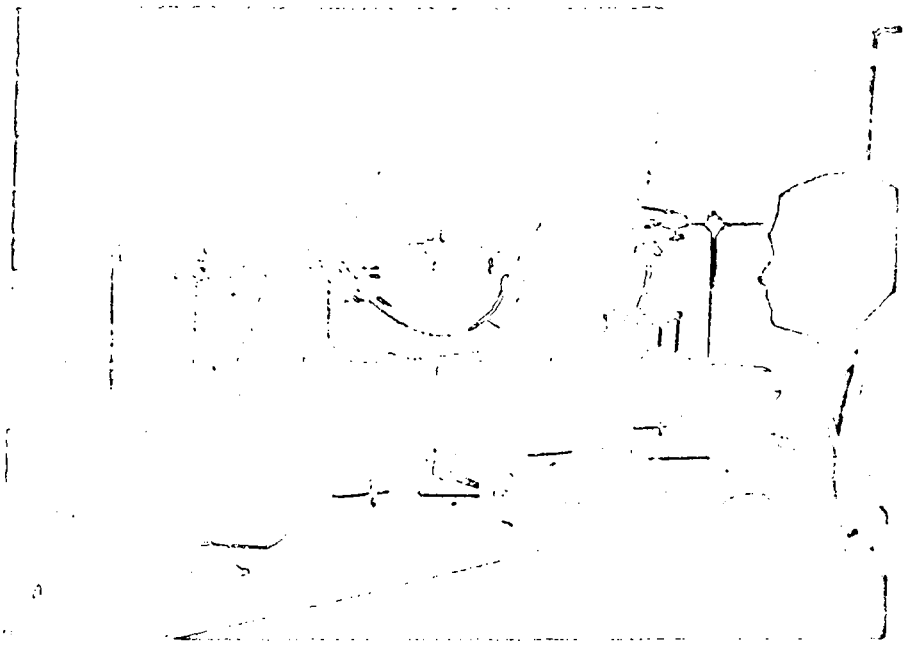
8.4.1 Acclimatization of the Filter

Even though the filter sand had been matured for

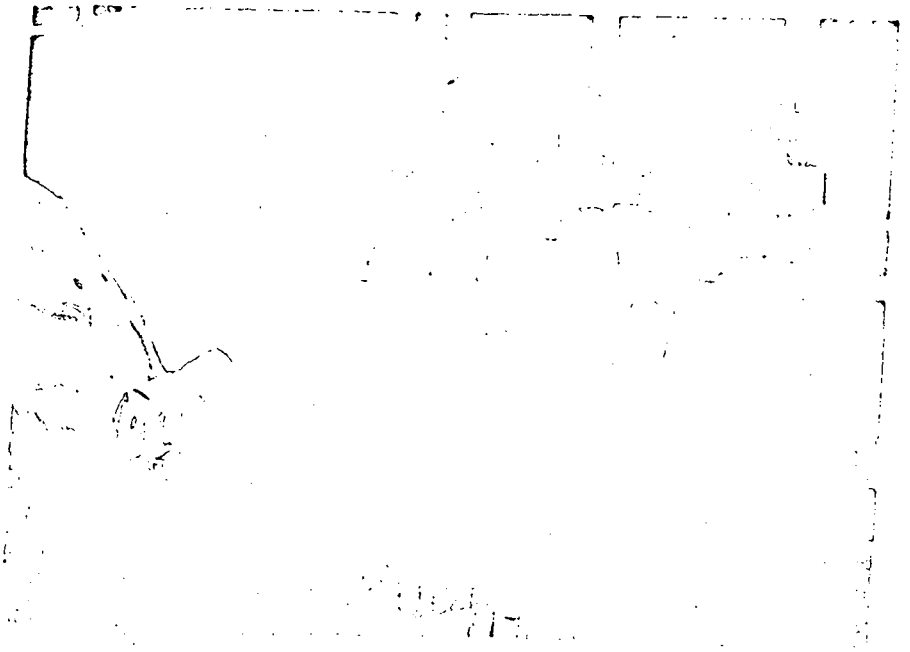
fifteen months, it never had previously experienced a phenol dose of 10 mg/l. Therefore to allow the filter bacteria to acclimatize and grow, the phenol dose in the inlet water was only gradually and progressively increased from 2 to 5 to 8 to 10 mg/l. In fact, this process took much longer (18 days) than anticipated, in contrast to M.W.B. (Windle Taylor, 1971-73).

8.1.2 Operating Procedure for a Filter Run

Operating procedure is discussed in four parts: starting and loading the filter, sampling, analysing the samples, and cleaning the filter at the end of the run. Starting: After ascertaining the proper removal of accumulacks, levelling of the bed surface and embedding of the top sample pipe (1 cm below the surface), the drain valve was closed and the pressure main valve opened for recharging. The recharging filtered water was allowed through the control valve, to the underdrainage channel, and allowed to rise through the gravel and sand gradually, to displace the air in the piping and bed. When the recharge water appeared on the surface, the raw water inlet valve (fig. 8.1.10) was opened and the low lift pump in primary filter house started. With the control valve and recharge valve closed, the drain valve was opened and the control valve regulated at a very low flow (less than 1" (0.025 m)/h) filtration rate. The rising of raw water to the desired level in the filter tank took about four hours. The filtration rate was kept at half (0.1 m/h) for one day and then continued at full (0.2 m/h) after that. Phenol dosing of raw water commenced at half rate (5 mg/l) for the first day and then at full designed rate (10 mg/l) for the rest of the run. The control filter operated without any phenol dose. The rate of filtration was kept constant at 0.2 m/h, by making small manual adjustments in the control valve every few days or so. The headloss in the manometer tubes was noted after rectifying any suspected airlock. The temperature of the inlet water was noted and samples collected. The start of filter run was taken to be after

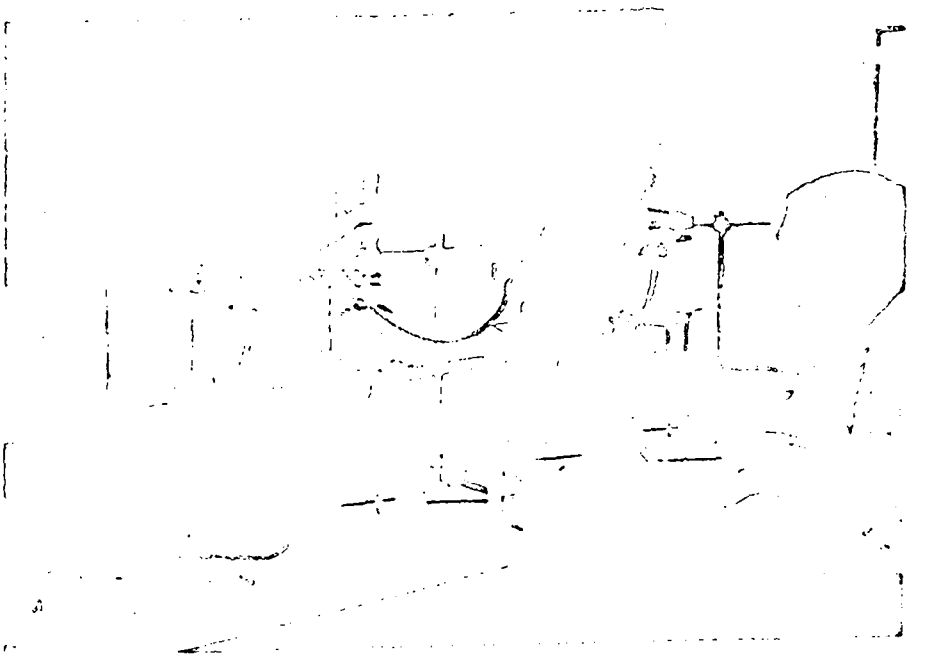


Volatilization of Phenol by all glass distillation apparatus.

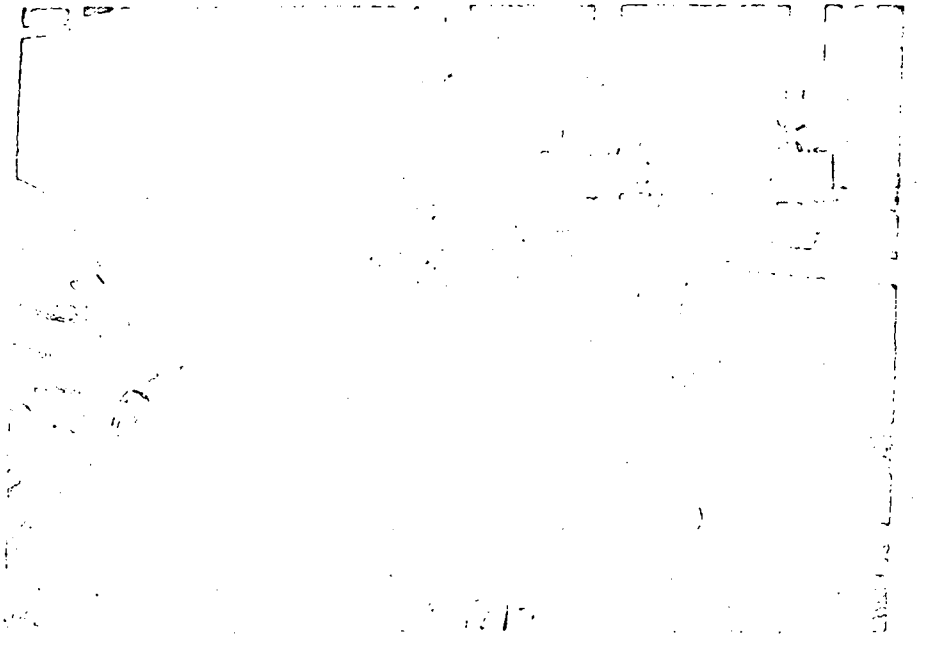


Chloroform extraction of Phenol solutions

Photo 8.4.1



Volatilization of Phenol by all glass distillation apparatus.



Chloroform extraction of Phenol solutions

Photo 8.6.1

displacement time.

Sampling: Table 8.3.1 indicates that tracer solution was dosed in Nos. 1, 2, 3 and 5 runs. It also indicates the bed depth in each run. Samples were collected on alternate days or twice in a week depending upon the requirement. Each time, the initial headloss was noted in the manometer tubes and then sample taps synchronised at 10 drops/ 26 seconds. Sample taps were allowed to run for one hour for draining, and then samples were collected for turbidity and phenol concentration determination.

Analysis: Measurement of turbidity was made immediately after sampling to avoid coagulation, which could alter the figure considerably (Holden ed. 1970). The rest of the samples were brought to the laboratory, and were distilled, extracted in chloroform (if necessary) and the resulting solutions read on spectrophotometer. The analytical procedure adopted for phenol determination was a modified form of method C & D of the Standard Methods (Taras et al. ed. 1971) which was used, after consulting the Water Examination Department of Thames Water Authority, based on the experience of that Department.

Cleaning: The filter bed was cleaned for each experiment by scraping the top 1 cm or 2 cm of sand manually to effectively remove the schmutzdecke. The assessment that the filter was clean was based on visual observation. Any disturbed surface was levelled and biological growths from side walls was removed and disposed. The relevant top sample tube was embedded in sand 1 cm below the sand surface.

8.5 Observations, Difficulties Encountered

8.5.1 Filtration

The visual observation through the glass panels gave some information about the accumulated biological deposits in the bed. Phenol determinations made from appropriate samples indicated an instantaneous value of concentration of substance in the flow. Although the tracer solution made from phenol was often difficult to control, constant

monitoring of phenol concentrations of the influent kept variations to a minimum. The ultimate effect of the biodegradation of phenol whether intense or marginal, should properly manifest itself in biological behaviour achieved by the filters.

In the filter tank, sometimes the colour of the water turned green, which was more manifest in the dosed filter and during runs in sunny periods. The walls of the filters accumulated gelatinous biological growths needing scraping and disposal at the time of cleaning. Sometimes floating debris like surface algae was noticed in the test filter. Browning of sand in the form of patches were noticed in both filters indicating the presence of zoo plankton.

8.5.2 Sampling (observations)

At the start of the run some discrepancy in the behaviour of the manometers was noticed. It was found that difference in head between two consecutive manometer tubes decreased instead of increase with passage of time in the initial stage of the run (e.g. encircled readings in tables 9.3.6, 9.3.8 and 9.3.9). The initial higher erratic headloss was traced to leaky [illegible]. It was cured by keeping the sample valves tightly closed and shaking out the locked air from the relevant manometer tube. The changing headloss pattern in the several successive runs can be attributed to the biodegradation in filter, in contrast to that by the aging of the media, as reported by Mohanka (69), Dispor (1961), Haines et al (1965) and Rimer (1968) for rapid filters. During summer months turbidities of many samples from within the sand-bed were noticeably high due to appearance of oily matter in the sample. It is thought to be due to metabolism of microfungi and algae, appearing in the samples as end products.

8.5.3 Analysis (observations)

At times the red colour due to phenol extraction in chloroform faded away quickly after formation. So the reading immediately after extraction would in such cases be higher than if allowed to wait for half an hour or so. This is indicative of quinone and other metabolic products registering as phenols.

No trouble was generally encountered in cleaning the filter, and there was no evidence of significant occurrence of short circuiting during the whole length of experimental period. An interesting observation is the decreasing initial headloss almost continuously. The increased bacterial activity within the filter may have resulted in purifying the filter organically, causing the initial headloss to decrease with phenol use. This point has been explained further in section 9.2.

8.6 Difficulties Encountered

The problem faced in preparing the phenol solution free of two separate phases has been amply described in section 8.2.1. Once 80% W/V phenol solution had been prepared, there was no difficulty in maintaining the solution in single (oil) phase at the intended concentration.

For overnight preservation of the samples, copper sulphate solution was added in some cases, after sampling. However, while analysing such samples, in some cases, a cloudy formation was encountered after the addition of aminoantipyrone, resulting in very high values of concentrations. Alternatively the sample was kept overnight without the addition of copper sulphate. This resulted in lowering the phenol concentration (by 15% on an average) apparently due to overnight degradation of phenol. This was remedied by analysing the samples the same evening, although there were difficulties due to the long distance from the site to the laboratory.

The micrometering dosing pump did not always pump at the set rate. Whenever discrepancies occurred, the pump always erred towards a reduced rate of pumping. This was due to the airlock and was remedied by working the pump at a much higher rate for some time, which displaced the air bubbles out of the pump head.

On one occasion, the pilot filters control room gate was opened only to find a pool of waist-deep water in it, with most of the tightly closed empty sample bottles floating in the water. The leak was traced to an ordinary polythene tube connected to the inlet pressure main. Reinforced polythene tubes were subsequently installed and worked satisfactorily against inlet and dosing pressures.

CHAPTER IX

EXPERIMENTAL RESULTS ON CLARIFICATION, HEADLOSS AND TURBIDITY PENETRATION (M.W.B. WALTON)

The experiments described in Chapter VIII were conducted in order to test the validity of the concept proposed earlier, that in a slow sand filter notable purification was achieved by biodegradation, and that it is necessary to study the pattern of headloss development and turbidity removal within it to be able to investigate the possibility of uprating it. The total experimental results have been divided into three parts, namely, headloss, turbidity, and phenol degradation, each part having three aspects investigated: behaviour, in depth, with time and in each layer of the bed. In addition aspects of initial headloss and composite effect of depth with time on the headloss and turbidity removal have been presented and analysed. Also production of phenol in slow sand filters has been presented.

In this chapter, the experimental data on headloss and turbidity penetration are presented in graphical form. Of the total 21 runs studied, run nos. 1, 2, 3 and 5 were dosed with phenol in the test filter. Run nos. 4 and 6 were for the desorption of phenol in filter, immediately after a dosed run. Run nos. 1/71-73 to 15/71-73 were for the normal slow sand filtration.

9.1 Experimental Results

The experimental results at the required filtration velocity and the inlet and other concentrations for the turbidity and phenol are shown in tabular form in Chapters IX and X. Altogether there are thirty-six tables giving typical results of the control (west) and pilot cont (east) filters observed during this work.

All headloss readings were corrected to a standard temperature of 20°C, using Hazen's formula, i.e.

$$\frac{H_T}{T_{20}} = \frac{\nu_T}{\nu_{20}} \qquad (9.1.1)$$

where H_T is the observed headloss, H_{20} corrected headloss at 20°C, ν_T and ν_{20} are kinematic viscosities at T and 20°C respectively (tables 9.3.1 to 9.3.12).

9.2 Initial Headloss

Graph 9.2.1 illustrates the initial headloss development in both test and control pilot filters at a constant filtration velocity of 0.2 m/h for the six runs. The curve for each run and filter can be identified from the legend. The curves clearly demonstrate a continuous trend of falling initial headloss. The trend is better pronounced and covers wider range in the case of test filter.

The decreasing initial headloss in slow sand filter can be considered from two angles. Firstly from the point of view of dosing the organic tracer substance, and secondly from the seasonal point of view. Phenol solution increased the biological activity within the filter, causing better degradation of organic impurities either already present in the filter or in the water during filtration, resulting in a cleaner filter for every subsequent run. Secondly, the six runs were conducted during warmer period of the year, starting from the end of February to that of August. Spring season and warm air contributed to the same phenomenon in the case of control filter. Obviously, in the absence of phenol in control filter, the effect is less dramatic and less clearly defined.

The third aspect of the decreasing thickness of sandbed cannot be said to be contributing substantially to this trend, as the results on Graph 9.2.1 are normalised with respect to distance from the inlet sand surface.

In the case of test filter, Rose's equation (Rose, 1945) and Kozeny's equation do not match the initial headloss behaviour. As the dosing and the filtration proceed, the internal condition of the bed changes, in increased biological activity and decreased retention of organic impurities

in the bed, so the interstitial velocity increases causing a greater hydraulic resistance resulting in shorter filter runs, and a reduction in initial headloss. The recent intensive contribution to the understanding of headloss by Sakthivadivel (et al, 1972) does not deal with this aspect of headloss, though sophisticated as it is.

9.3 Headloss within Filter with Time

As detailed below, a set of curves were prepared by plotting the headloss results obtained from experiments during phenol dosing, immediately following normal, slow sand filtration.

(a) Pressure curves; headloss versus depth for varying time intervals.
(b) Total headloss versus time.
(c) Hydraulic gradient versus time for various layers in depth.

Graphs (9.3.1-9.3.8) show the headloss development within the depth of filter at different time intervals as the run proceeds. The bulk of headloss in a filter occurs in the top layer of the filter and the build-up of headloss in subsequent layers is not significant. As the top layer of the filter becomes clogged, there does not appear to be a notable shift in headloss development in the lower reaches. The phenomenon is evident from the rather parallel nature of pressure curves in the subsequent length of run. It can be seen that in a slow sand filter the top 5 cm of bed effectively removes the bulk of impurity flowing into the filter, resulting in a very high headloss in the top layer as shown in Graphs (9.3.1-9.3.8). As the run proceeds the headloss build-up in bottom layers of the filter is in fact negative.

Graph (9.3.9) shows that total headloss in the filter bed when plotted against time produces an exponential curve indicating that there is surface mat formation, otherwise it would tend to be a straight line. This behaviour is in contrast to that of a rapid filter, as observed by Cleasby and Baumann (1962). All the headloss curves in this graph for dosed runs (RT1, RT2, RT3 and RT5) have explicitly a shorter run than either the two desorption curves (RT4 and RT6) or the control filter curves, suggesting that a high biological growth has developed within the filter. The control filter curves are similar and grouped closely.

Graphs (9.3.10-9.3.17) illustrate variation of hydraulic gradient with time in different layers throughout the filter beds, for the test and control filters. These curves show in a significant manner the work done by the various layers of filter bed. A scrutiny of these curves makes it clear that in a slow sand filter the top layer is responsible for almost the entire load. The lower layers behave in a very interesting manner, that the headloss actually decreases in these layers instead of increasing with time. This phenomenon is clearly indicated in the phenol degradation runs. As headloss is a function of specific deposit, no significant change in headloss per unit length indicates insignificant removal from water and deposition of suspension in the bed. Therefore backwashing a slow sand filter would never be worthwhile. Curves for the test filter, in phenol degradation runs, for the bottom layers exhibiting decreasing headloss build-up indicate a possible self-cleansing action in the bed. This is in conformity with the decreasing trend of initial headloss as discussed in Section 9.2. Due to addition of phenol, there appears to be a lot more bacterial activity in schmutzdecke and the top layer of filter, causing consumption of most, if not all, of the incoming oxygen and usual organic impurity, thus restricting the growth of bacteria in lower layers, which get dislodged resulting in recovery of head in those layers of the bed.

9.4 Turbidity Removal in Filter Depth

The results of residual turbidity in the depth of the filter obtained from experiments were plotted and a set of curves were prepared as detailed below

(a) During runs of phenol degradation;
(b) During runs which follow immediately; and
(c) During runs of standard filtration.

The above three aspects have been presented in graphs (9.4.1-9.4.8) which show removal of turbidity during experiments in the test (east) and control (west) filters. The filter of depth is plotted in inches along the base of each graph whereas the vertical ordinate represents C/Co, i.e. the turbidity (Formazin Turbidity Units) at a particular depth represented as a fraction of the incoming turbidity at the inlet ball valve (E8 and W8). This way of normalising the results allows direct comparison between daily fluctuating turbidity concentrations. The temperature correction has not been attempted as the variation of temperature of the samples was small, not exceeding $3^{o}C$.

The data has been largely interpreted based on the fact that slow sand filtration is also a depth related phenomenon as well as time dependent. Typical graphs and those for the average turbidity, covering about a third of the run are plotted for both test and control filters side by side to enable comparison of their performance, showing the turbidity removal through the depth during a filter run, with normalised fluctuating turbidity at the filter inlet.

The following legend has been used to identify curves in the graphs (9.4.1-9.4.8) particularly, and in other graphs generally.

E4 = Test filter 4 days after the commencement of the run, etc.
W8 = Control filter 18 days after the commencement of the run, etc.

Graphs (9.4.1-9.4.4) illustrate the performance of the test and control filters at a filtration velocity of 0.2 m/h with an inlet phenol concentration of 10 mg/l. Both filters show a rise of turbidity in the filter tank, a great improvement in the top layer and then also a substantial gradual improvement of filtrate in the rest of the filter

depth. The whole of the filter depth is active in removing the turbidity. This finding is in contrast to the behaviour of rapid filter, in which the bottom layers are considered ineffective for this purpose. There is also an indication of better clarification in the test filter than in the control filter. In the test filter there is improvement in clarification in the beginning of the run, but deterioration in the effluent quality in the later part of the run. This effect is not clear in the case of the control filter. In graph 9.4.4 there is an increase in turbidity in the bottom 6 inches of bed, especially in the later part of the run. In phenol dosed runs this was the longest run and the decreasing availability of oxygen and normal organic solids may have caused dislodgementof bacteria in the bottom most layer of the bed accentuating the situation near the very end of the run. On the whole the removal pattern in the two filters is the same except that the test filter gets clogged earlier due to increased biological activity thereby shortening the filter runs.

Graphs (9.4.5 and 9.4.6) elucidate the performance of the test and control filters at a filtration velocity of 0.2 m/h with respect to the appearance of phenol in filter depth. The residual turbidity curves are similar to those of the phenol dosed runs except for the following details. There is no indication of the expected better clarification in test filter. Actually the test filtrate has deteriorated as is clear from graph 9.4.6. There also appears to be constant improvement in the quality of filtrate as the run proceeds, which is nearer to the behaviour of the control filter during phenol dosed runs. The most noticeable feature is the increase of turbidity at a point six inches above the bottom of the bed (Valve E5/W5) which in contrast is the depth of almost the best clarification for dosed runs.

Graphs (9.4.7-9.4.8) describe the typical performance of the east and west filters during runs of normal slow sand filtration at a filtration velocity as indicated in the time-table on the next page. The residual turbidity curves, representing a fraction of the incoming turbidity, within the depth of the east and the west filters are drawn for the first third, the middle third and the last third duration of the run. These curves are generally resembling those, as for the control filter in phenol dosed runs, or those during the immediately following runs. The entire depth of the bed is active in removing the turbidity of the water. Graph (9.4.7) drawn for run no.11/71-73 is for a run length of

77 days, which happens to be one of the longest runs, of a total of 81 runs studied for this purpose. Three important factors have combined to make this run so long. With both filters covered, the filtration ran through the coldest months (mid-November through to January) when the west filter was resanded immediately beforehand and the east filter sand was only one run old. In graph (9.4.8) a consistently better clarification is depicted by the respective curves for west filter, for all the three durations of the run, which could be attributed to the ozonisation of the west filter during that run

Timetable of Filter Runs with Operations

	Test Filter (East)			Control Filter (West)		
Time	Filter Run	Phenol	Ozone Covered	Filter Run	Phenol	Ozone Covered
1971						
Apr. 17	1/1971-73			1/1971-73		
23						
30						
May 7						
14						
21	2/71-73			2/71-73		
28						
Jun. 4						
11						
18	3/71-73		C	3/71-73		
25			C			
Jul. 2			C			
9			C			
16			C			
23			C			
30			C			
Aug. 6			C			
13			C			
20	4/71-73		C	4/71-73		C

Filter Run Timetable contd.

Time	Test Filter (East) Filter Run	Phenol	Ozone	Covered	Control Filter (West) Filter Run	Phenol	Ozone	Covered
Aug. 27				C				C
Sep. 3				C				C
10				C				C
17				C				C
24				C				C
Oct. 1	5/71-73			C	5/71-73			C
8				C				C
15	6/71-73			C	6/71-73			C
22				C				C
29				C				C
Nov. 5				C				C
1972	7/71-73				7/71-73			
Ja 1				C				C
7				C				C
14				C				C
21				C				C
28				C				C
Feb. 4				C				C
11				C				C
18				C				C
25				C				C
Mar. 3				C				C
10				C				C
17				C				C
24				C				C

Filter Run Timetable contd.

Time	Test Filter (East) Filter Run	Phenol	Ozone	Covered	Control Filter West Filter Run	Phenol	Ozone	Covered
Mar. 31								
Apr. 7	8/71-73			C	8/71-73			C
14				C				C
21				C				C
28				C				C
May 5				C				C
12				C				C
19				C				C
26	9/71-73			C	9/71-73			C
Jun. 2				C				C
9				C				C
16				C				C
23				C				C
30				C				C
Jul. 7				C				C
14								
21								
28								
Aug. 4	10/71-73			C	10/71-73			C
11				C				C
18				C				C
25				C				C
Sep. 1				C				C
8				C				C
15				C				C

[illegible] Data Subscription cont'd.

	Test Filter (East)				Control Filter West			
Date	Filter Run	Phenol	Ozone	Covered	Filter Run	Phenol	Ozone	Covered
Mar. 31								
Apr. 7	8/71-73			C	8/71-73			C
14				C				C
21				C				C
28				C				C
May 5				C				C
12				C				C
19				C				C
[illegible]	9/72-73			C	9/72-73			C
[illegible] 3				C				C
9				C				C
16				C				C
23				C				C
30				C				C
Jun. 7				C				C
14								
21								
28								
[illegible] 4	10/72-73			C	10/71-73			C
11				C				C
18				C				C
25				C				C
[illegible] 1				C				C
8				C				C
15				C				C

Filter Run at Pueblo contd.

Time	Test Filter (East) Filter Run	Phenol	Ozone	Covered	Control Filter West Filter Run	Phenol	Ozone	Covered
Sep. 22				C				C
29				C				C
Oct. 6				C				C
13				C				C
20				C				C
27				C				C
Nov. 3	11/71-73			C	11/71-73			C
10				C				C
17				C				C
24				C				C
Dec. 1				C				C
8				C			o	C
15				C			o	C
22				C			o	C
29				C			o	C
1972				C			o	C
Jan. 5				C			o	C
12				C			o	C
19				C				
26	12/71-73				12/71-73			
Feb. 2								
9								
16							o	
23							o	
Mar. 2							c	

[illegible] Run Timetable cont'd.

Time	Test Filter (East) Filter Run	Phenol	Ozone	Covered	Control Filter (West) Filter Run	Phenol	Ozone	Covered
Mar. 9							o	
16							o	
23	13/71-73				13/71-73		o	
30							o	
Apr. 6							o	
13							o	
20								
27								
May 3	14/71-73			C	14/71-73			C
10				C				C
17				C				C
24				C				C
31								
June 7	15/71-73				15/71-73			
14								
1974								
Feb. 25	1	P			1			
Mar. 4		P						
11		P						
18	2	P			2			
25		P						
Apr. 1								
8	3	P			3			
15		P						
22		P						

[illegible] contd.

Time	Test Filter (East)				Control Filter (West)			
	Filter Run	Phenol	Ozone	Covered	Filter Run	Phenol	Ozone	Covered
Apr. 29	4				4			
May 6								
13								
20								
27								
Jun. 3								
10								
17	5				5			
24		P						
Jul. 1		P						
8		P						
15								
22								
29	6				6			
Aug. 5								
12								
19								
26								

9.5 Turbidity Removal with Time

Graphs (9.5.1-9.5.8) show removal of the turbidity during filter runs on the test and control pilot slow sand filters. The length of the run is plotted in days along the base of each graph, and the vertical ordinate represents C ÷ Co, i.e. the turbidity in filter depth at a particular time of the run, represented as a fraction of the incoming turbidity of the raw water as measured at the inlet ball valve. This way of expressing the results is useful for direct comparison of turbidity removal at any time of the run. Also the FTU ratio C/Co is similar to weight ratio and volume ratio.

Interpretation of the data is based on the assumption that slow sand filtration is also a time related phenomenon. Typical curves are plotted for both test and control filters, on the same sheet, to be able to compare the performance showing the percentage of residual turbidity at a bed depth during the filter run. Graphs (9.5.1-9.5.4) illustrate the turbidity removal of both filters during runs of [illegible] day. Ignoring graph (9.5.1) which is essentially for the study of the action of algal bacteria, graphs (9.5.2-9.5.4) clearly demonstrate the change in the test filter. Firstly, the improvement of filtrate in turbidity removal occurs in the first and the last quarters of the run, and the middle half of the run on the contrary causes a rise of turbidity. The rise of turbidity could be attributed to the dying and dislodging of bacteria in the sand bed due to insufficient supply of oxygen and food, this view thus supporting the finding as expressed in Section 9.3. Secondly, the above curves also clearly exhibit a clearer water in bottom layers than the top layers, testifying to the finding of Section 9.4, thus strengthening the view that the whole of the bed is engaged in the clarification process. On one hand, clarification improves in the lower reaches of the bed, and on the other, head is recovered in the same region of the bed (Section 9.3). The two conflicting trends could be explained in the self-cleansing nature or the biodegrading purification in a slow sand filter.

Graphs (9.5.5 and 9.5.6) show the turbidity removal of the test and the control filters during the immediately following undosed runs. The curves of graphs illustrate two trends in a muted way. There is gradual improvement in clarification as the run proceeds, except the

[illegible] of the run, as if the effect of disinfecting bacteria (as observed in previous graphs) has been shifted from middle half to the last quarter of the run, in the absence of any phenol dosing. Also, the curves for the test filter show a higher turbidity than those for the control filter suggesting phenol appearance occurs along with bacteria dislodgement.

Graphs (9.5.7-9.5.8) illustrate the typical curves of turbidity removal in normal slow sand filtration. These curves generally behave as there for the control filter, showing gradual improvement of filtrate with depth of the bed and time of the run.

9.6 Turbidity Removal in the Layer

Graphs (9.6.1-9.6.6) illustrate removal of turbidity in each layer of the sand bed, during filter tests on the test and control filters. [illegible] of each graph is plotted in days of the length of the run and [illegible] ordinate indicates the percent gradient of turbidity [illegible] in a layer, obtained by dividing the percent turbidity removal in a layer by the depth of the layer. The layers are considered corresponding to the position of sampling probes in the bed, and generally the depth of the layer is 6 inches except the top layer which is ½" or [illegible]. Here the turbidity (removal) gradient for the bottom layer of the test filter is calculated as

$$\frac{100(C_{B5} \div C_{B8}) - (C_{B5} \div C_{B8})}{Di_{B6} - Di_{B5}}$$

[illegible] .... C_{B8} are the turbidities at probe depths B5 .... B8 and Di_{B6} is [illegible] depth of probe B6 (in inches) etc. The results have been normalised [illegible] to [illegible] between 0.3 to 9.5.

Typical curves are drawn for the test and control filters side by side for easy comparison. Graphs (9.6.1-9.6.4) show the curves of layer turbidity gradient for the two filters for the phenol dosed runs. It can be clearly seen from the curves that the top layer has a considerably higher gradient than that of the bottom layers, suggesting surprisingly high clarification in the top layer. This finding supports

were also presented in Sections 9.4 and 9.5. Comparing the bottom and middle layer turbidity removal, it can be seen that in the majority of cases, the curve for the middle layer is lowermost with minimum turbidity gradient. It suggests that either there is little turbidity removal in the middle layer, or turbidity removal is mitigated by the dislodgement of bacteria in that layer. This explanation agrees with the finding of Sections 9.3 and 9.5. By scrutinising the curves closely, it may be observed that there is a faint trend of better clarification in the top layer and inferior clarification in the bottom layer as the run progresses. Graphs (9.6.5-9.6.6) show the curves of layers turbidity gradient for the test and control filters for the immediately following backwash runs. It may be seen that the behaviour of the curves is about the same as that for the phenol degradation runs, except that the negative turbidity removal gradient for the middle layer is more accentuated in these runs suggesting heavy dislodgement of bacteria.

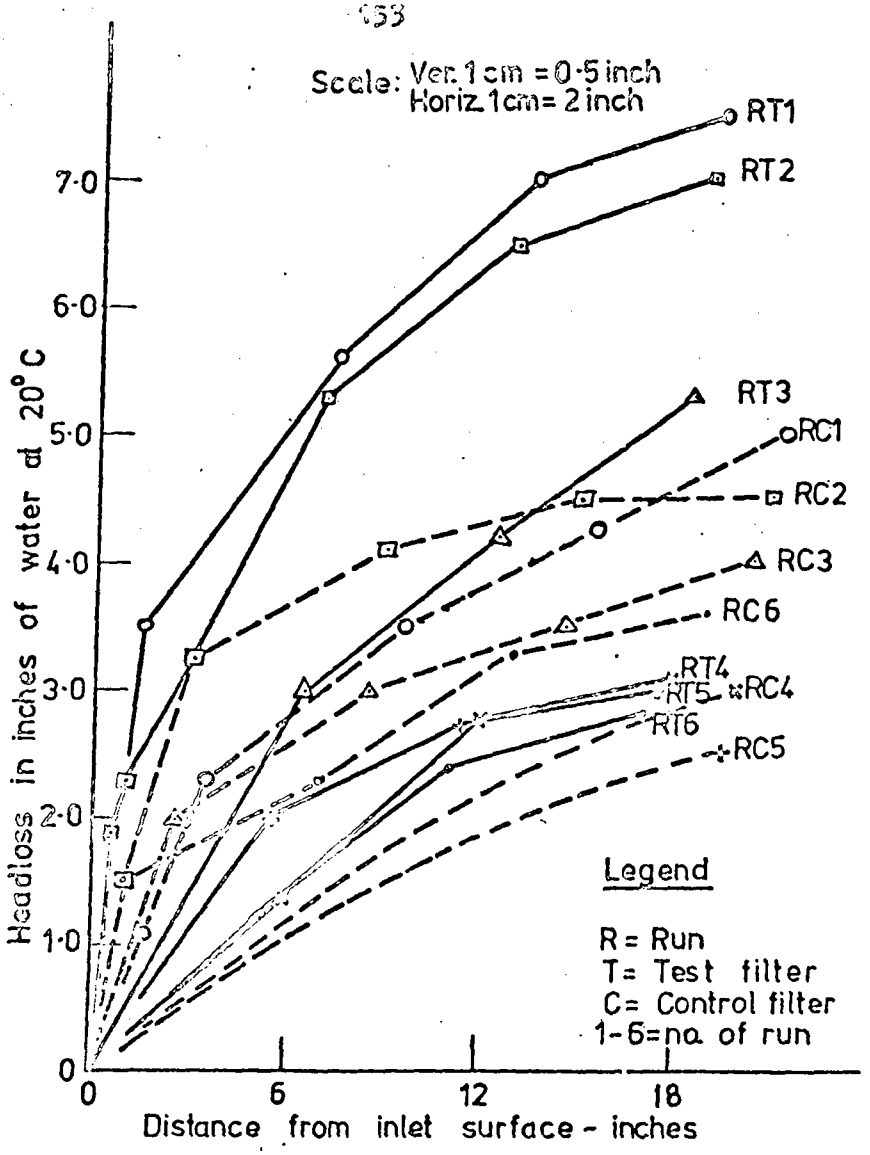
Table 9.3.13 (Headloss)

Run No. 8/72-73

Rate of Filtration = 0.25 m/h

Mode of Filtration = normal

Headloss in inch, cast filter						
Valve	D1	D2	D3	D4	D5	D6
D2	0.5"	3.5"	9.5"	15.5"	21.5"	27.5"
0						
1	0.15	1.40	2.40	3.40	3.90	3.90
3	-	-	-	-	-	-
5	0.45	3.00	3.90	5.60	5.10	5.30
13	0.60	4.00	5.00	5.70	6.20	6.40
17	4.00	7.60	8.90	9.90	10.50	10.80
30	17.60	21.90	23.40	24.40	25.00	25.20



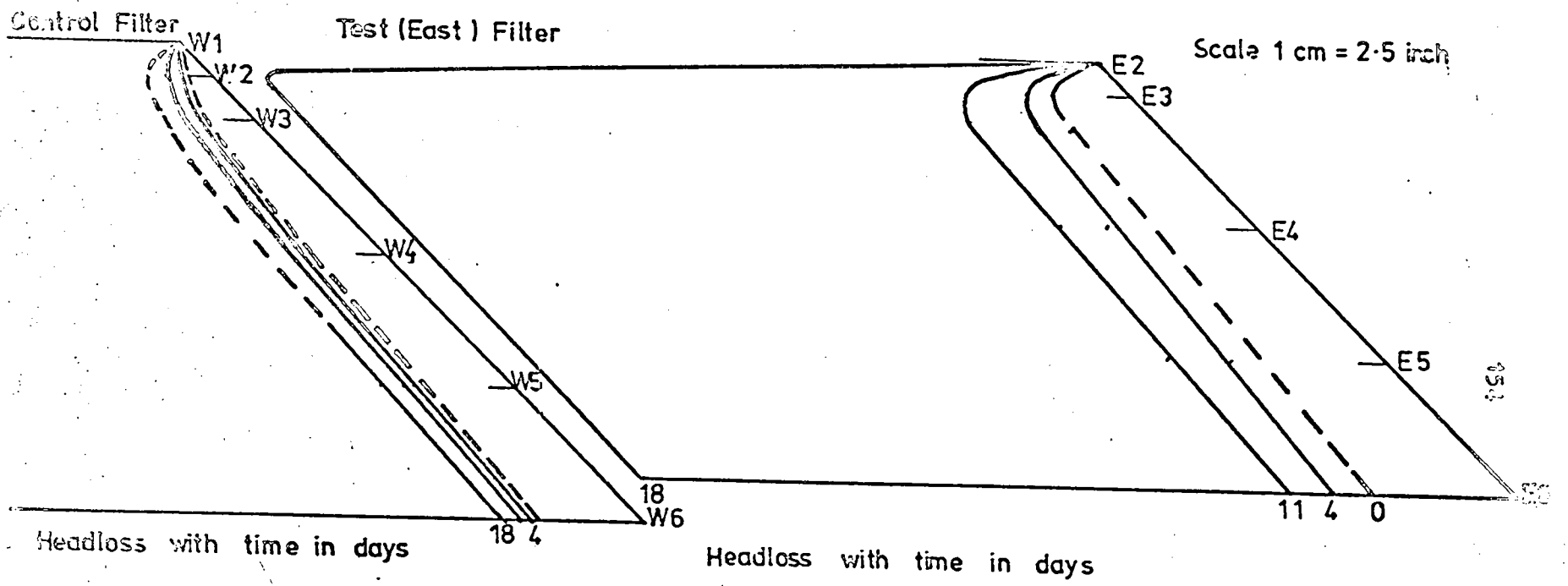
GRAPH 9,2,1

Initial Headloss Curves

Initial Headloss of all runs

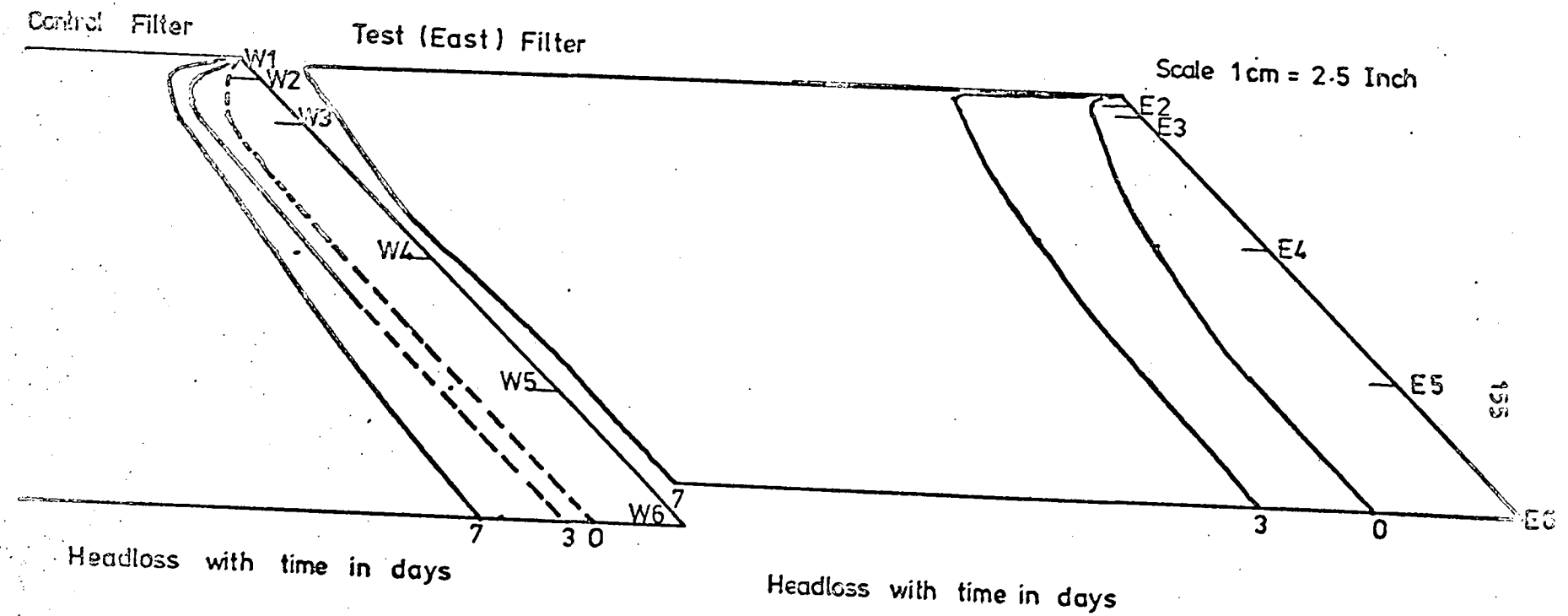
Run no.	hl initial		Duration	Remarks
	Test	Control	Days	
1	7·5	5·0	18	
2	7·0	5·5	7	
3	4·8	4·4	16	
4	3·1	3·0	44	No Phenol
5	3·0	2·5	25	
6	2·8	3·6	23	No Phenol

TABLE 9,2,1



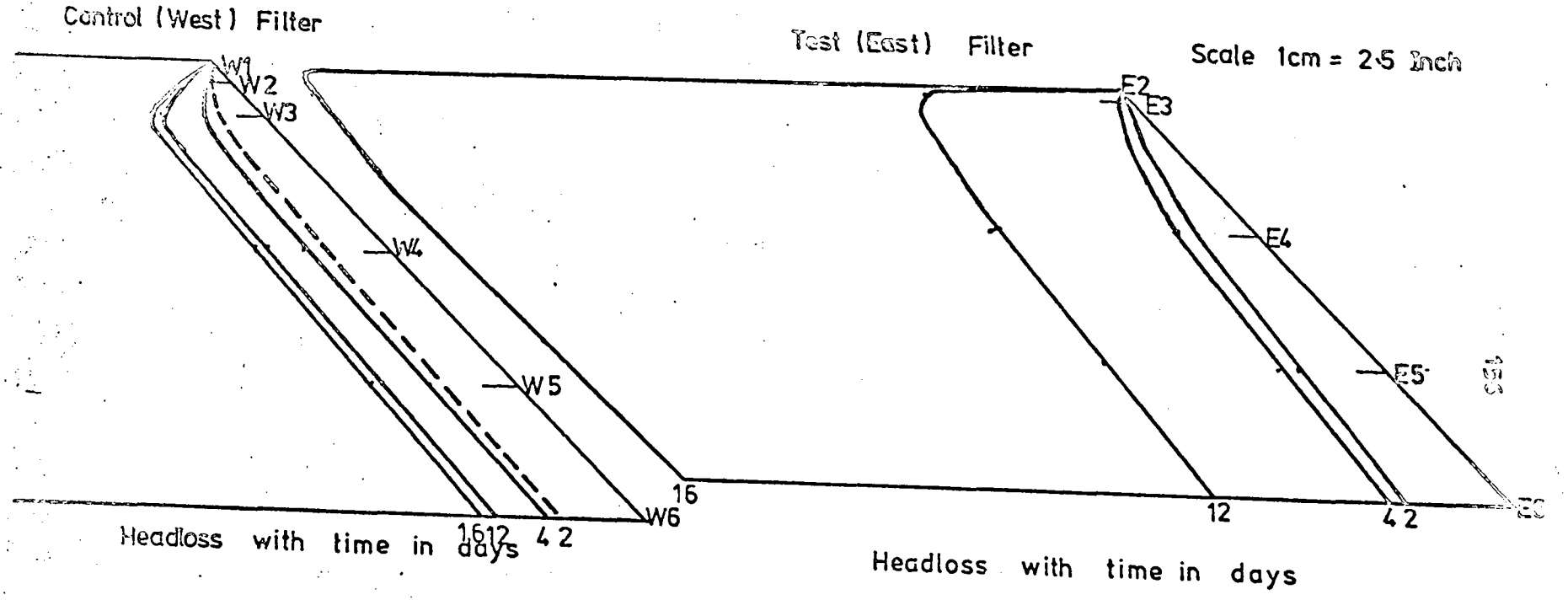
GRAPH 9.3.1

Depth Time Headloss Curves - Run no.1



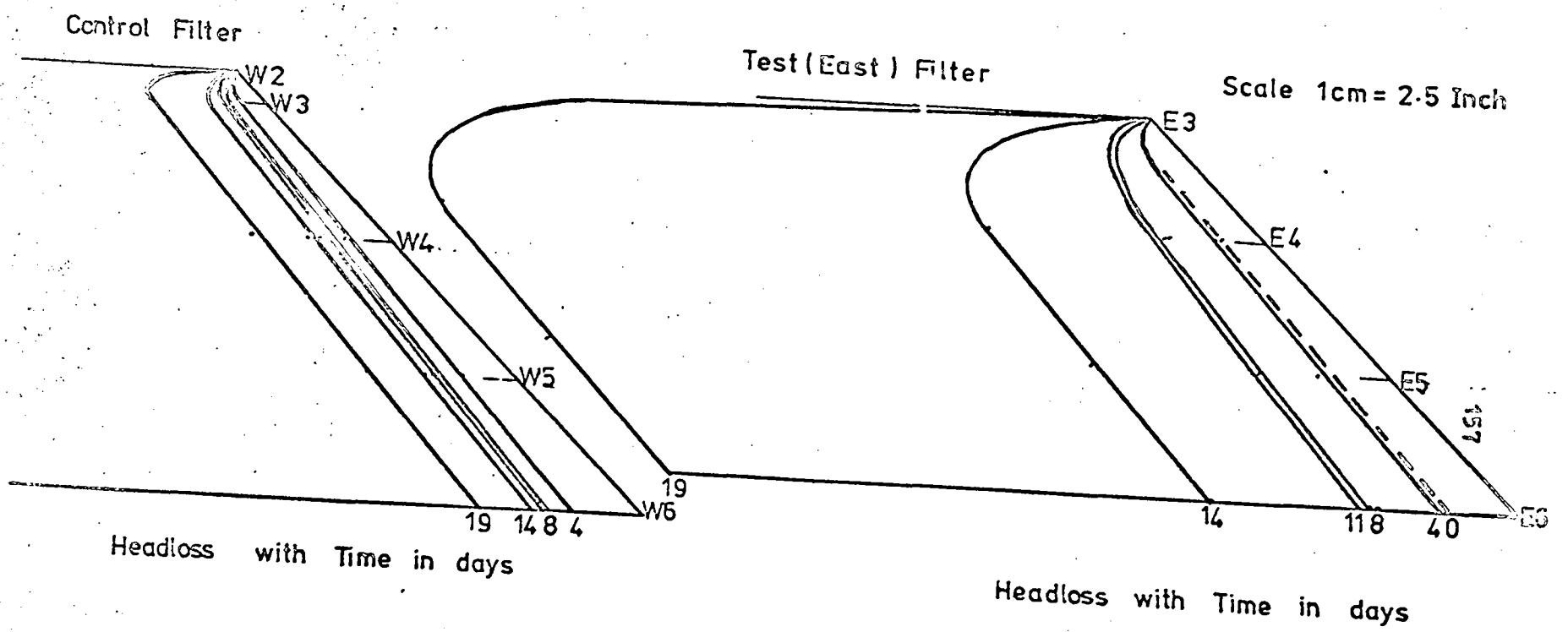
GRAPH 9,3,2

Depth Time Headloss Curves - Run no.2



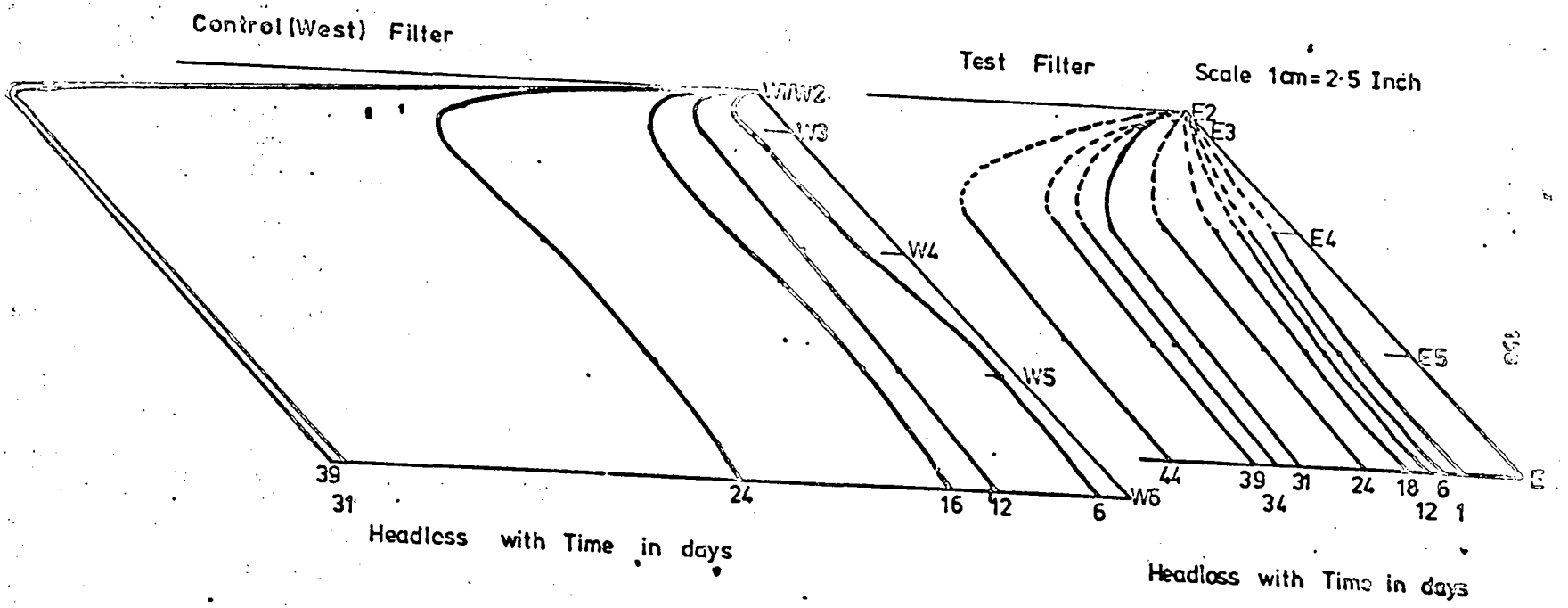
GRAPH 9,3,3

Depth time Headloss Curves -Run no. 3



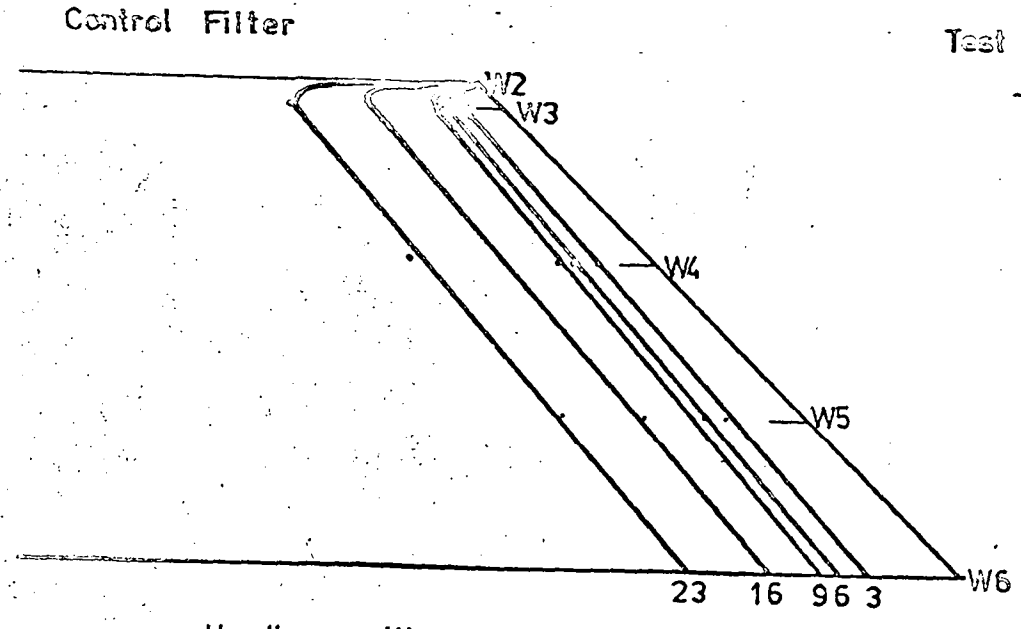
GRAPH 9,3,4

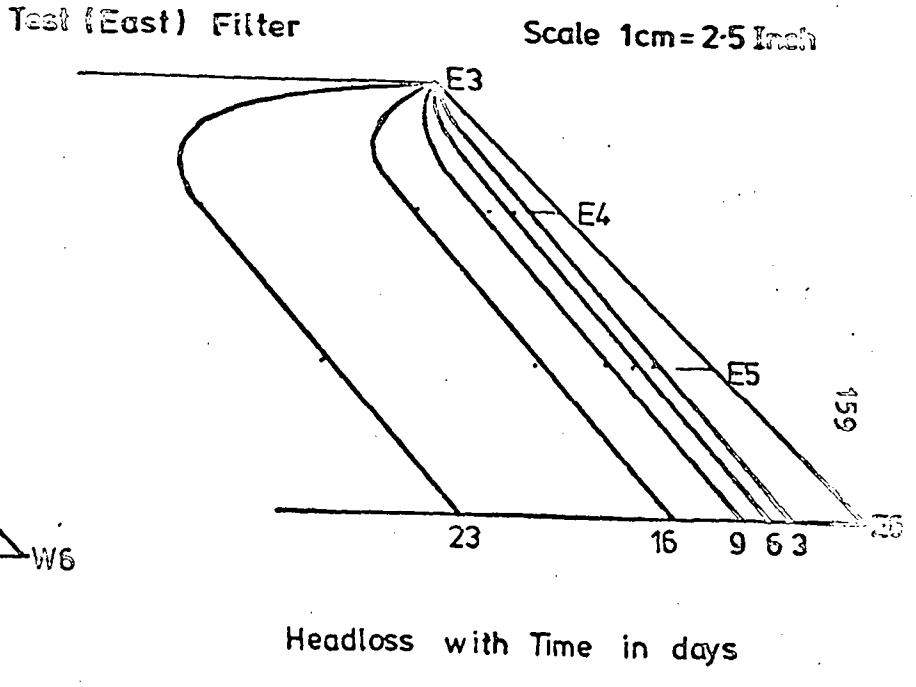
Depth Time Headloss Curves - Run no.5



GRAPH 9,3,5

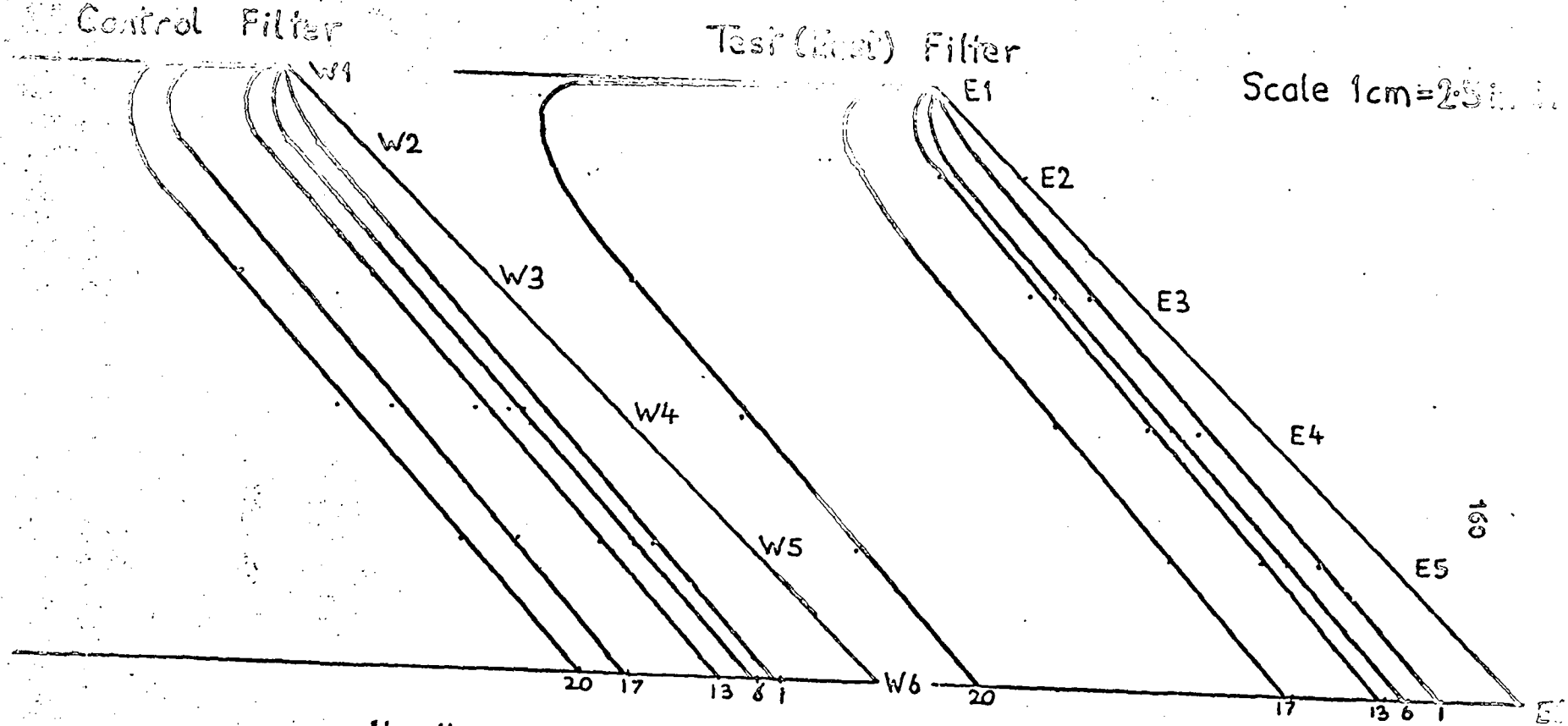
Depth Time Curves - Run no.4





GRAPH 9,3,6

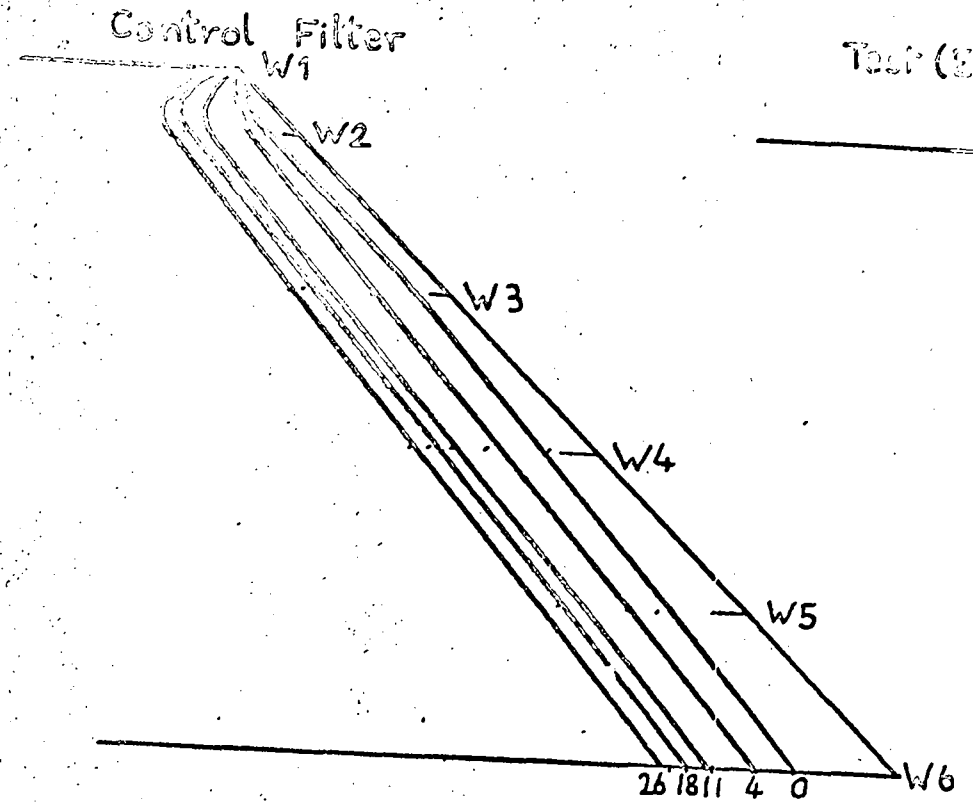
Depth Time Headloss Curves - Run no.6



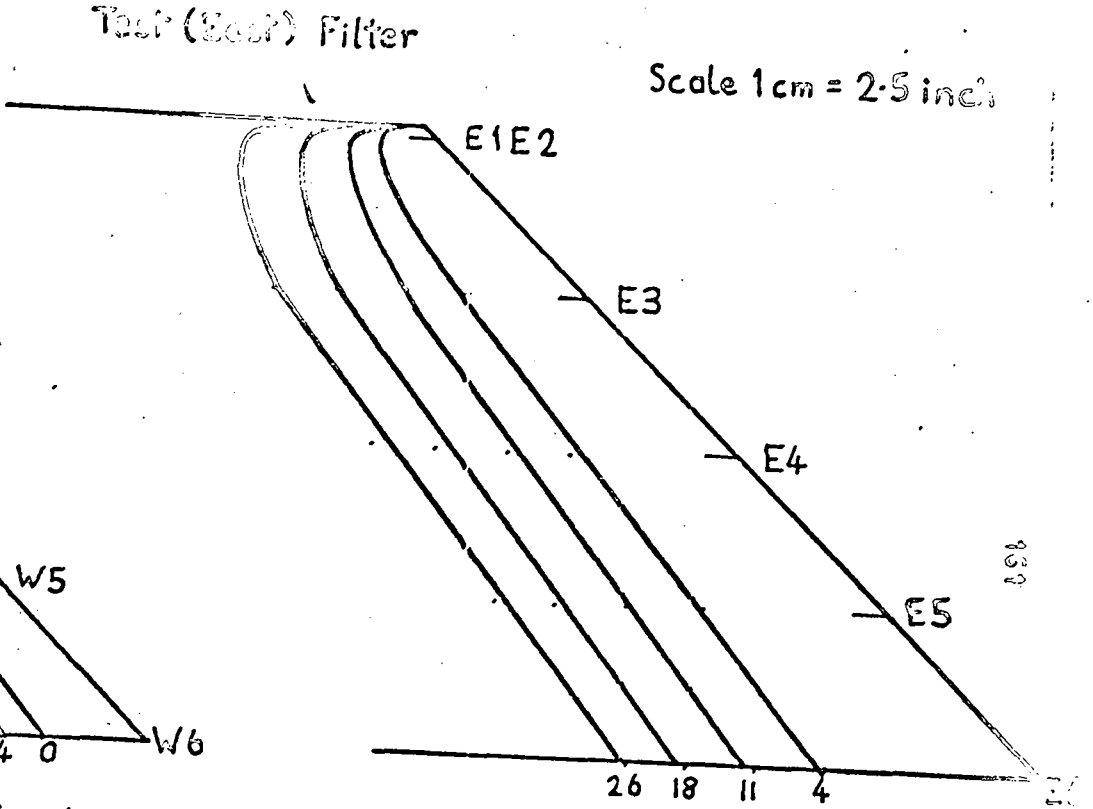
GRAPH 9,3,7

Depth Time Headloss Curves - Run no. 2/71-73

(on tables 9,3,13-16)



Headloss with Time in days

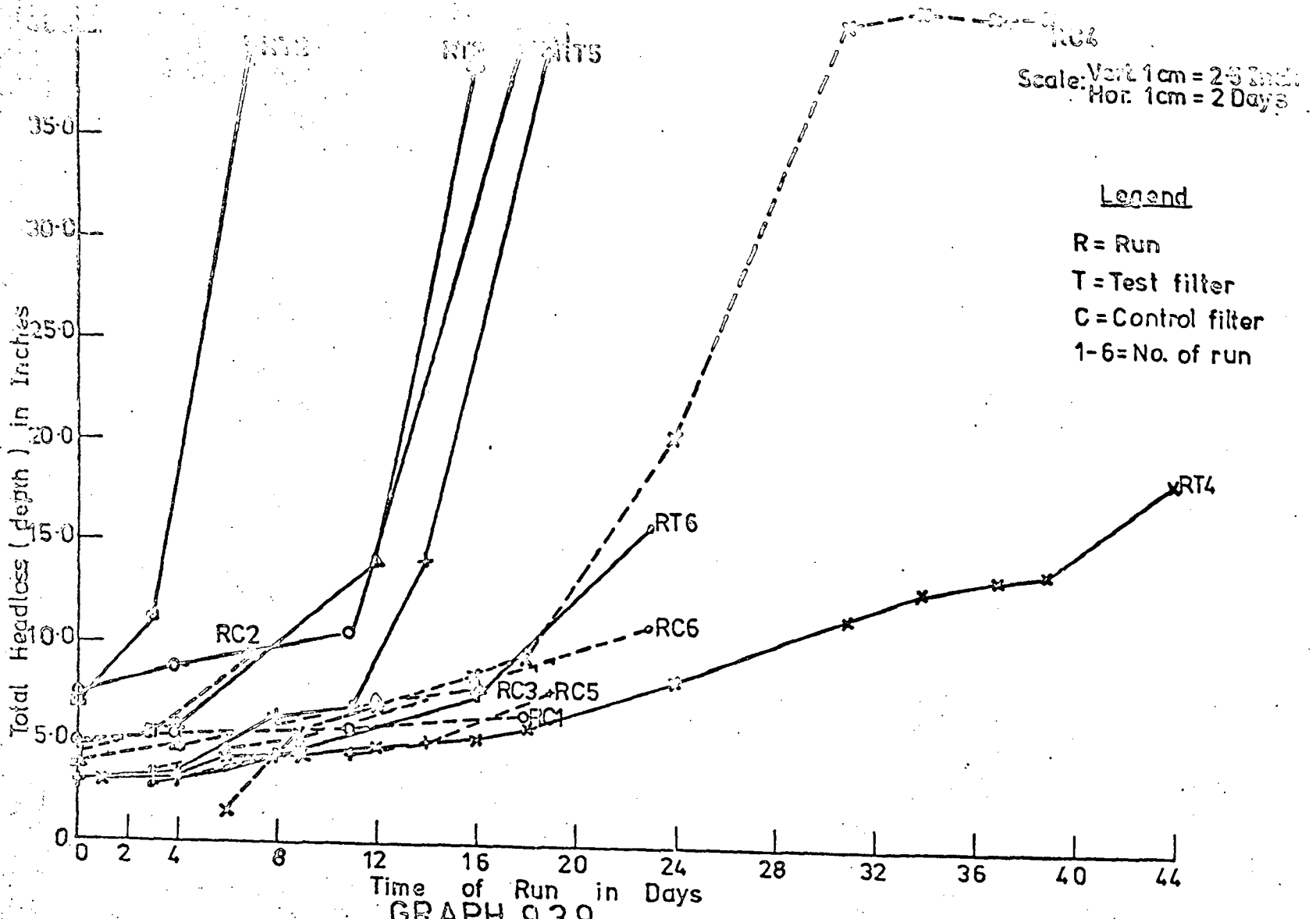


Headloss with Time in days

GRAPH 9,3,8

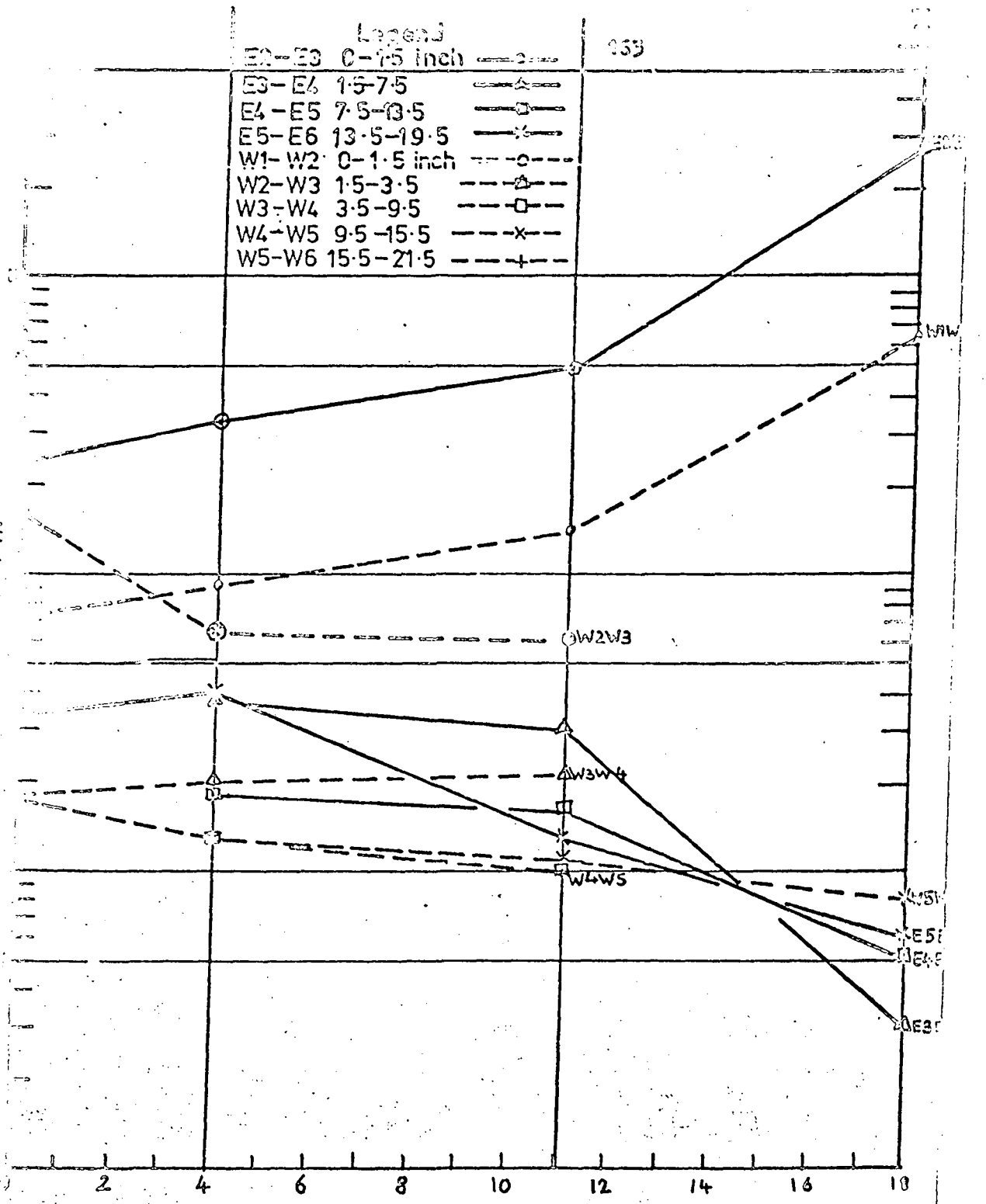
Depth Time Headloss Curves - Run no.14/71–73

(on tables 9,3,15–16)



GRAPH 9,3,9

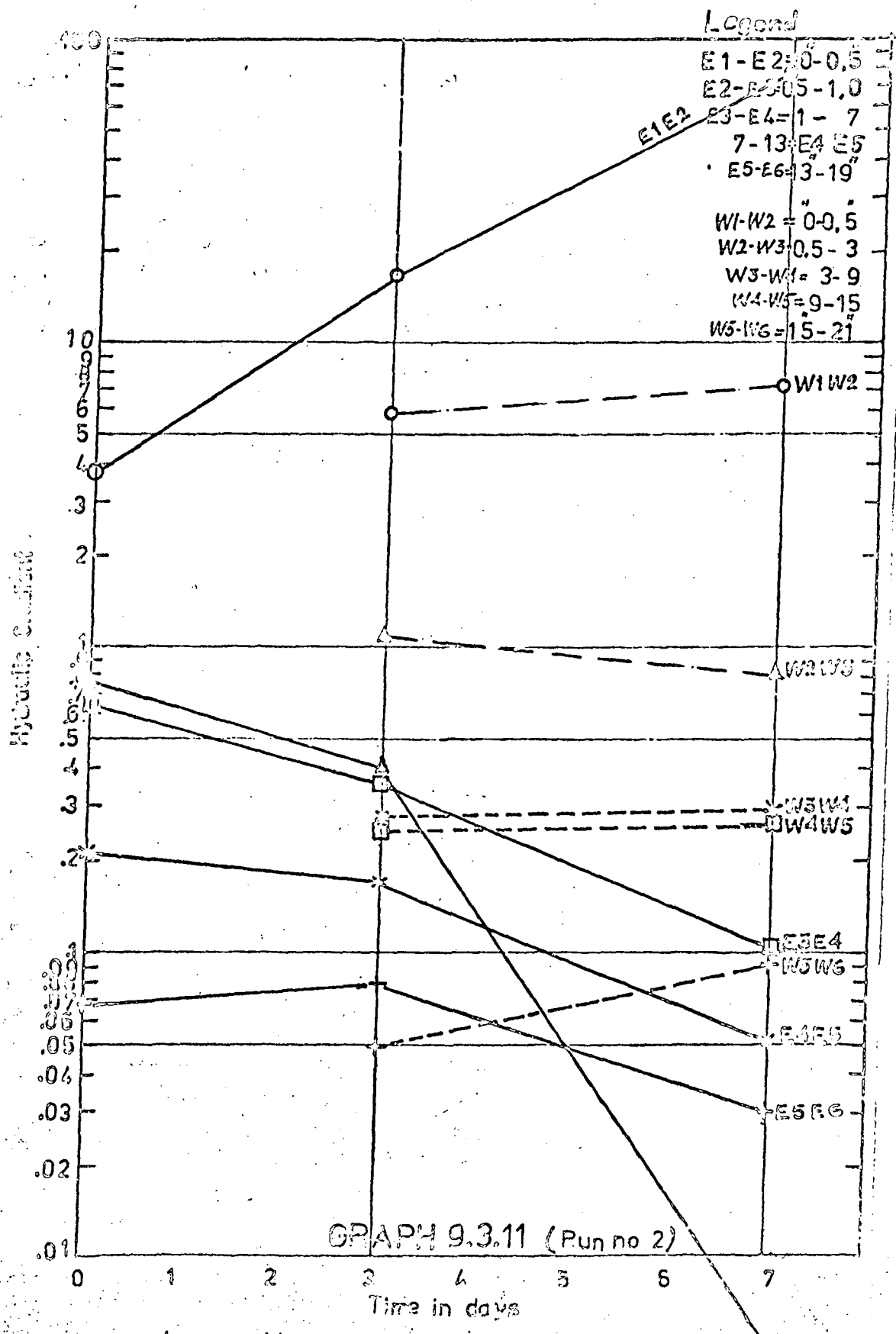
Total Headloss Curves (On Trito 9,3,17)



Time in days

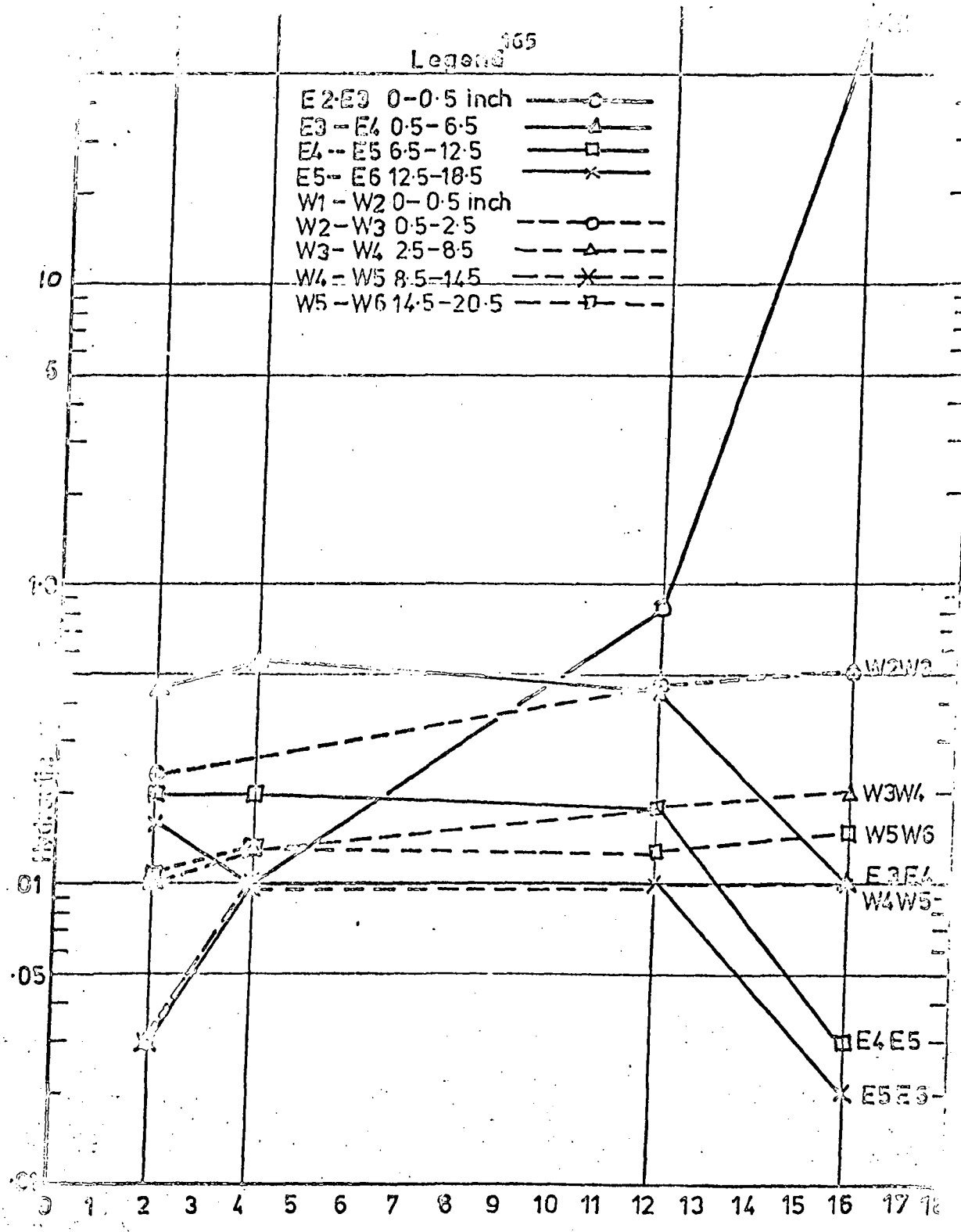
GRAPH 9,3,10 (Run no.1)

Layer Hydraulic Gradient with Time Curves



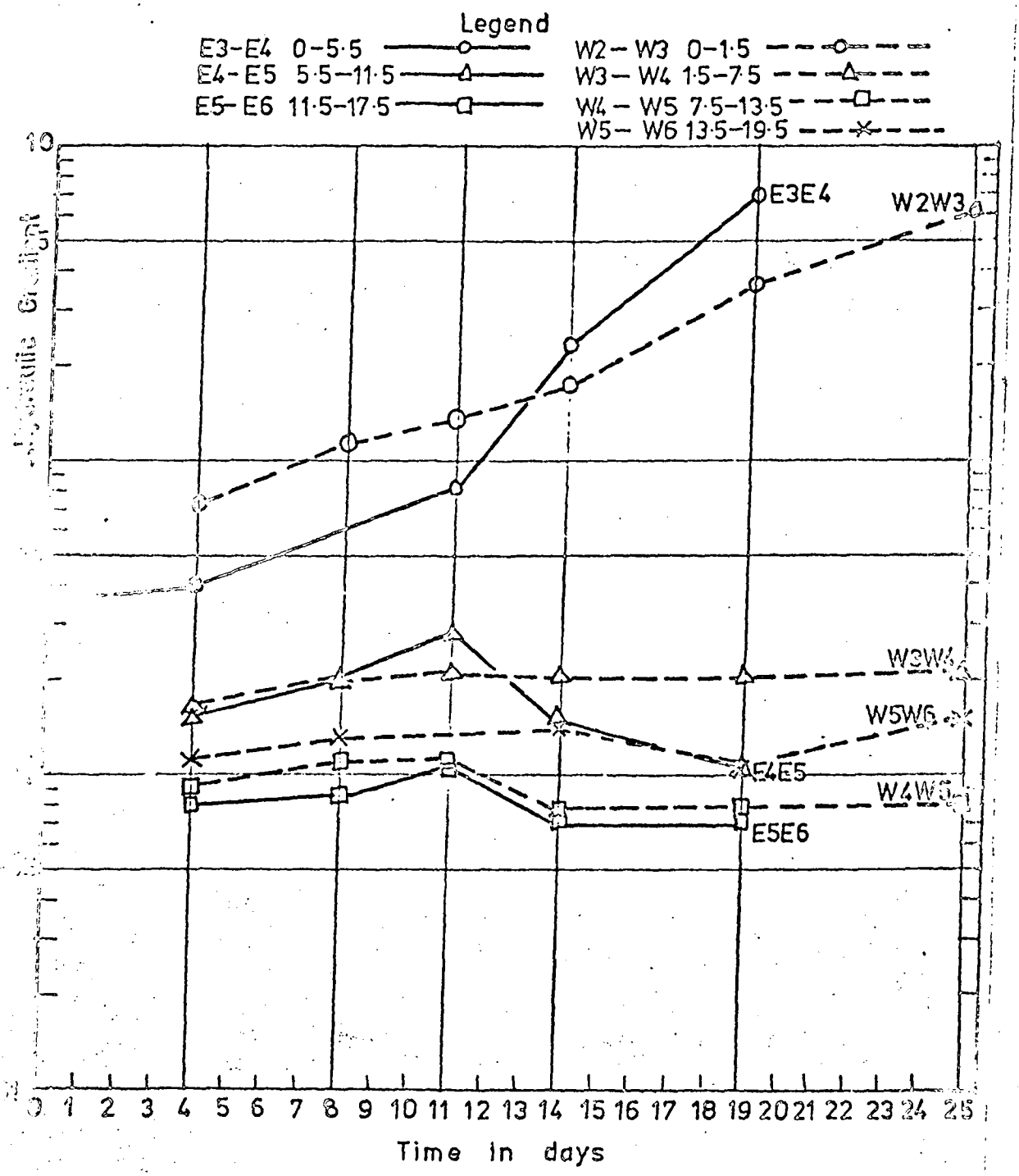
GRAPH 9.3.11 (Run no 2)

Lower Hydraulic Gradient with Time



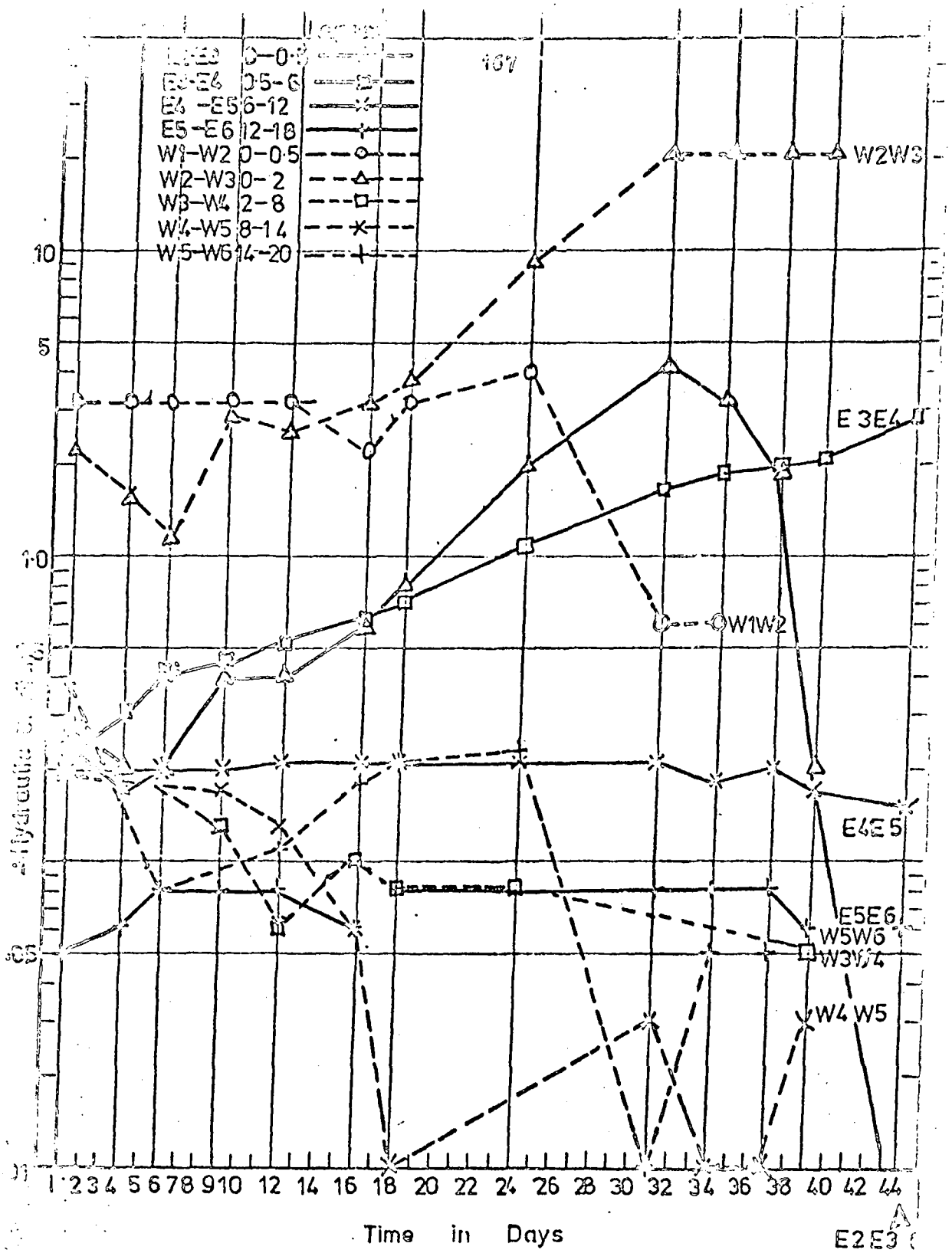
GRAPH 9,3,12 (Runno3)

Layer Hydraulic Gradient with Time



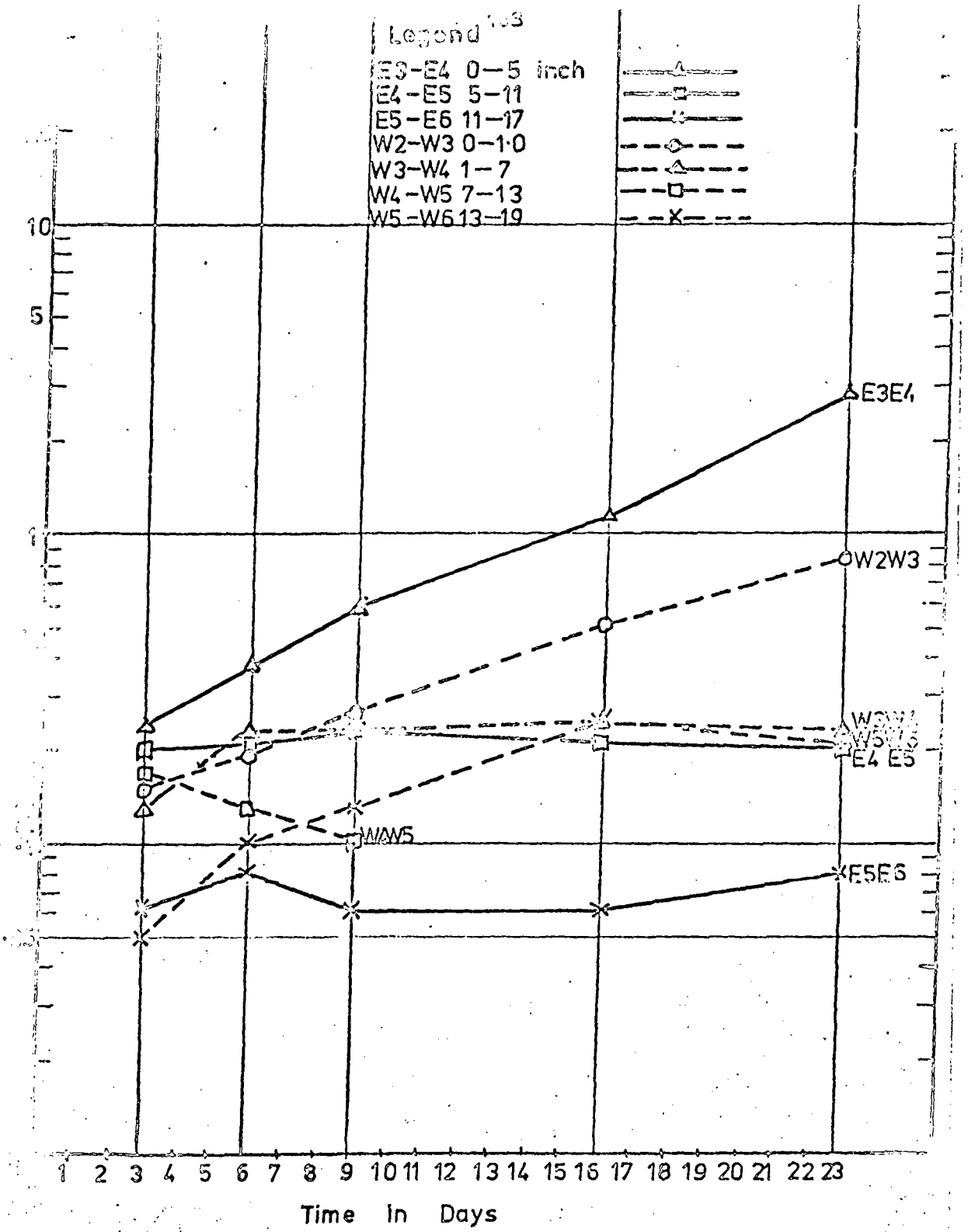
GRAPH 9,3,13 (Run no.5)

Layer Hydraulic Gradient with Time



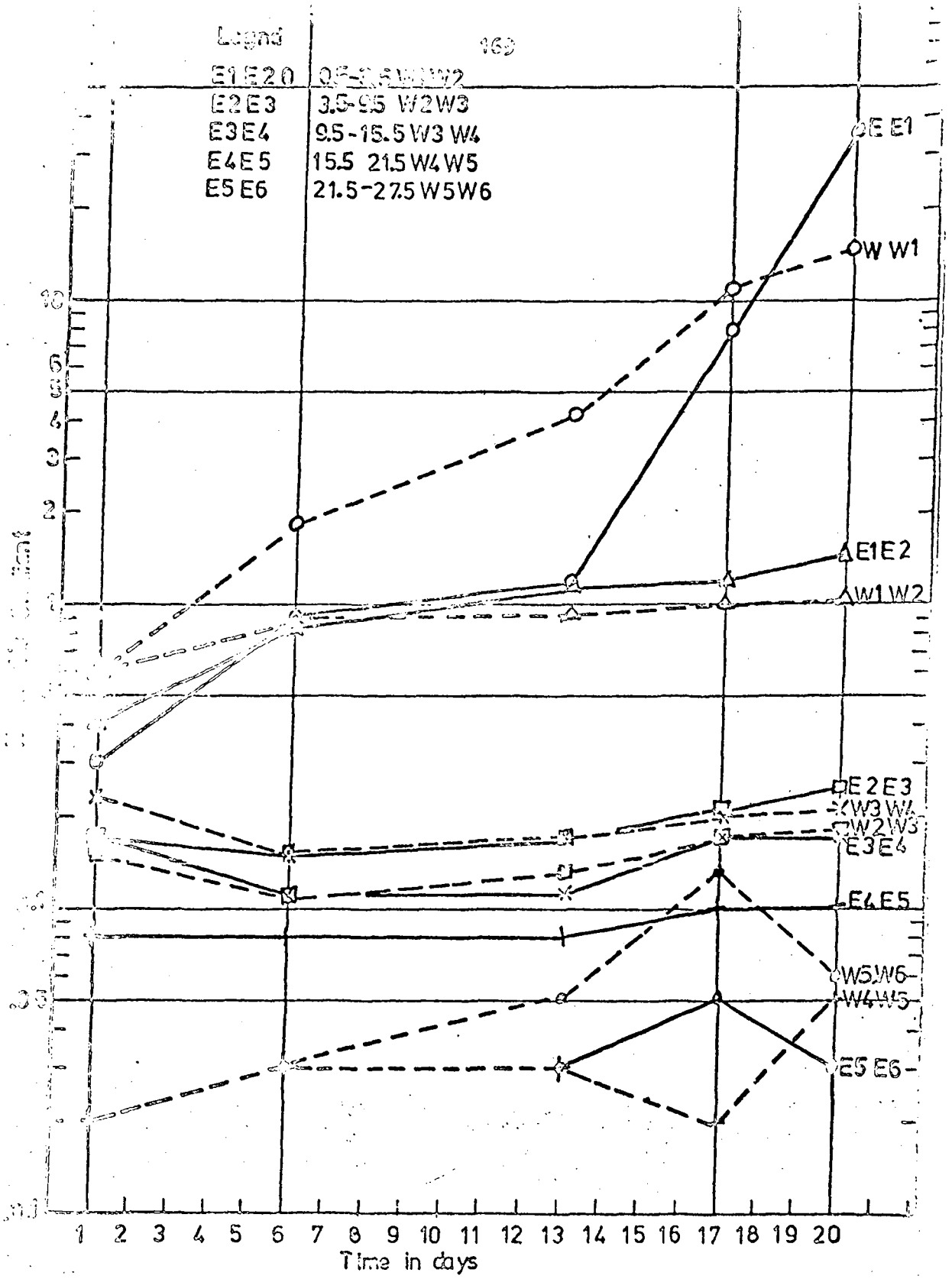
GRAPH 9,3,14 (Run no.4)

Layer Hydraulic Gradient with Time

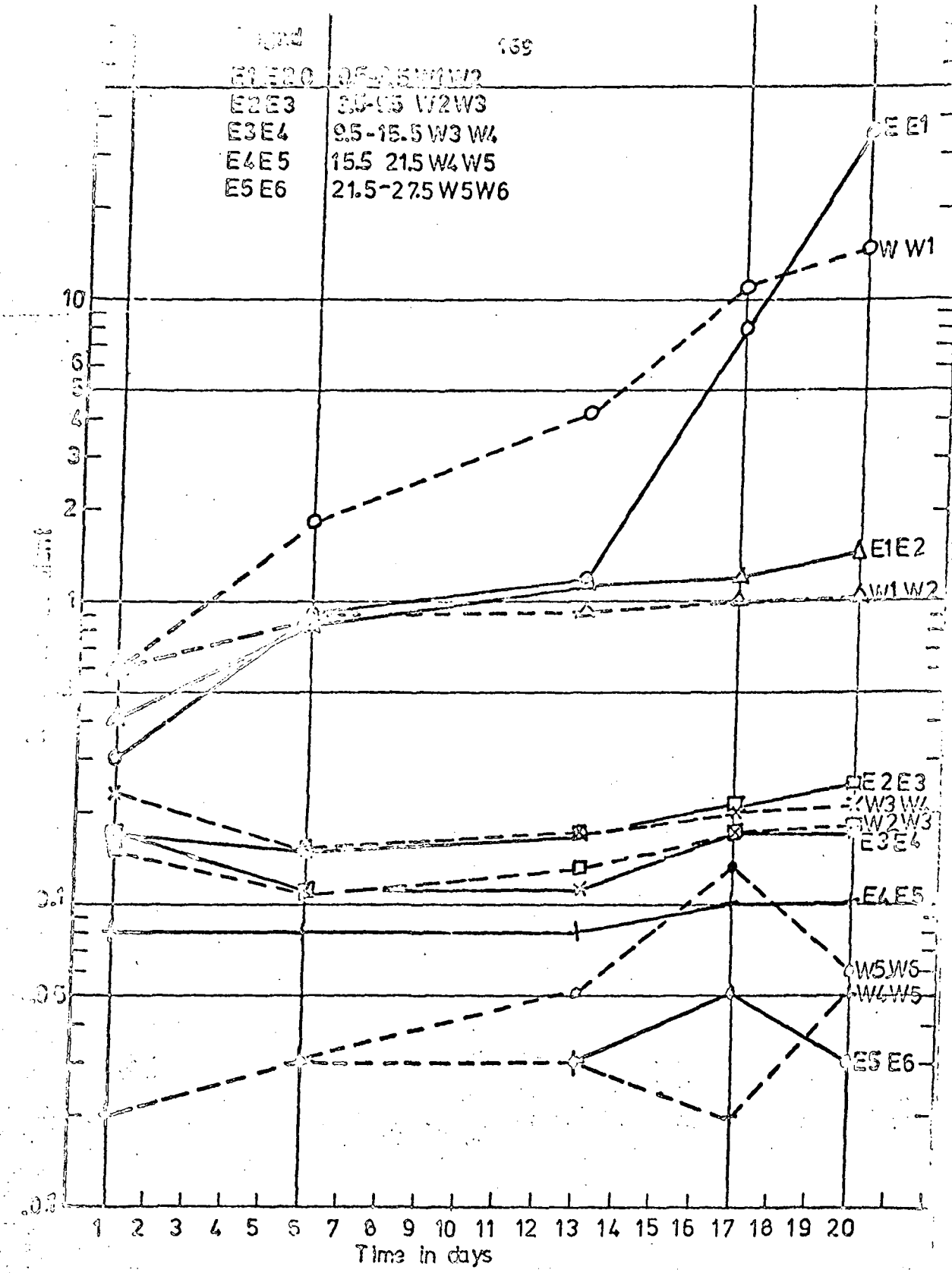


GRAPH 9,3,15 (Run no 6)

Layer Hydraulic Gradient with Time



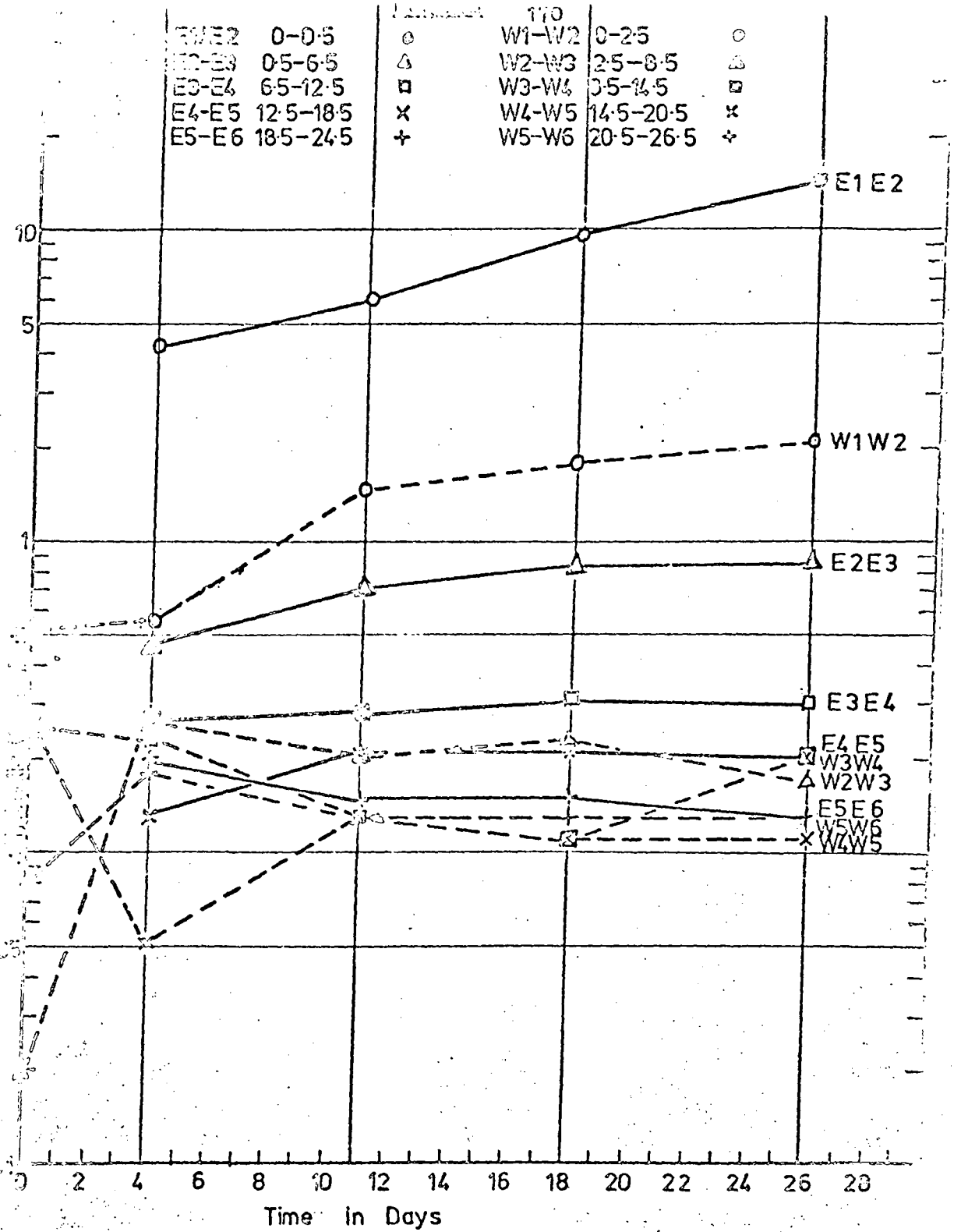
GRAPH 9.3.15
(Run no 2/71-73)
LAYER HYDRAULIC GRADIENT WITH TIME



GRAPH 9.3.16

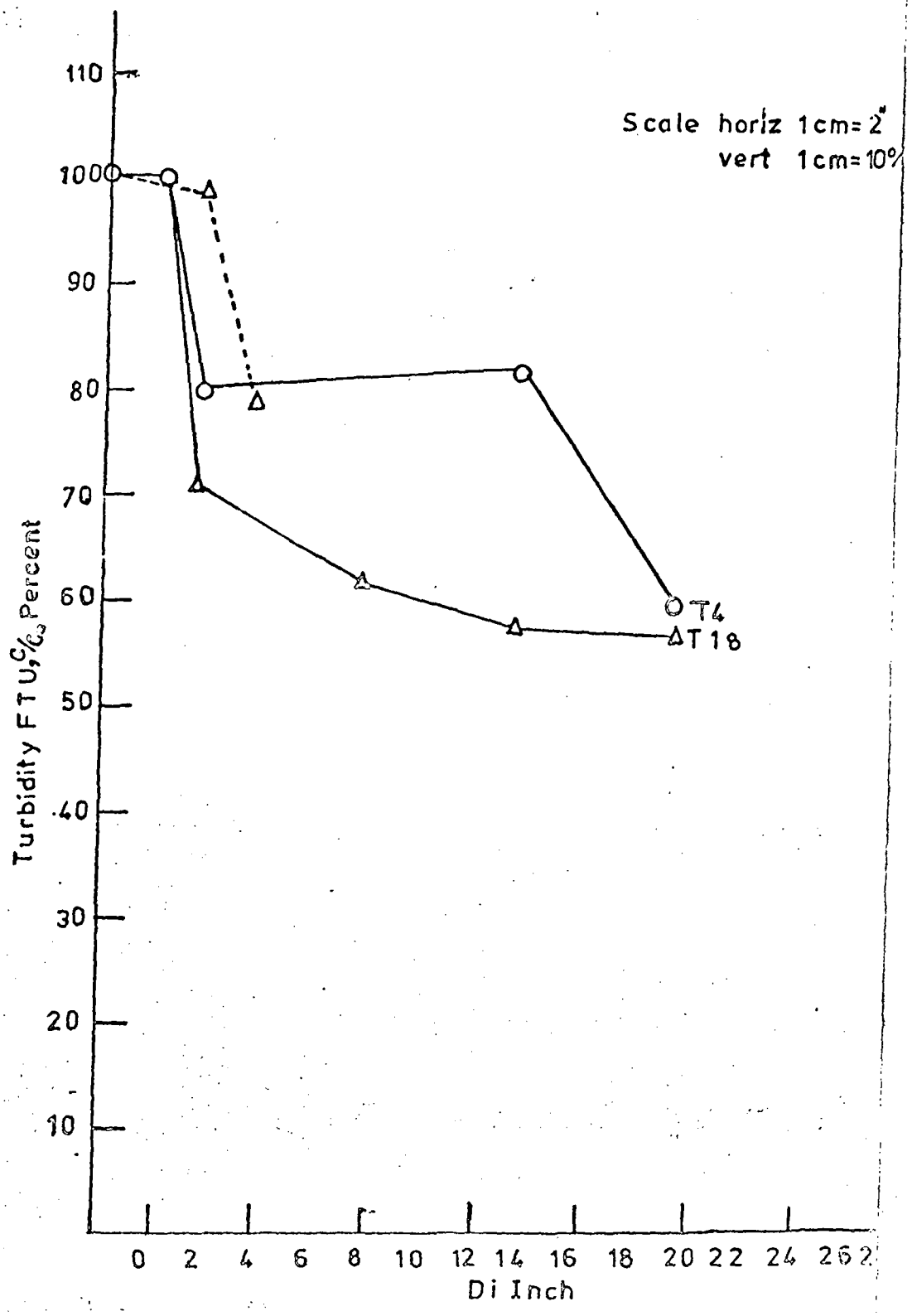
(Run no 2 (71-73)

LAYER HYDRAULIC GRADIENT WITH TIME



GRAPH 9,3,17 (Run no.14/71-73)

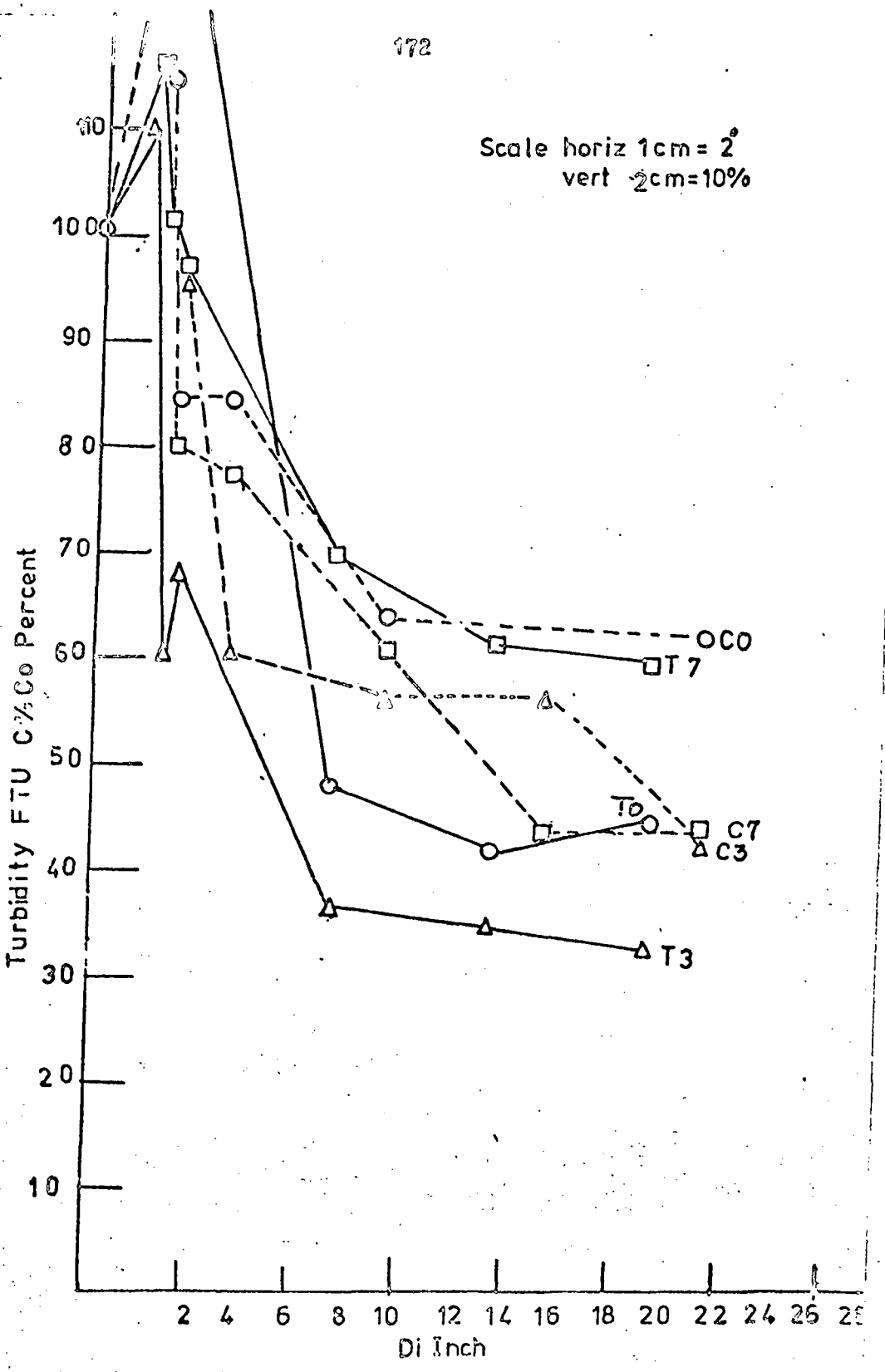
Layer Hydraulic Gradient with Time



GRAPH 9.6.1

(Table 9.6.1/2, Run 1)

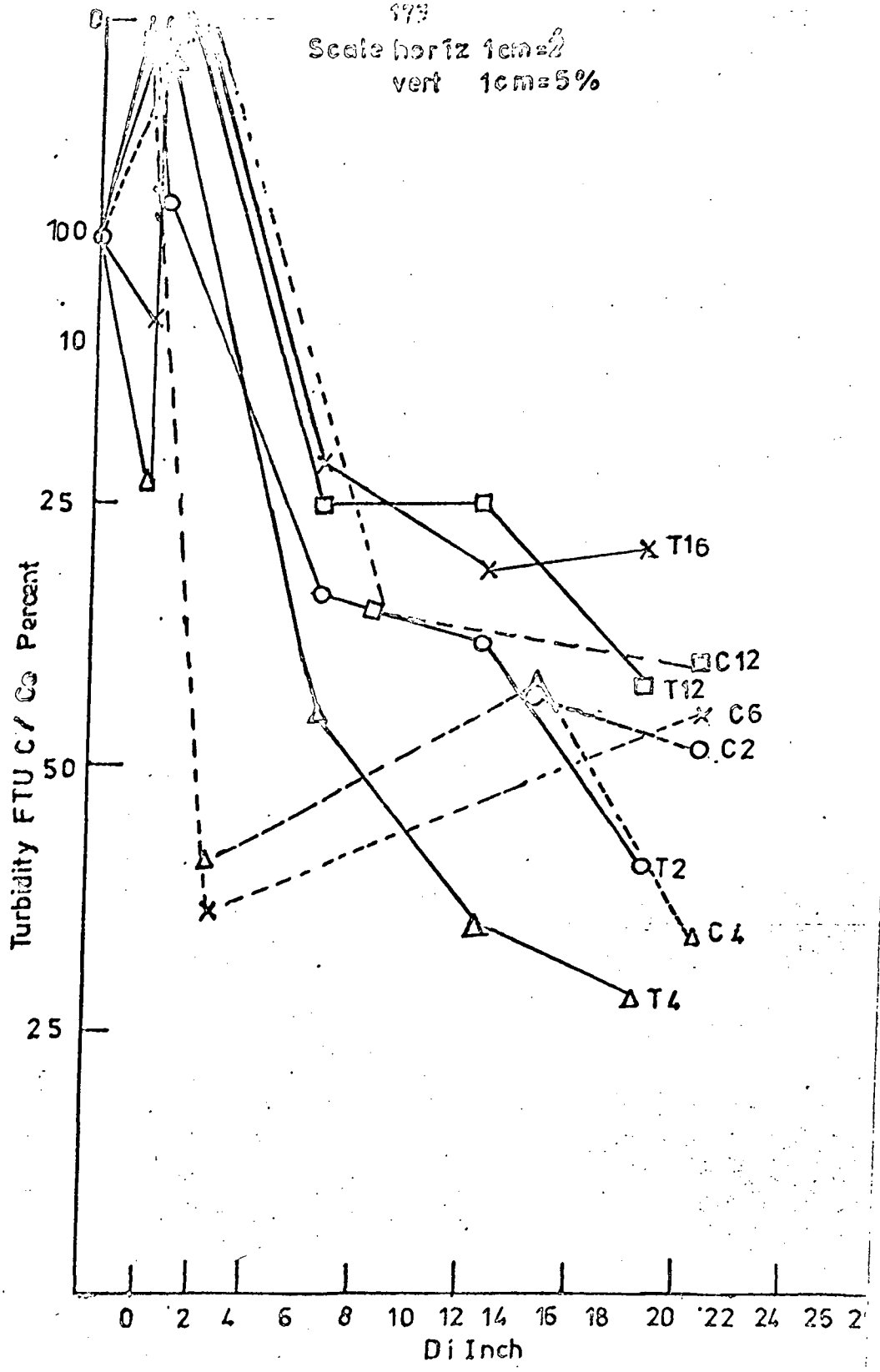
Turbidity Removal in Depth Curve



GRAPH 9.4.2

(Table 9.4.3/4 Run no 21)

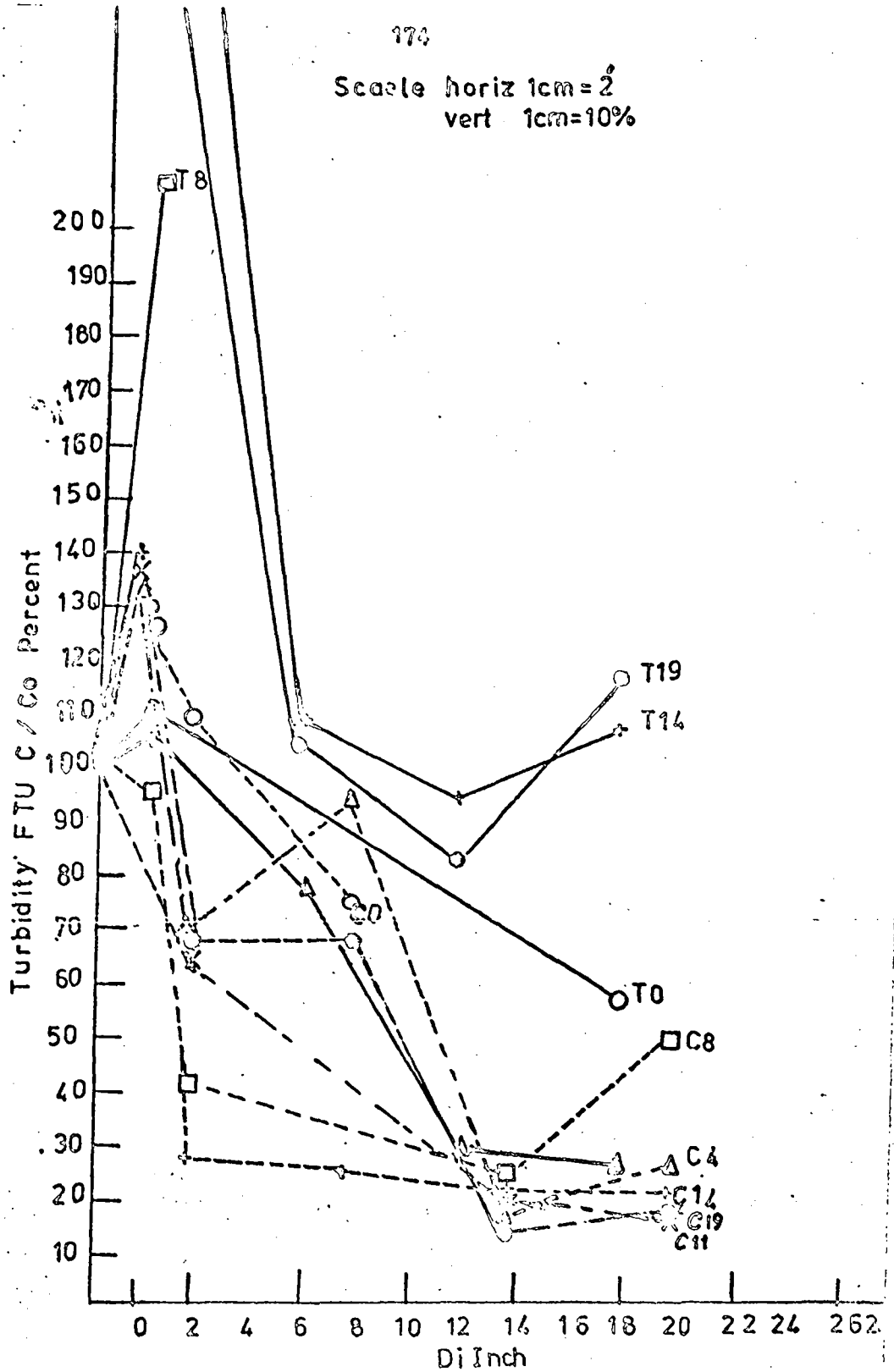
Turbidity Removal in Depth Curves



GRAPH 9,4,3

(Table 9.4.5-6, Run no 3)

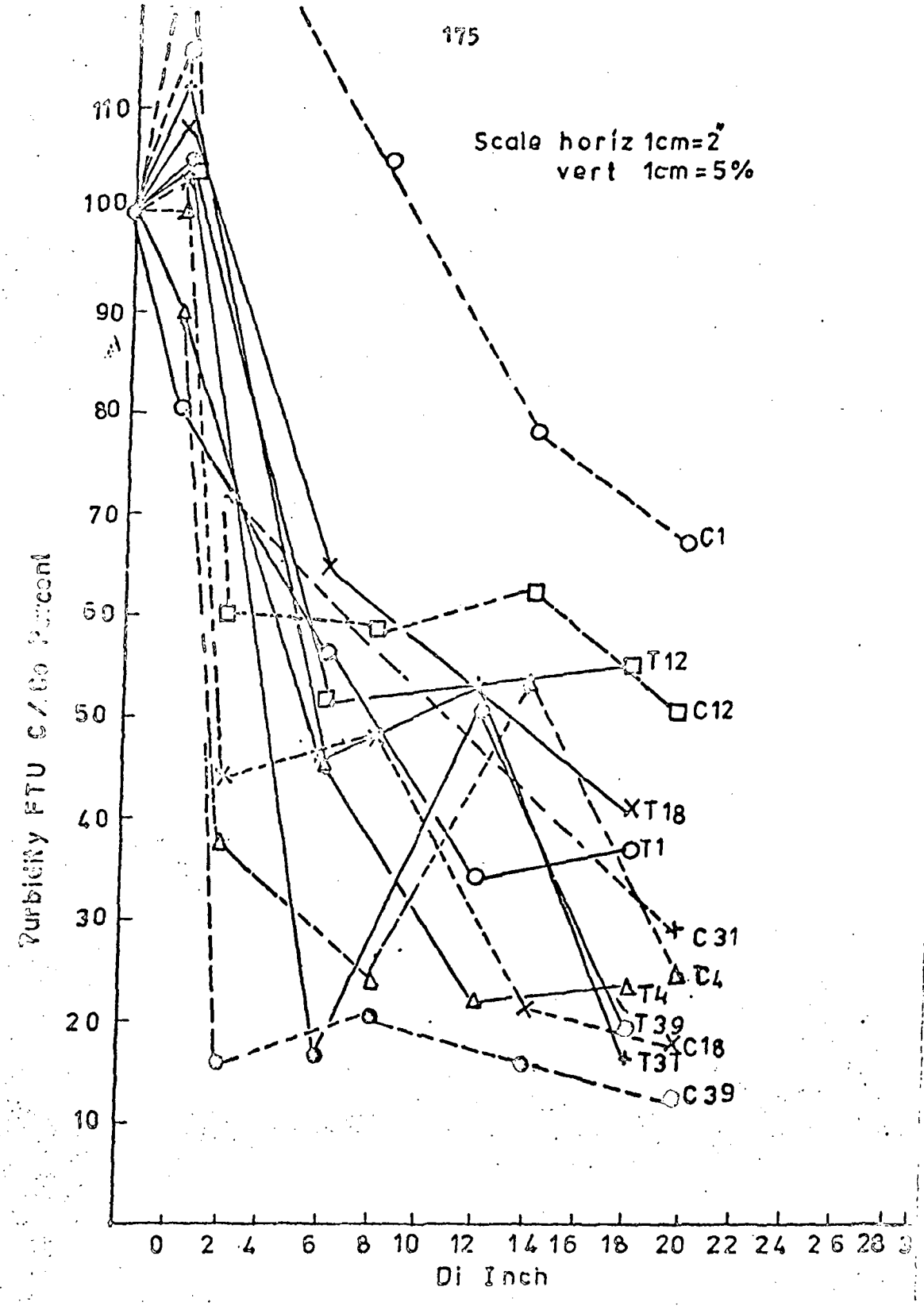
Turbidity Removal in Depth Curves



GRAPH 9.4.6

(Table 9.4.9-10, Run no 5)

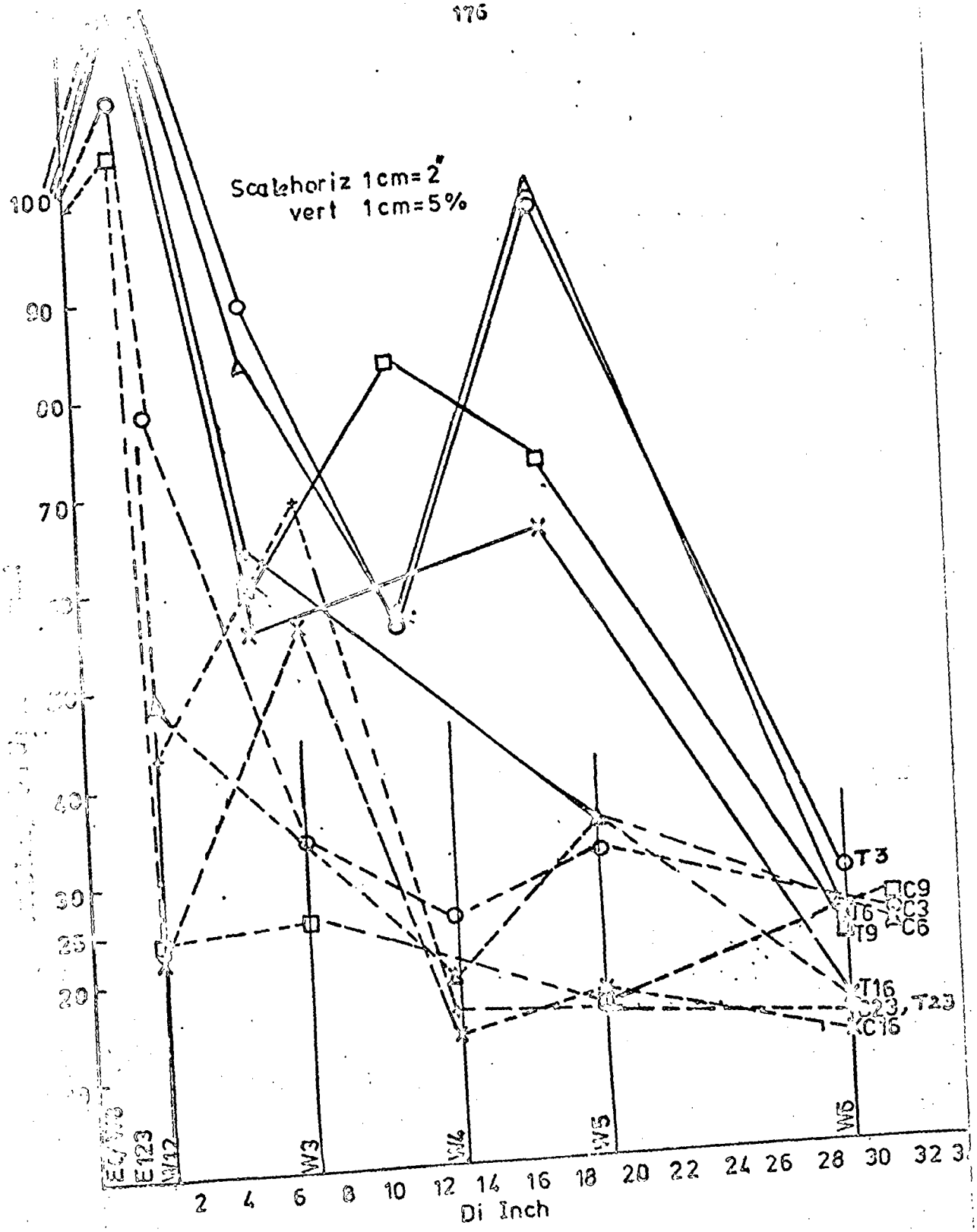
Turbidity Removal in Depth Curves



GRAPH 9.4.5

(Table 9.4.7,-8 Run no 4)

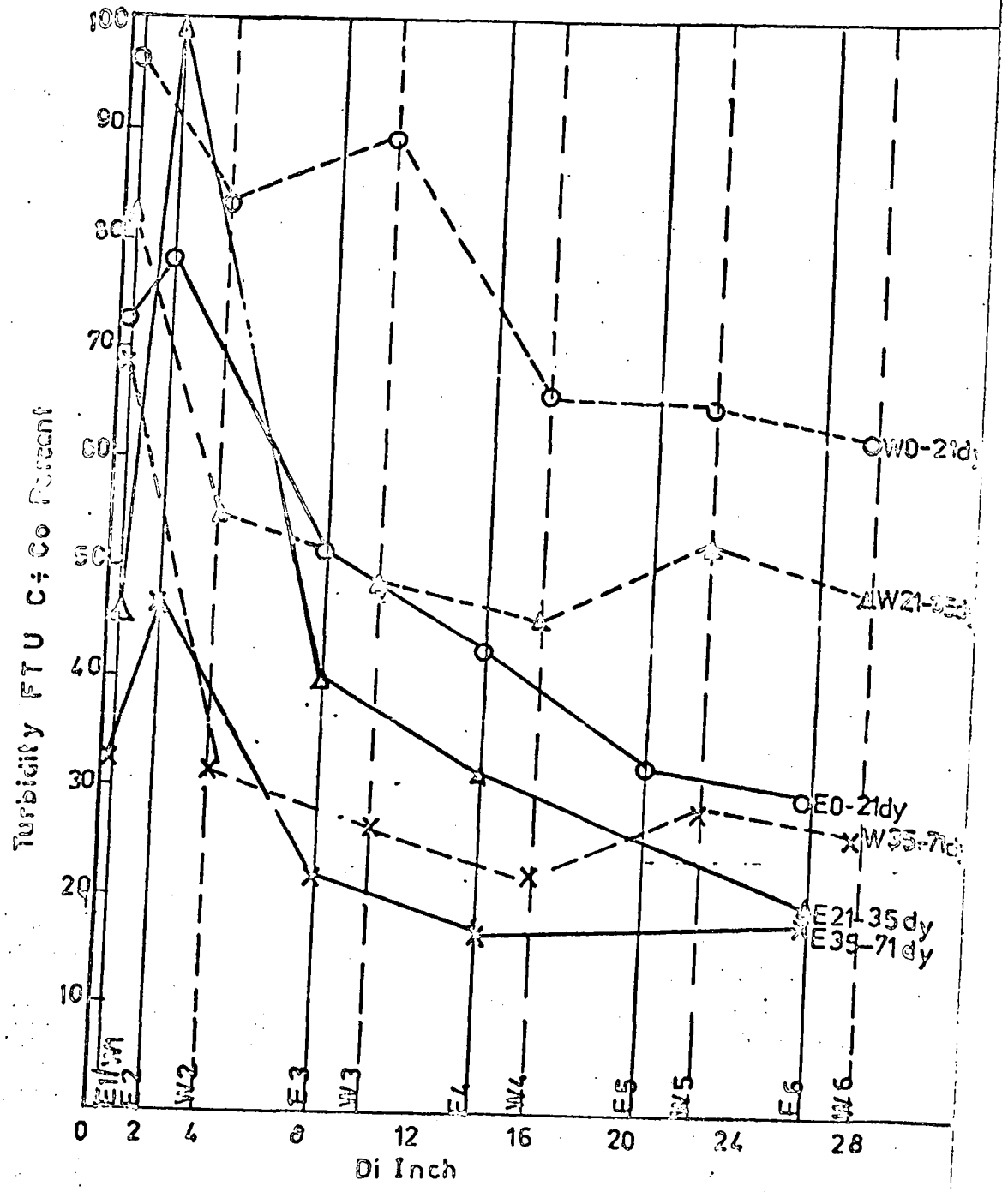
Turbidity Removal in Depth Curves



GRAPH 9.4.6

(Table 9.4.11-12, Run no 6)

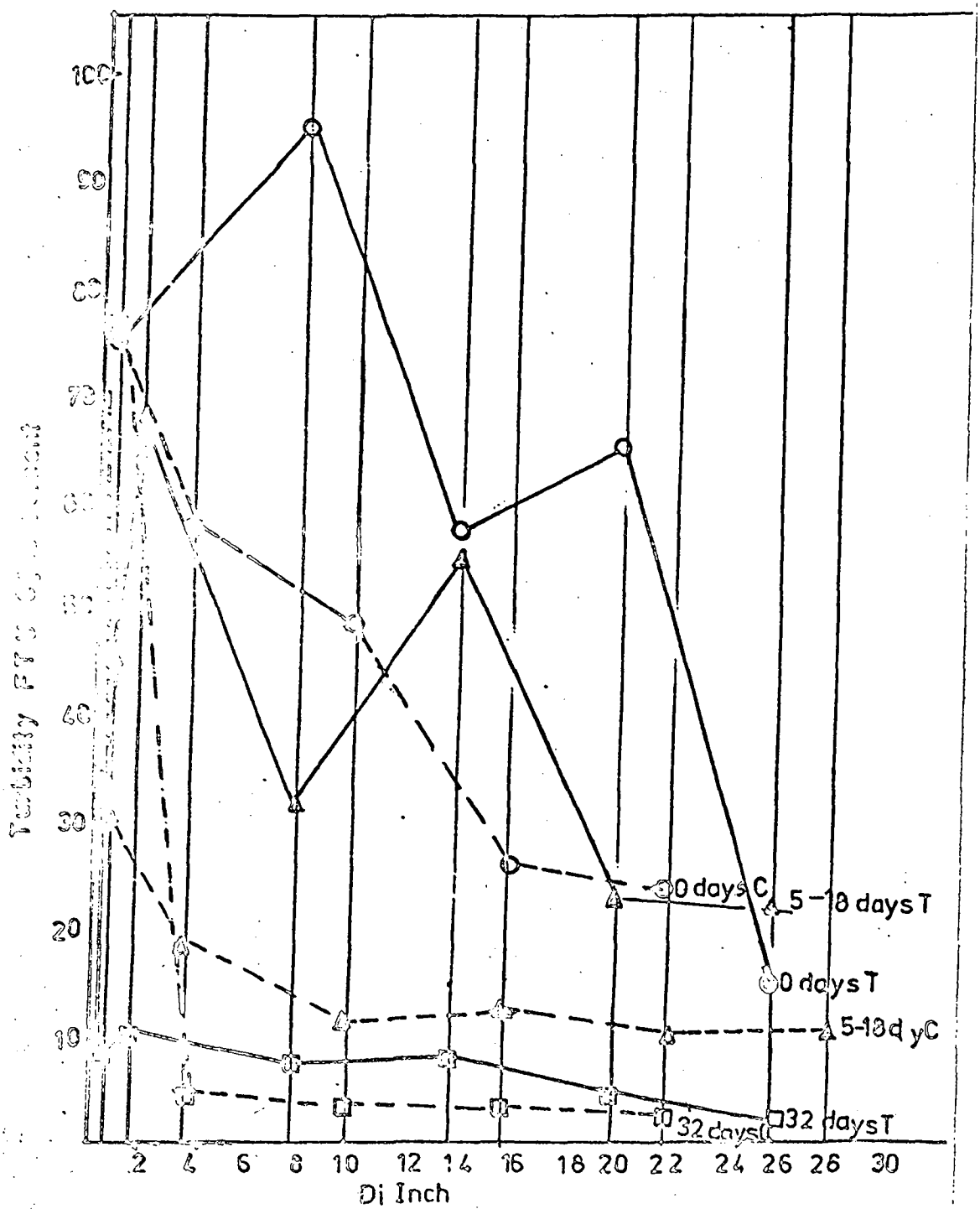
Turbidity Removal in Depth Curves



GRAPH 9.4.7

(Table 9-4-13/14, Run 11/71-73)

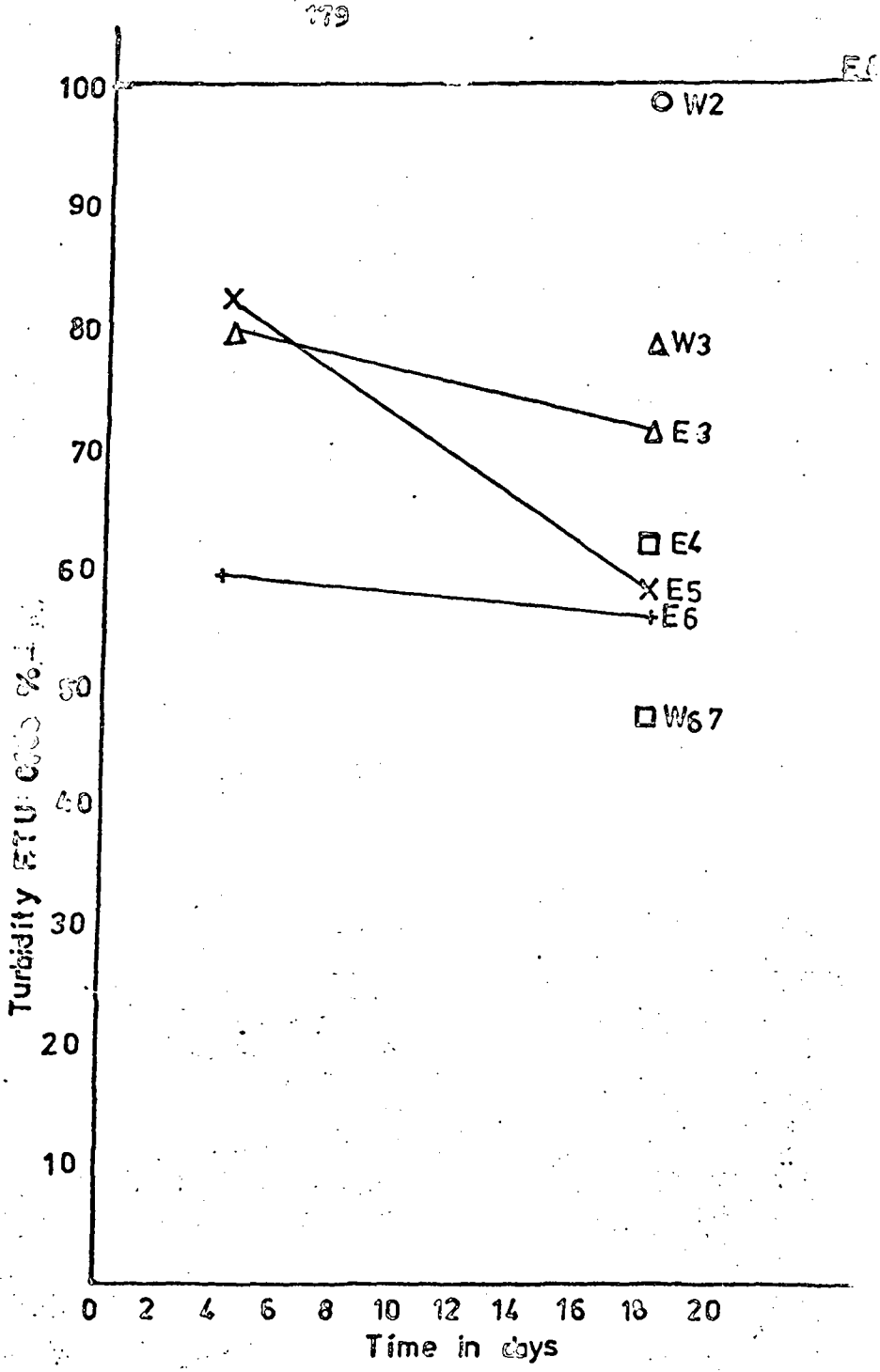
Turbidity Removal in Depth Curves



GRAPH 9.4.8

(Table 9.4.15/16, Run 12/71–73)

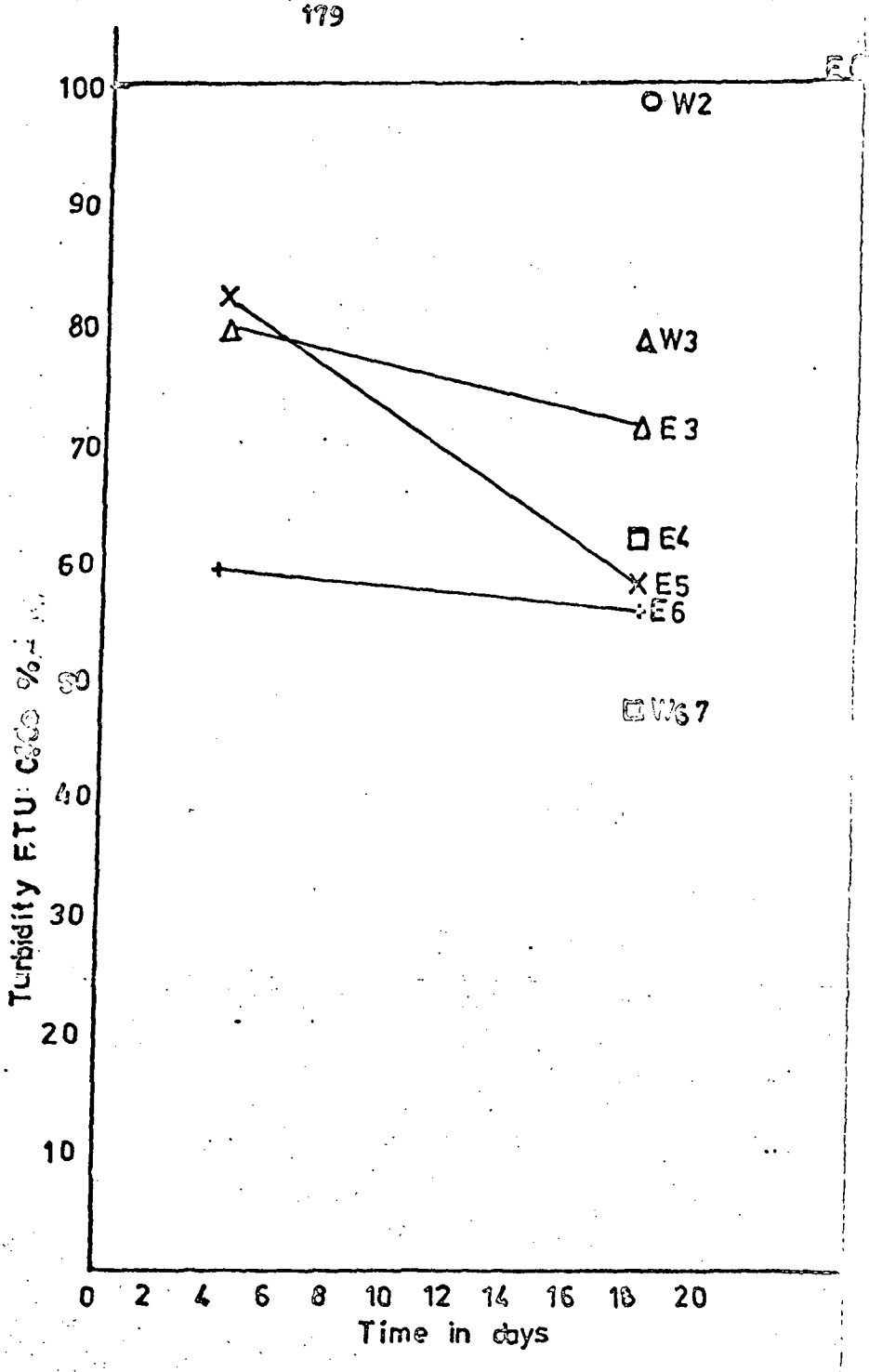
Turbidity Removal in Depth Curves



GRAPH 9.5.1

(Table 9.4.1/2, Run no 1)

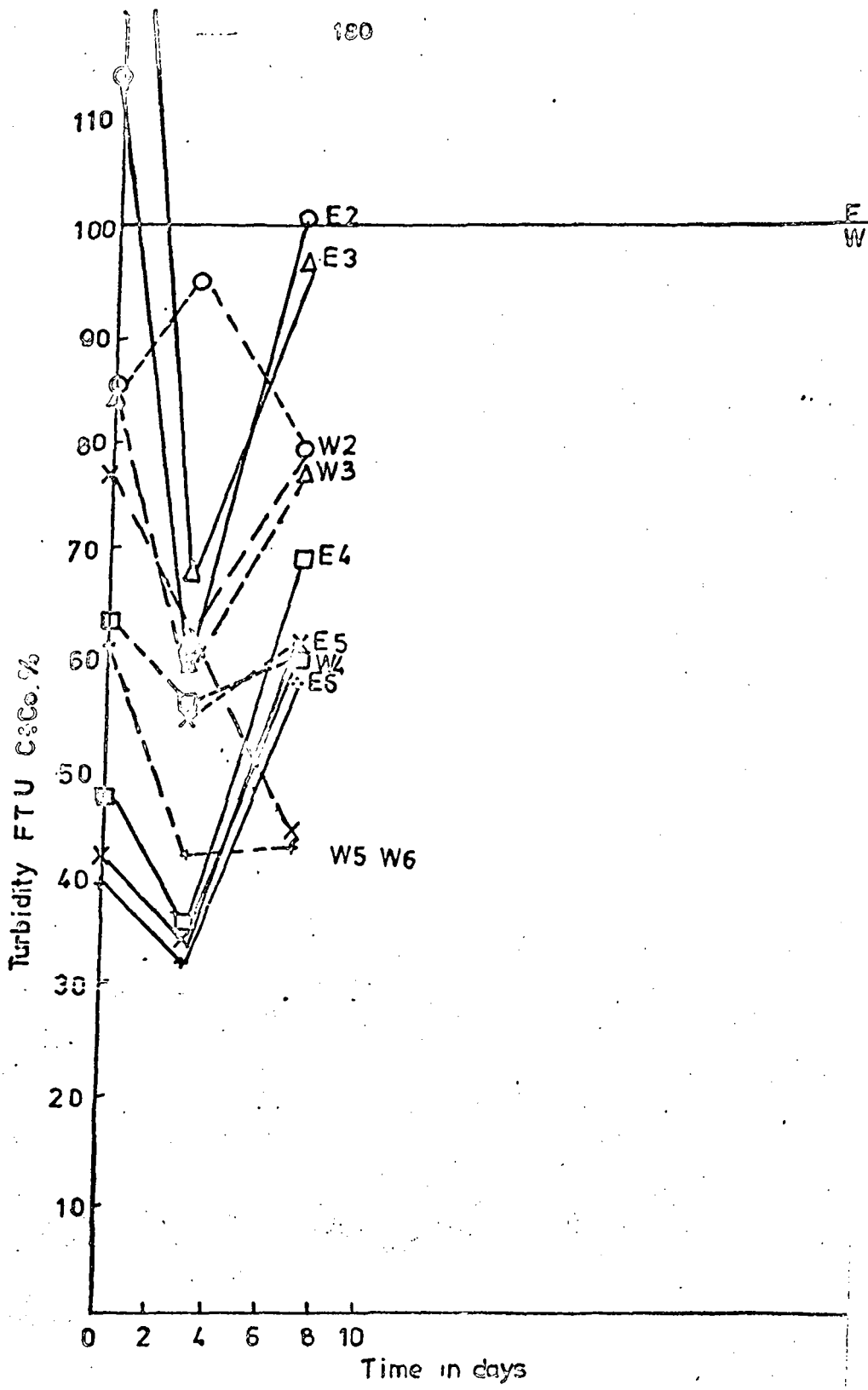
Turbidity Removal with Time



GRAPH 9.5.1

(Table 9.4.1/2, Run no 1)

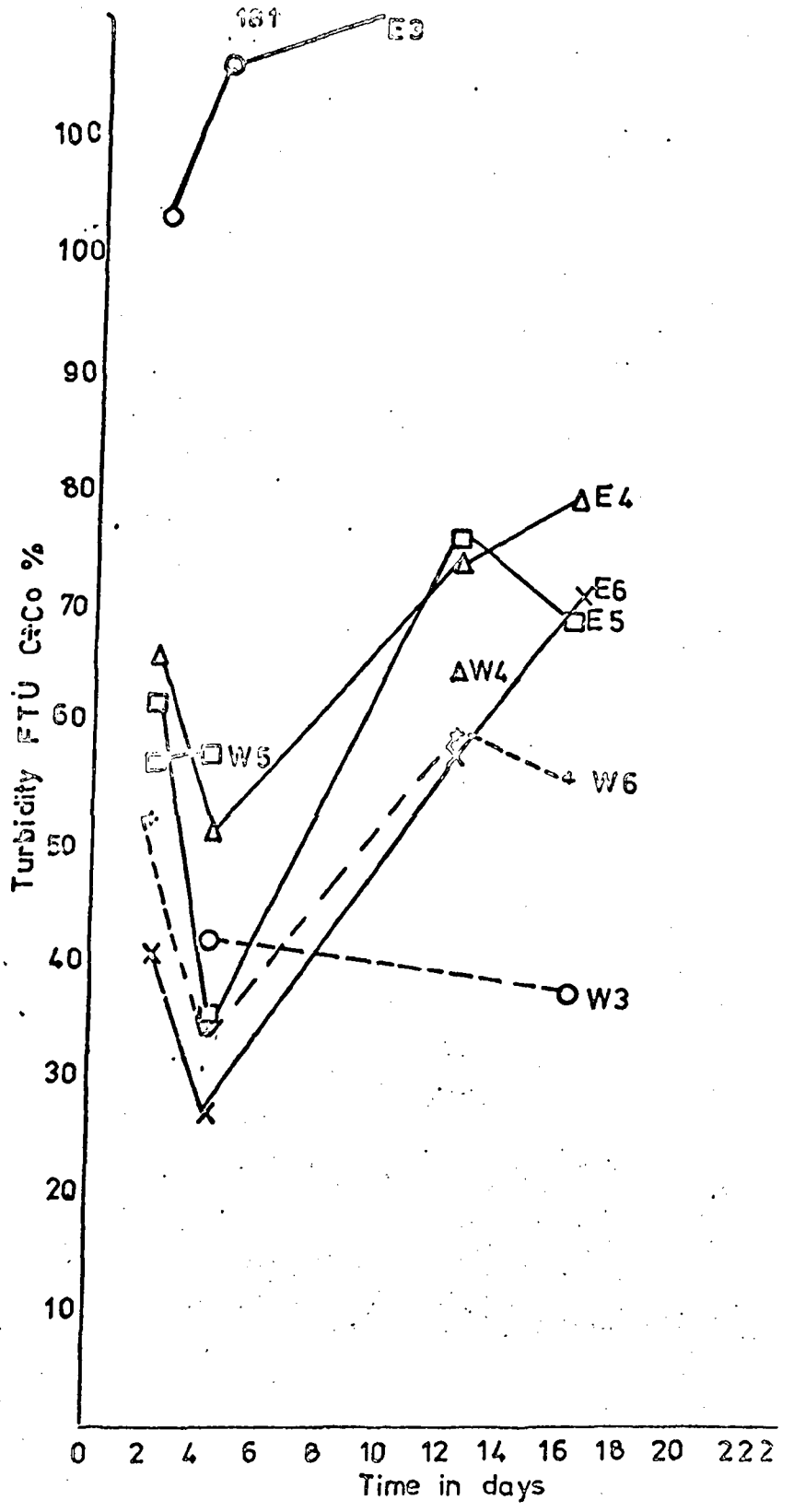
Turbidity Removal with Time



GRAPH 9.5.2

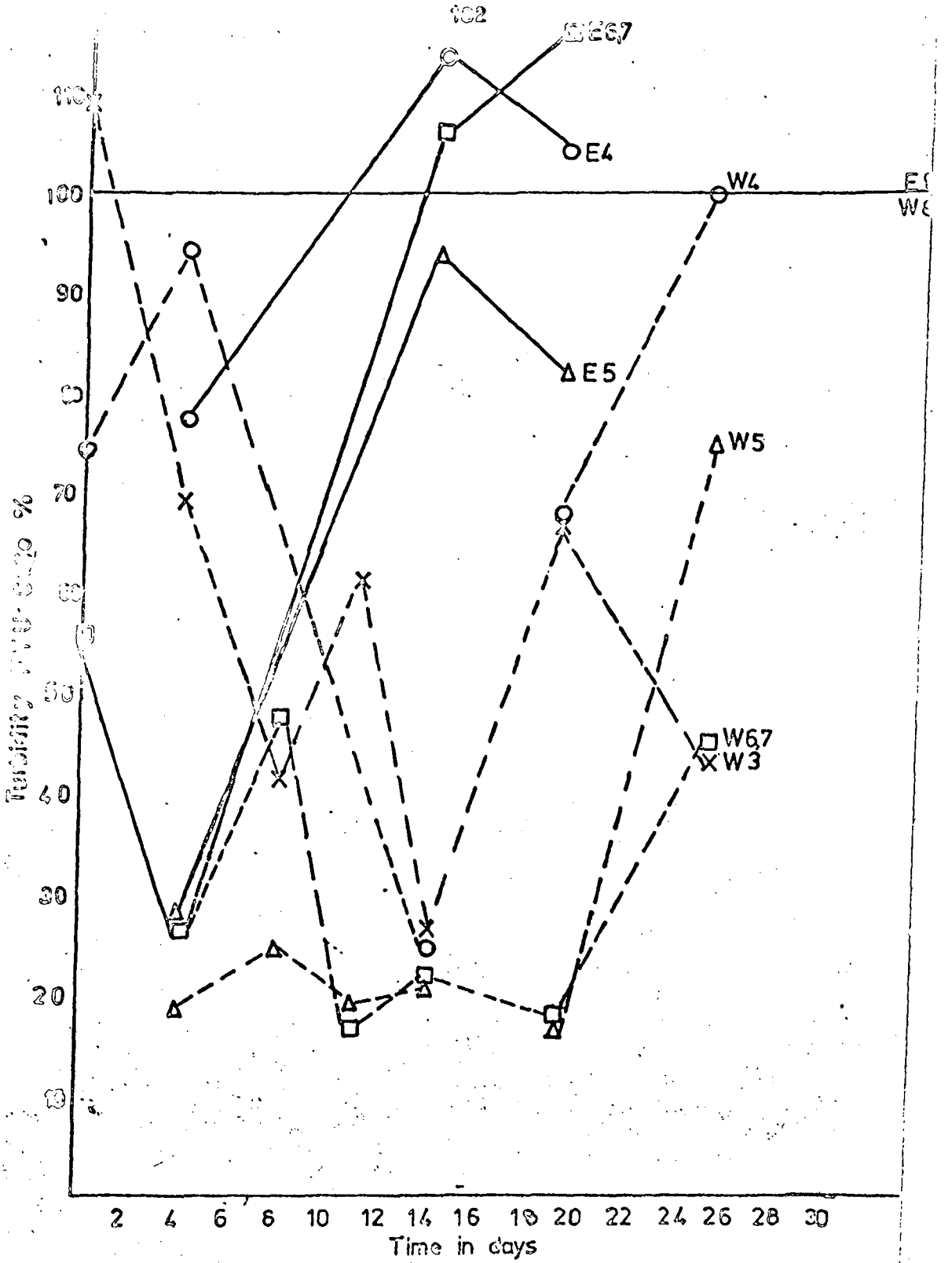
(Run no 2 Tables 9.4.3/4)

Turbidity Removal with Time Curves



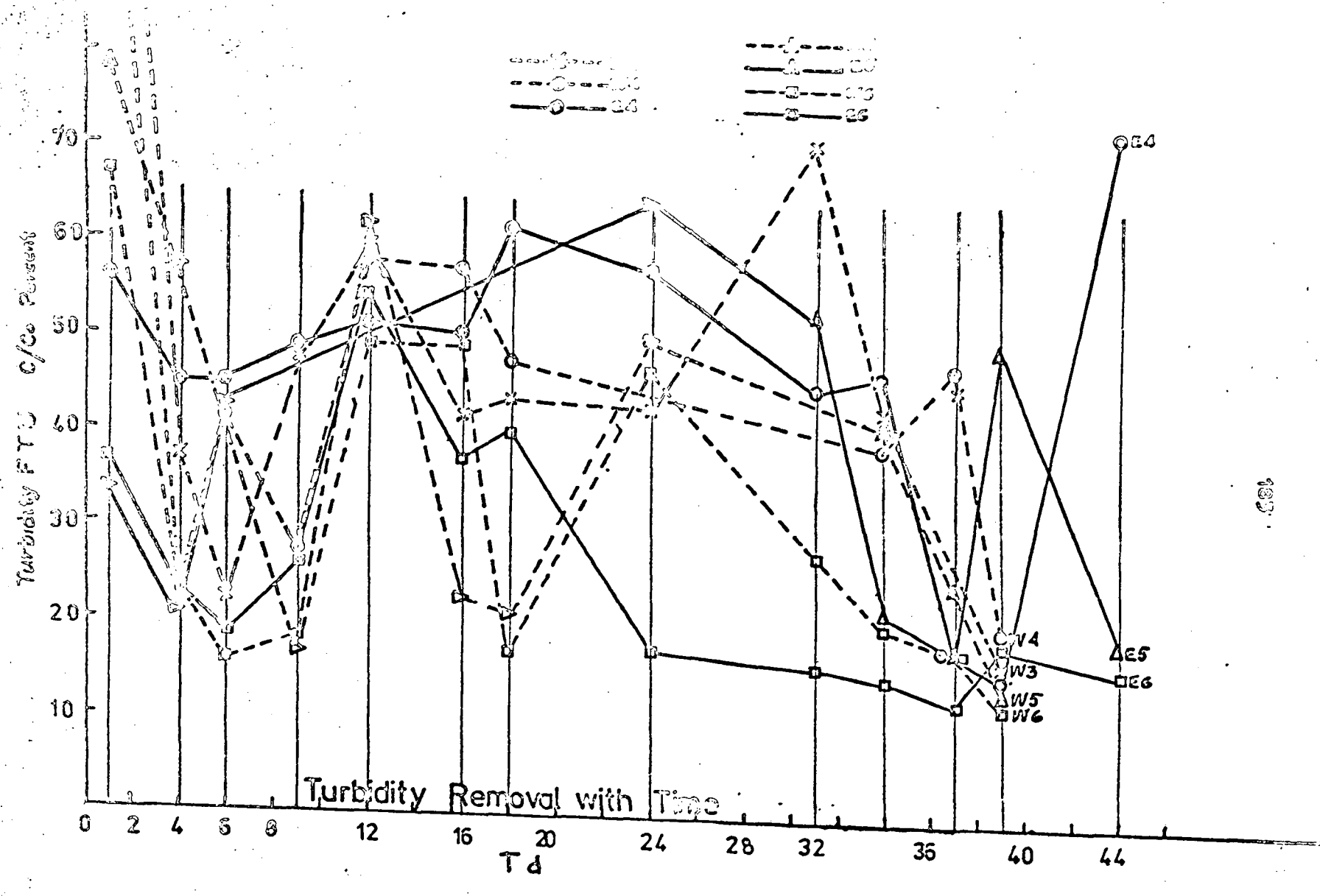
GRAPH 9.5.3

(Run no 3)

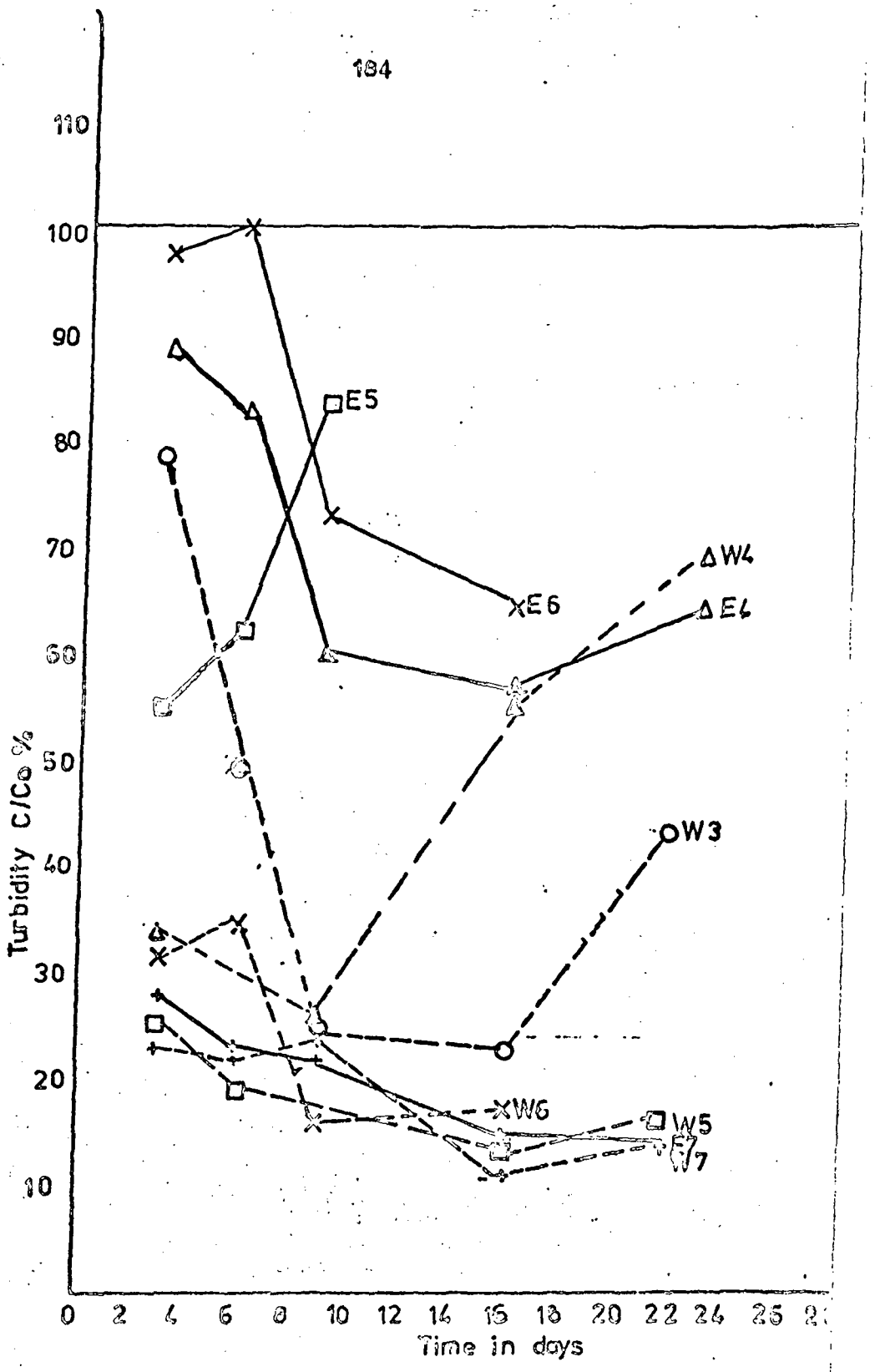


GRAPH 9.5.4

(Table 9.5.9/10 Run 5)



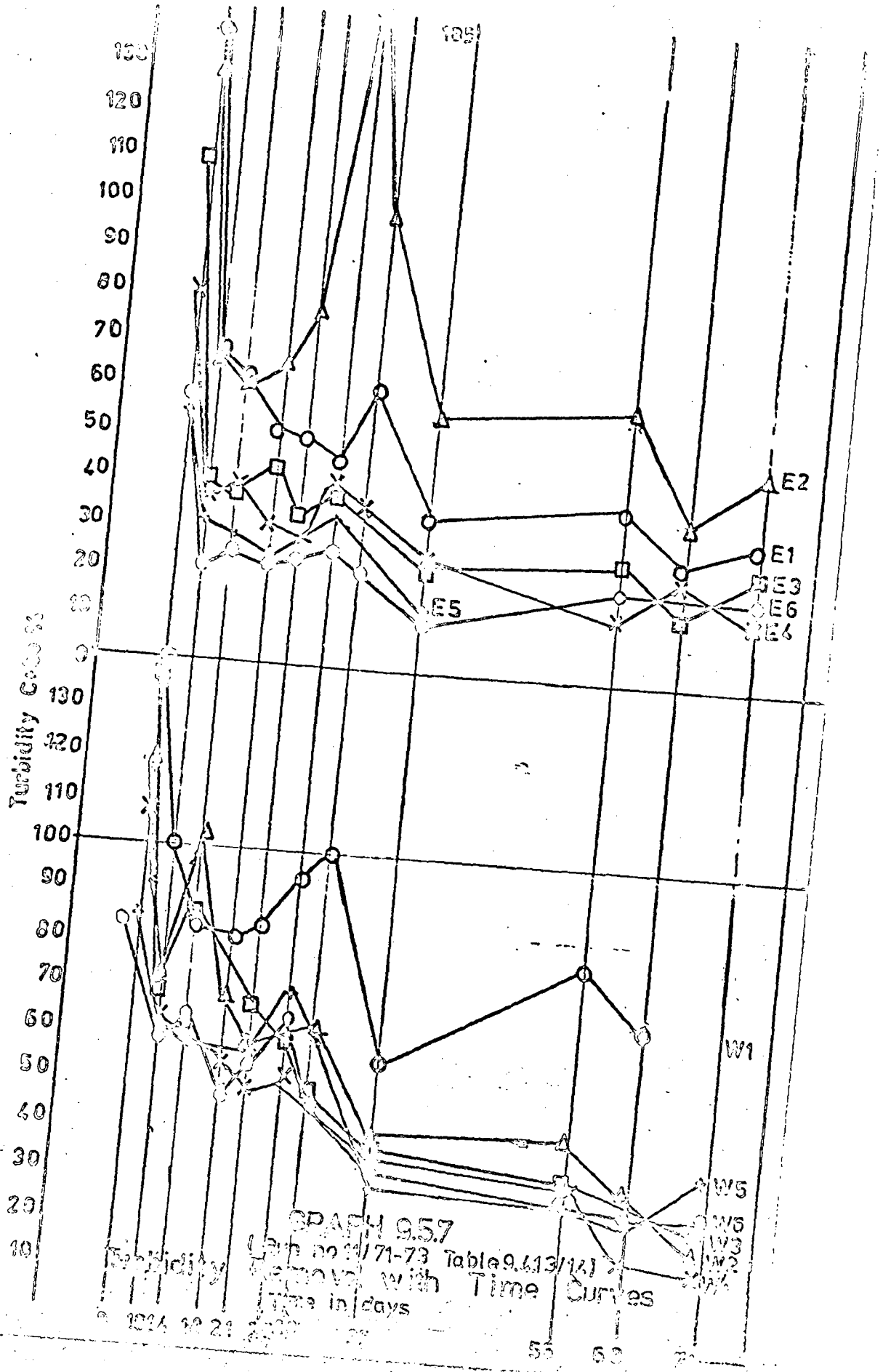
GRAPH 9.5.5 (Table 9.5.7/C Run no 4)



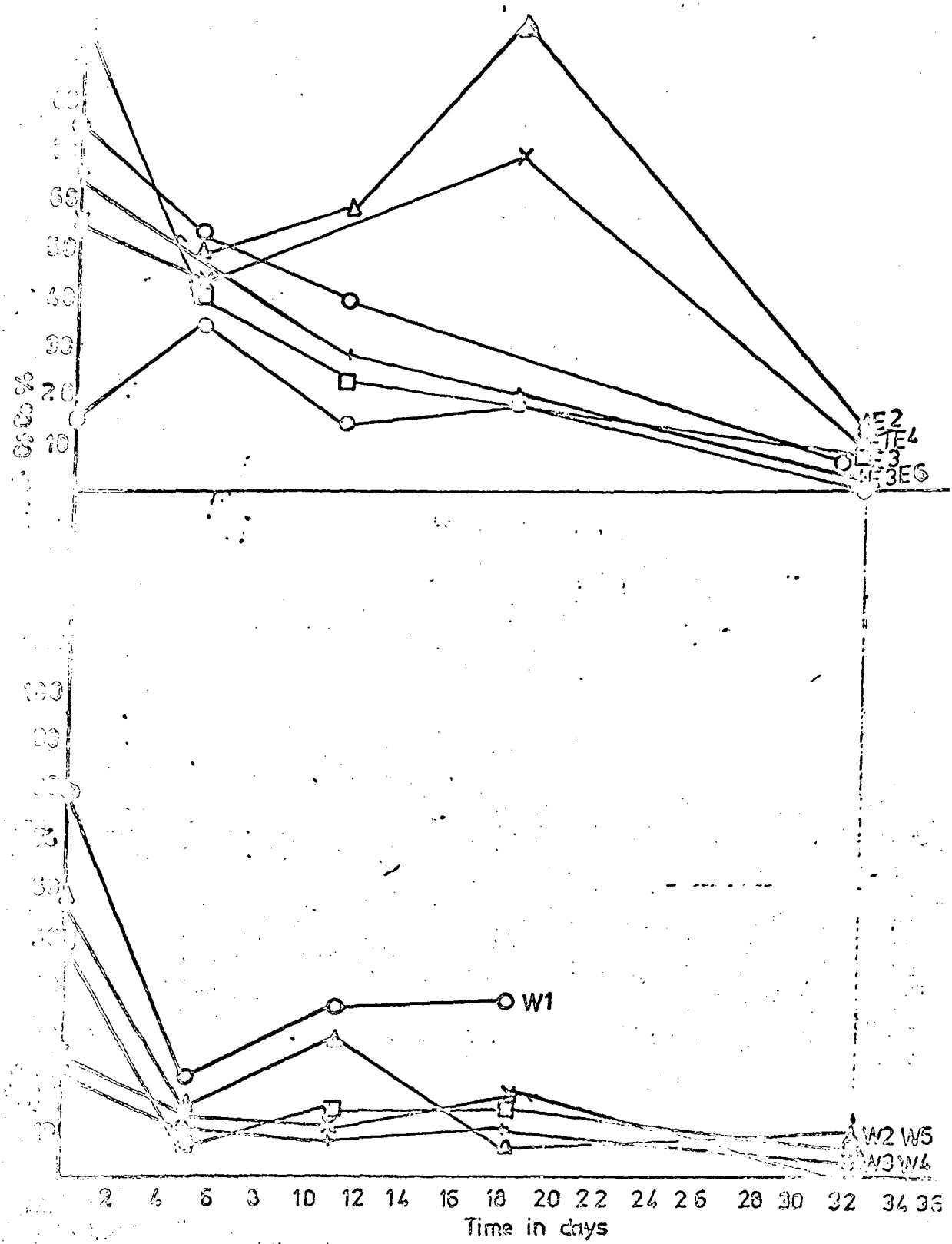
GRAPH 9.5.6

Run no 3 Table 9.4.11 /12

Turbidity Removal with Time Curves

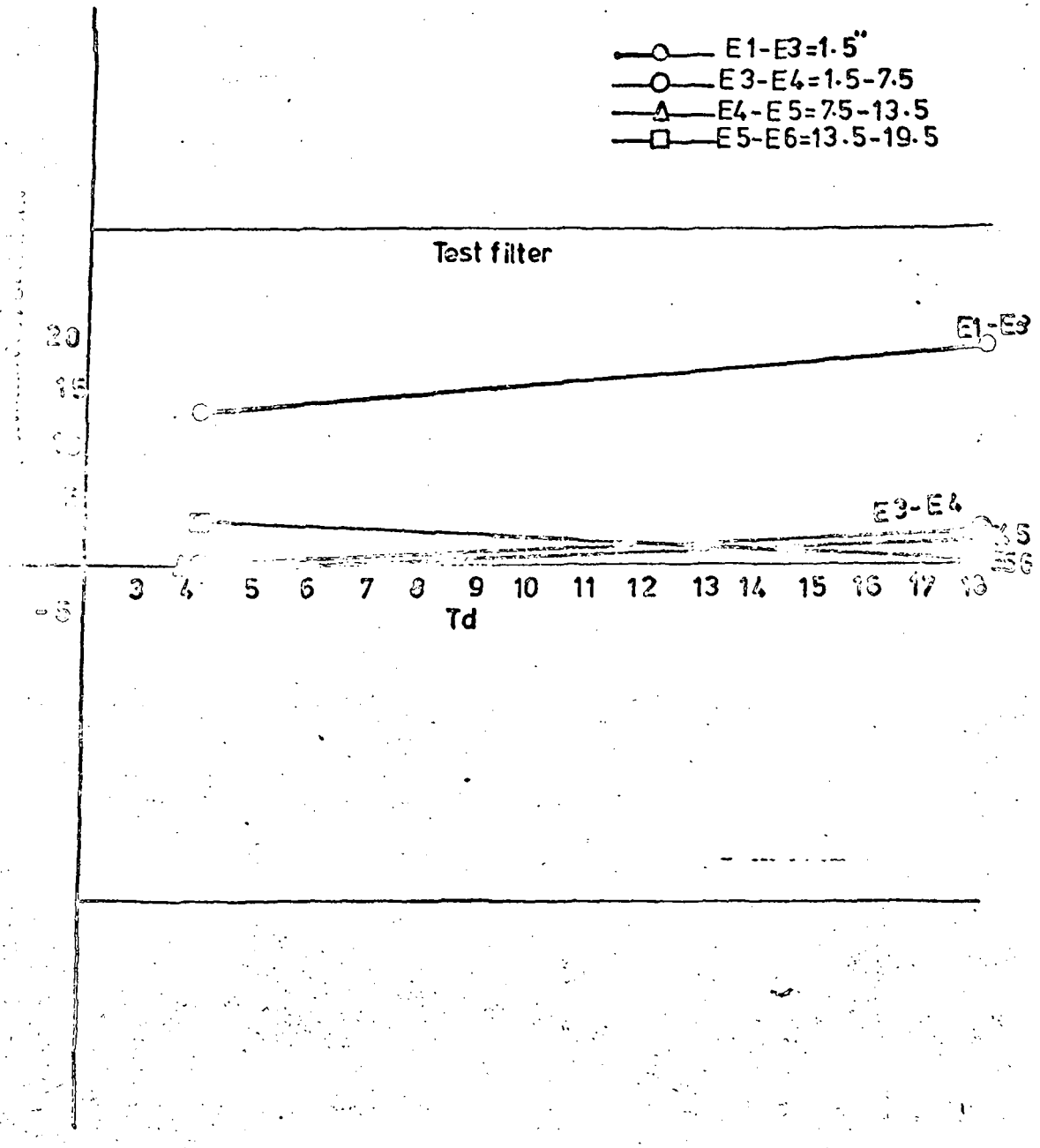


GRAPH 9.5.7
Turbidity Removal with Time Curves



GRAPH 9.5.3

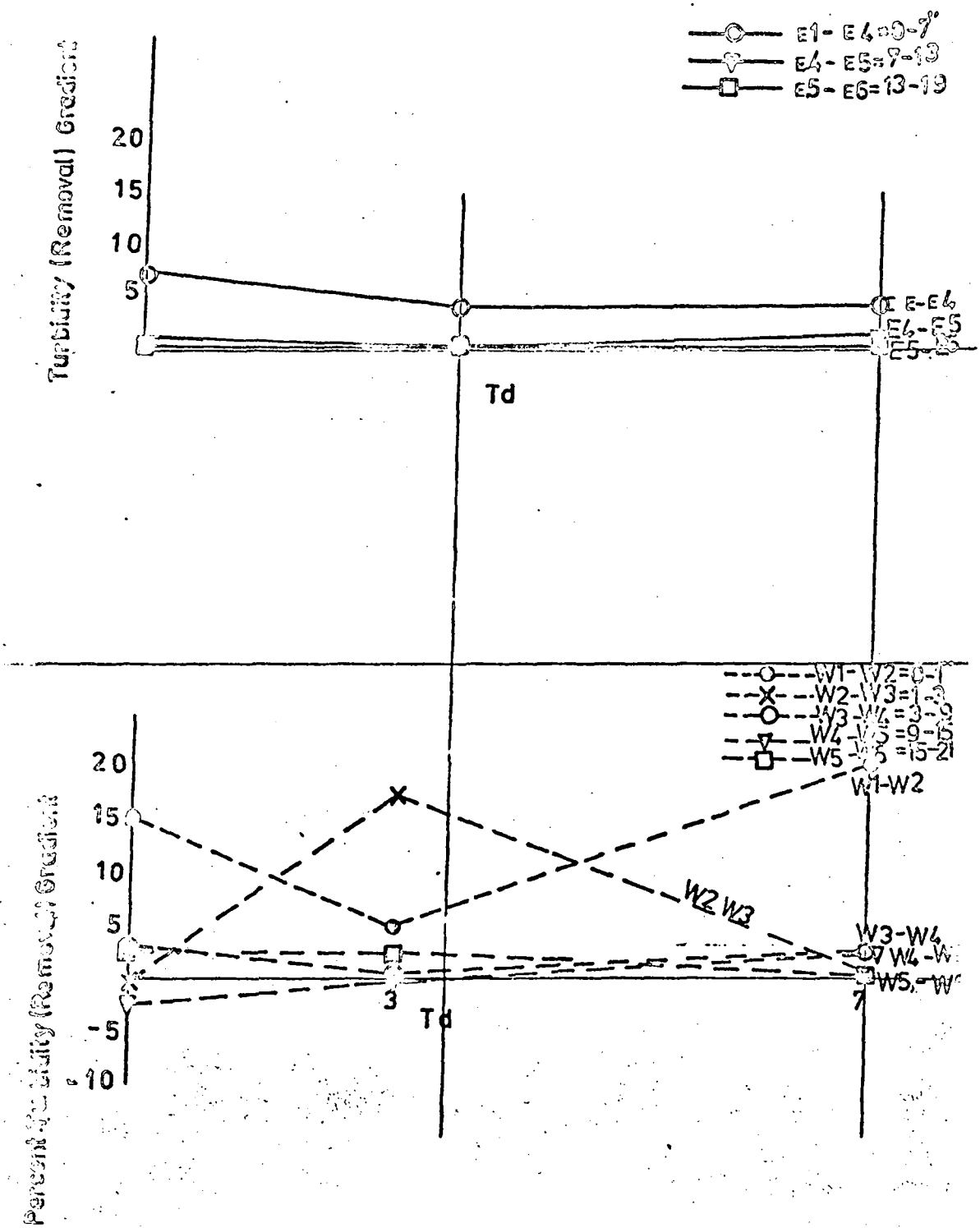
(RNE no 12/71-73 Tables 9.4.15/16)



GRAPH 9.6.1

(Run no 1)

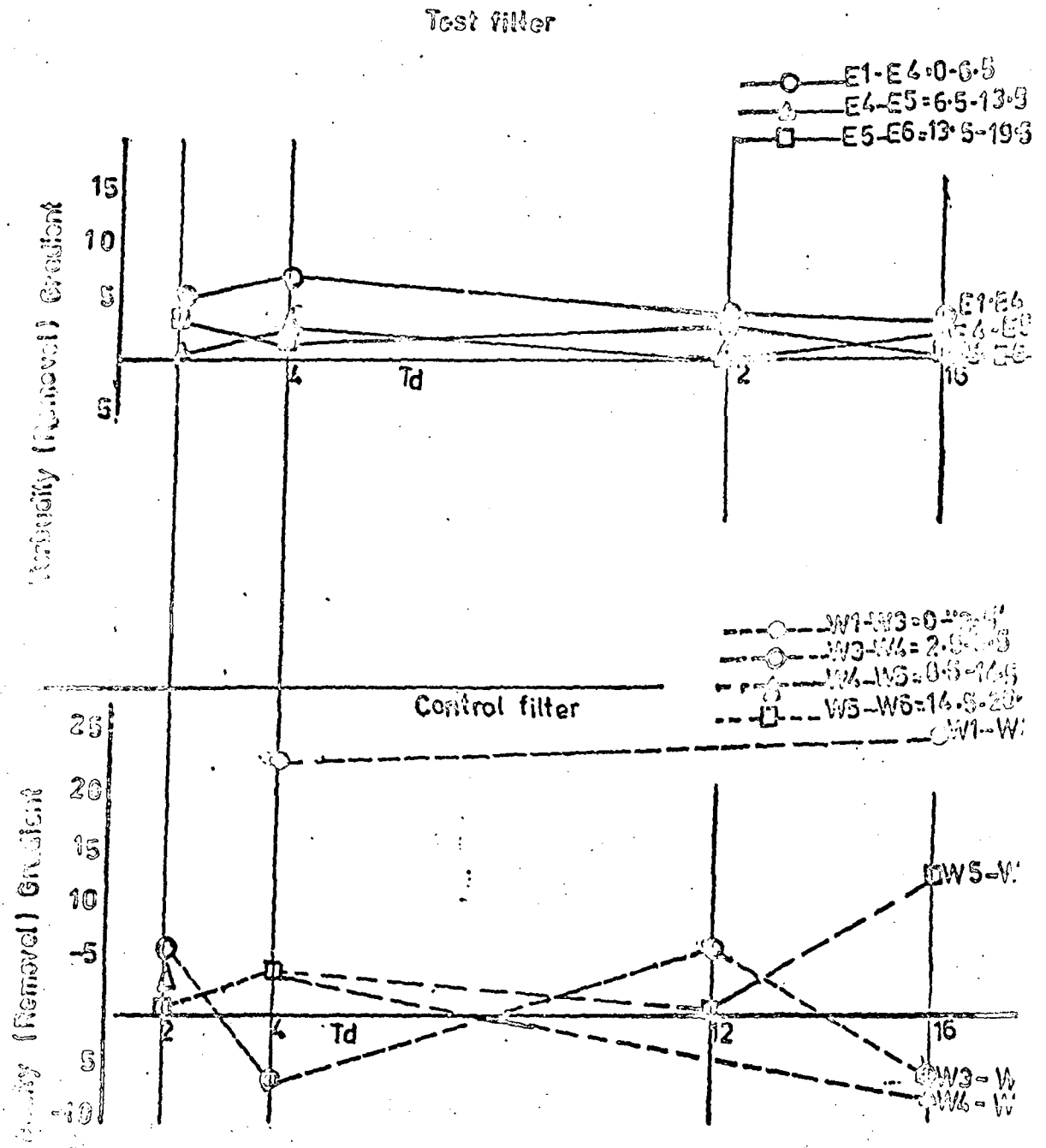
Layer Turbidity (Removal) Gradient Curves



GRAPH 9.6.2

(Runno 2)

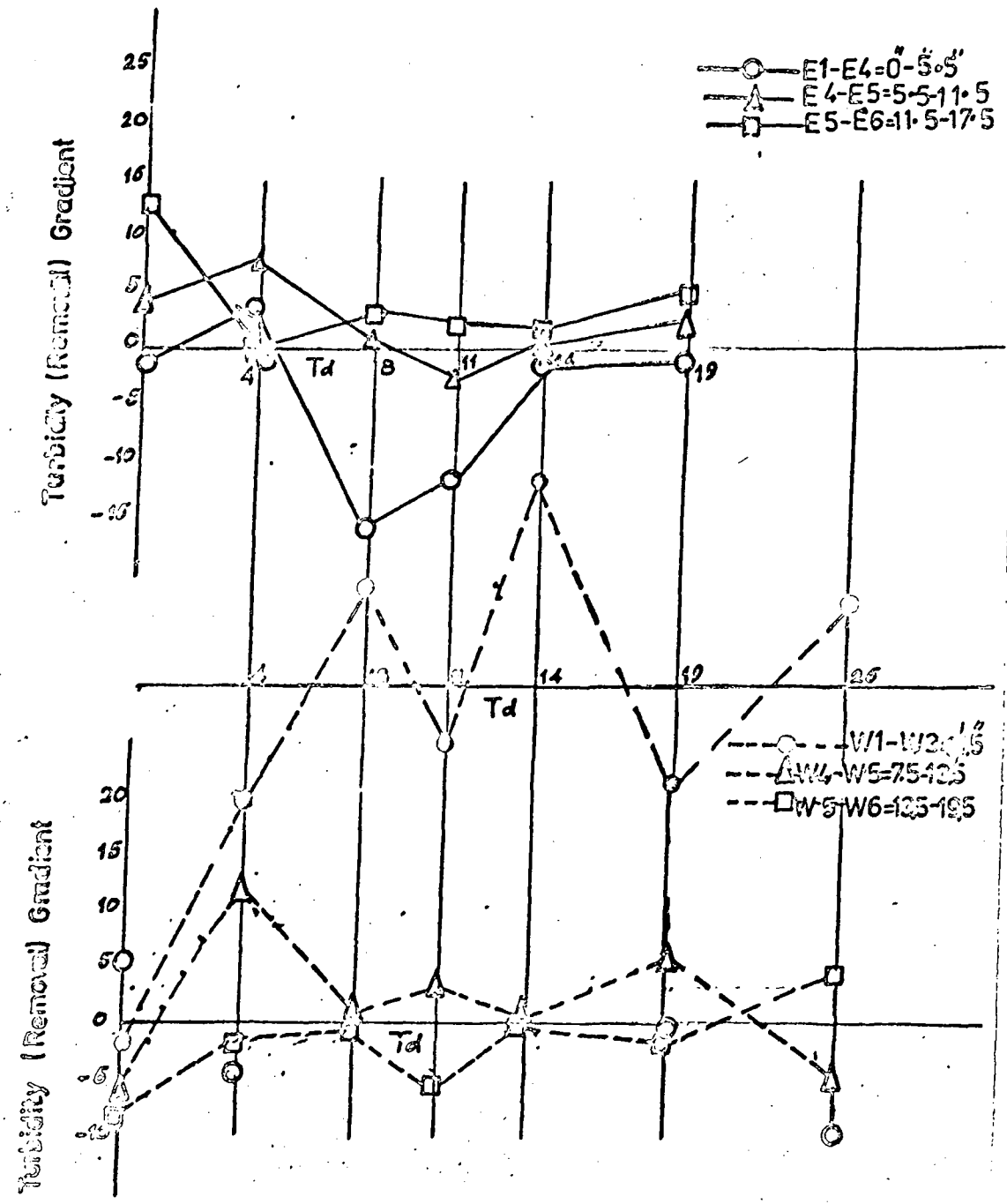
Layer Turbidity (Removal) Gradient Curves



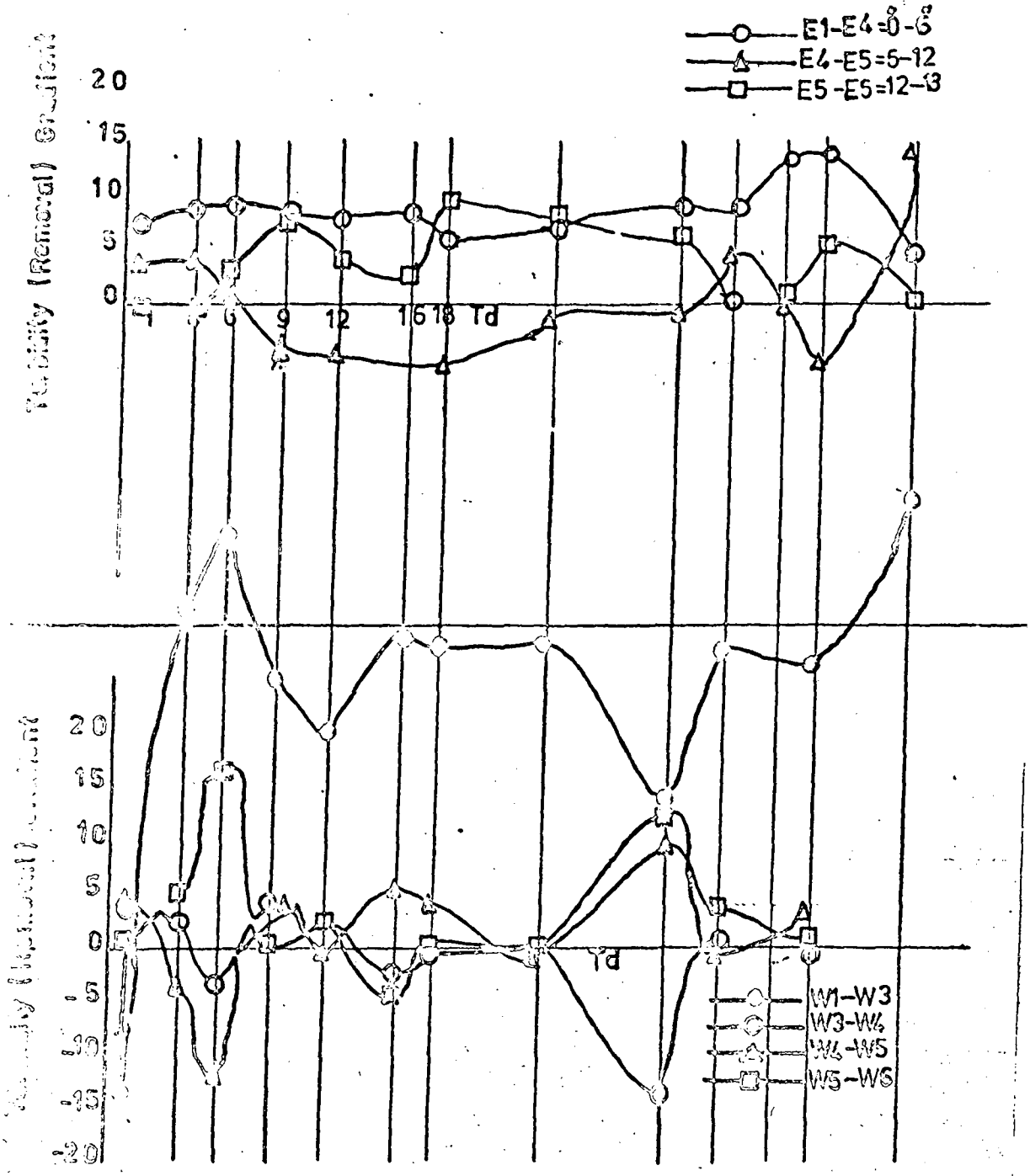
GRAPH 9.6.3

(Run no 3)

Layer Turbidity (Removal) Gradient Curves



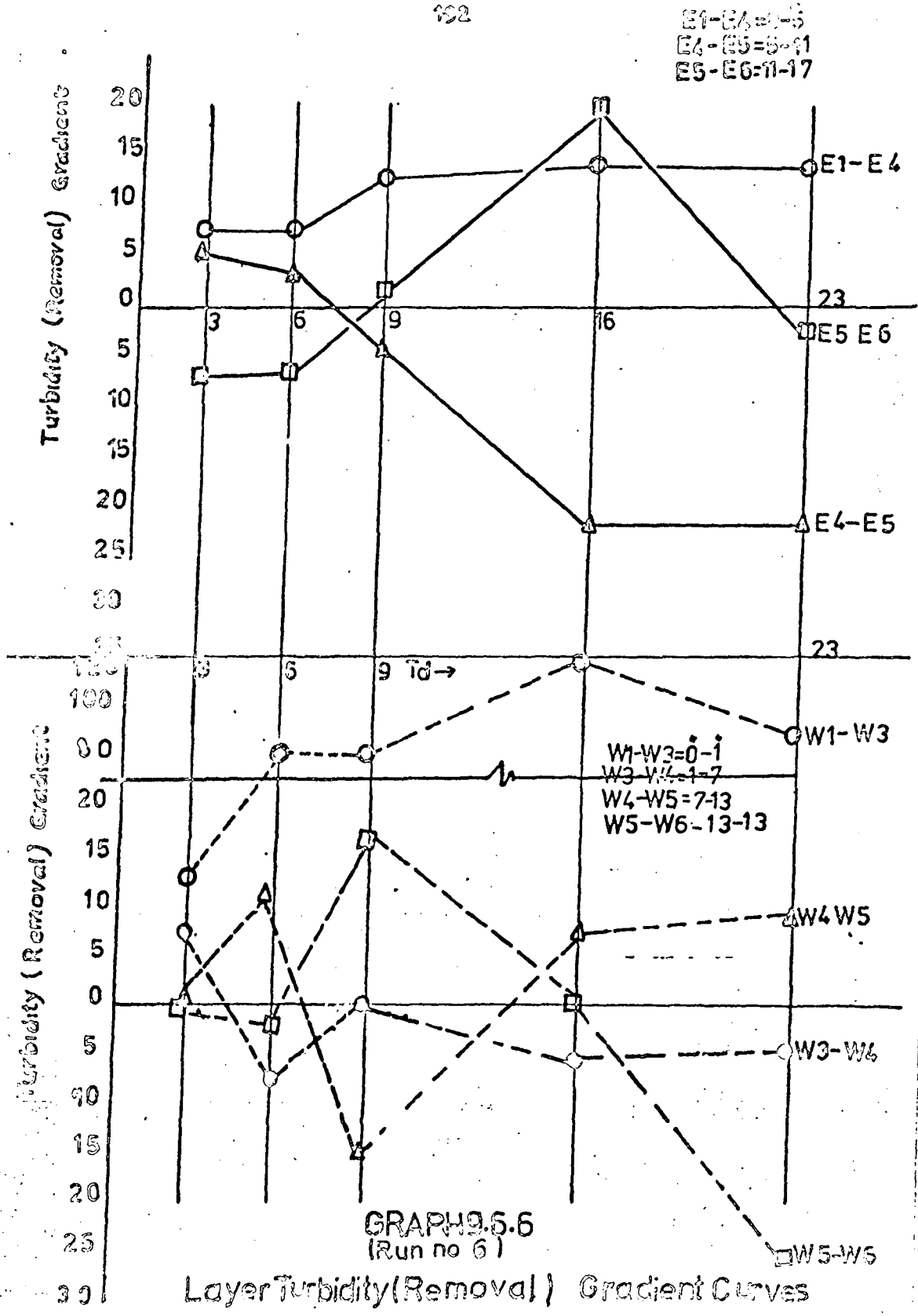
GRAPH 9·5·4
(Run no 5)
Layer Turbidity (Removal) Gradient Curves



GRAPH 96.5

(Run no 4)

Layer Turbidity (Removal) Gradient Curves


E1-E4=-5
E4-E5=5-11
E5-E6=11-17
Turbidity (Removal) Gradient
20
15
10
5
0
5
10
15
20
25
30
3
6
9
16
23
E1-E4
E5 E6
E4-E5
Td→
100
00
W1-W3
W1-W3=0-1
W3-W4=1-7
W4-W5=7-13
W5-W6=13-13
W4 W5
W3-W6
W5-W6
GRAPH 9.6.6
(Run no 6)
Layer Turbidity (Removal) Gradient Curves

Run No. 1 Filtration Rate = 0.2 m/h

Test (east) filter, dosed at 10 mg/l (phenol)

pH of the inlet sample: 8.0

Probe (valve)	hL							
	E0	E1	E2	E3	E4	E5	E6	E7
Di inch	Ref	0	0	1.50	7.50	13.50	19.50	Under dr ins
Time in days 0	-	0	0	3.50	8.90*	11.10*	11.10*	11.60*
4	-	0	0	4.80	7.10	8.20	8.80	8.80
11	-	0	0	7.40	9.20	10.20	10.40	10.40
18	-	0	0	10.0	10.20	10.50	10.60	10.60

TABLE 9.7.2 (Headloss, Depth & Time)

Run No. 1 Filtration Rate = 0.2 m/h

Control (west) filter, without dosing tracing solution

pH (average) of the inlet sample = 8.0

Probe	hL							
Di	W0	W1	W2	W3	W4	W5	W6	W7
inch	Ref	Exposed	1.50	3.50	9.50	15.50	21.50	Under drainage
Time in days 0	-	0	1.10	4.40*	6.40*	6.00*	7.10*	6.60*
4	-	0	1.40	2.70	3.90	4.70	5.50	5.50
11	-	0	2.10	3.30	4.60	5.20	5.90	6.30*
18	-	0	9.40*	5.20*	6.50*	6.10	6.60	8.00*

Note 1: Headloss values with an asterisk to be ignored because of inconsistancy.

Note 2: For abbreviations see appendix.

TABLE 9.3.3 (Headloss, Depth & Time)

Run No. 2 Filtration Rate = 0.2 m/h

Test (east) filter, dosed at 10 mg/l (phenol)

pH (average) of the inlet sample = 7.9

Probe	hL							
	E8	E1	E2	E3	E4	E5	E6	E7
Di inch	Ref	0"	0.5"	1.0"	7"	13"	19"	under drainage
Time in days 0	-	0	1.90	2.30	5.30	6.60	7.00	7.10
3	-	0	8.30	8.50	10.80	11.80	12.30	12.30
7	-	0	38.50	38.50	39.10	39.40	39.60	39.60

TABLE 9.3.4 (Headloss, Depth & Time)

Run No. 2 Filtration Rate = 0.2 m/h

Control (west) filter, without dosing tracing solution

pH (average) of the inlet sample: 7.9

Probe	hL							
	W8	W1	W2	W3	W4	W5	W6	W7
Di inch	Ref	0	1"	3"	9"	15"	21"	under drainage
Time in days 0	-	0	-	-	-	-	-	-
3	-	0	2.90	4.70	6.30*	5.00*	8.30*	8.30*
7	-	0	3.60	5.70	7.30	8.80	9.50	9.50

Note 1: Headloss values with an asterisk have been ignored.

Note 2: For abbreviations see appendix.

TABLE 9.3.5 (Headloss, Depth & Time)

Run No. 3 Filtration Rate = 0.2 m/h

Test (east) filter, dosed at 10 mg/l (phenol)

pH (average) of the inlet sample 7.9

Probe	E8	E1	E2	E3	E4	E5	E6	E7
D1 inch	Ref	0	Partially Exposed	0.5"	6.5"	12.5"	18.5"	under drainage
Time in days 2	-	0	0	0.20	3.00	4.20	5.00*	4.8
4	-	0	0	0.60	3.90	5.10	5.70	5.70
12	-	0	4.80*	9.70	12.30	13.40	14.00	14.00
16	-	0	2.50	38.80	39.40	39.60	38.70	38.70

TABLE 9.3.6 (Headloss, Depth & Time)

Run No. 3 Filtration Rate = 0.2 m/h

Control (west) filter, without dosing phenol solution

pH (average) of the inlet sample: 7.9

Probe	W8	W1	W2	W3	W4	W5	W6	W7
D1 inch	Ref	0	0-0.5"	2.5"	8.5"	14.5"	20.5"	under drainage
Time in days 2	-	0	2.30*	3.70*	4.30*	4.50*	5.20*	6.50*
4	-	0	2.10*	3.70	3.50	4.10	4.90	4.90
12	-	0	2.00	4.60	5.70	6.30	7.10	7.10
16	-	0	2.00	5.10	6.30	6.90	7.80	7.80

Note 1: Headloss values with an asterisk have been ignored.

Note 2: For abbreviations see appendix.

TABLE 9.3.7 (Headloss, Depth & Time)

Run No. 4 Filtration Rate = 0.2 m/h

Test (east) filter, without dosing phenol solution

pH (average) of the inlet sample: 7.9

Probe		E8	E1	E2	E3	E4	E5	E6	E7
Di ins		Ref	0	0	0-0.5" Partially Exposed	6"	12"	18"	u.d.
Time in days					hL				
1	-		0	0	0.10	1.40	2.80	3.10	3.20
4	-		0	0	0	1.90	2.90	3.30	3.30
6	-		0.10	0	0.10	2.50	3.70	4.20	4.20
9	-		0.20	0	0.20	2.70	3.90	4.40	4.40
12	-		0.10	0	0.10	3.10	4.50	4.90	4.90
16	-		0	0	0.30	3.70	5.00	5.40	5.50
18	-		0.10	0.20	0.40	4.20	5.50	6.00	6.00
24	-		0	0	1.00	6.50	7.80	8.30	8.30
31	-		0	0	2.10	9.80	11.10	11.60	11.60
34	-		0	0	1.60	11.30	12.40	12.90	12.90
37	-		0	0	0.90	11.90	13.10	13.60	13.60
39	-		0	0	0.10	12.50	13.50	13.90	13.90
44	-		0	0	0	17.20	18.10	18.50	18.50

Note 1: Headloss values with an asterisk have been ignored.

Note 2: For abbreviations see appendix.

TABLE 6.3.8 (Headloss, Depth & Time)

Run No. 4 Filtration Rate = 0.2 m/h

Control (west) filter, without dosing phenol solution

pH (average) of the inlet sample 7.9

Probe	W8	W1	W2	W3	W4	W5	W6	W7
Di ins	Ref	0	Partially exposed	2"	8"	14"	20"	u.d.
Time in days				hL				
1	-	0	1.50	4.30*	6.10*	7.30*	9.60*	9.60
4	-	0	1.50	3.10*	2.80*	1.00	2.60*	3.80
6	-	0	1.50	2.30	1.80	1.10	1.60	2.40
9	-	0	1.50	5.80*	6.60*	7.60*	7.50*	7.10
12	-	0	1.60	5.00	5.40	6.20	6.90	6.90
16	-	0	1.60	6.20	6.80	7.20	8.30	8.30
18	-	0	1.50	7.50	8.00	8.10	9.40	9.50
24	-	0	2.00	19.30	19.00	19.00	20.40	20.40
31	-	0	0.30	40.70	40.70	40.90	41.00	41.50
34	-	0	0	41.70	41.50	41.60	41.90	41.90
37	-	0	0	41.30	41.20	41.30	41.60	41.60
39	-	0	0	40.90	41.20	41.40	41.70	41.70
44	-	-	-	-	-	-	-	-

Note 1: Headloss values with an asterisk have been ignored.

Note 2: For abbreviations see appendix.

TABLE 9.3.9 (Headloss, Depth & Time)

Run No. 5 Filtration Rate = 0.2 m/h

Test (east) filter, dosed at 10 mg/l (phenol)

pH (average) of the inlet sample: 7.9

Probe	E8	E1	E2	E3	E4	E5	E6	E7
Depth	Ref	Expo-sed	Expo-sed	0-0.5"	5.5"	11.5"	17.5"	u.d.
Time in days 0	0	0	0	0	2.00	3.80*	4.60*	4.30*
4	0	0	0	0	2.20	3.10	3.50	3.50
8	0	0	0	0	4.70*	5.90	6.40	6.40
11	0	0	0	0	4.50	6.20	6.30	6.30
14	-0.10	-0.10	0	0	13.80	13.70	14.10	14.20
19	0	0	0	0	38.50	38.90	39.30	39.70
25	-	-	-	-	-	-	-	-
pH of the inlet sample	8.0	7.9	7.9	7.9	7.9	8.0	7.9	7.9

TABLE 9.3.10 (Headloss, Depth & Time)

Run No. 5 Filtration Rate = 0.2 m/h

Control (West) filter, without dosing tracing solution

pH (average) of the inlet sample : 7.9

Probe	W8	W1	W2	W3	W4	W5	W6	W7
Depth	Ref	0	0	1.5"	7.5"	13.5"	19.5"	u.d.
Time in days 0	-	0.30*	-0.10*	2.30*	3.80*	4.70*	5.50*	5.60*
4	-	0	0	1.10	2.10	2.60	3.30	3.30
8	-	0	0	1.70	2.90	3.60	4.40	4.40
11	-	0	0	2.00	3.30	3.90	4.60	4.60
14	-	0	0	2.60	3.80	4.30	5.10	5.10
19	-	0	0	5.30	6.50	7.00	7.70	7.70
25	-	-	-	-	-	-	-	-

Note 1: Headloss values with an asterisk have been ignored.

Note 2: For abbreviations see appendix.

TABLE 9.3.11 (Phenol vs. Depth & Time)

Run No. 6 Filtration Rate = 0.[illegible] m/h

Test (east) filter: No phenol dosed

pH (average) of the inlet sample: 7.9

Probe	W8	W1	W2	W3	W4	W5	W6	W7
Di ins	Ref	0	0	0-0.5 Partially Exposed	5"	11"	17"	u.d.
Time in days 3	-	0	0	0	1.20	2.40	2.80	2.80
6	-	0	0	0.20	1.90	3.20	3.70	3.70
9	-	0	0	0.20	2.90	4.30	4.70	4.70
16	-	0	0	0.20	5.70	7.00	7.40	7.40
23	-	0	0	0	14.20	15.40	15.90	15.90

TABLE 9.3.12 (No dia. vs. Depth & Time)

Run No. 6 Filtration Rate = 0.2 m/h

Control (west) filter, without dosing phenol solutions

pH (average) of the inlet sample: 7.9

Probe	W8	W1	W2	W3	W4	W5	W6	W7
Di ins	Ref	0	0	1"	7"	13"	19"	u.d.
Time in days 3	-	0	0	1.50	2.30	3.30	3.60	3.60
6	-	0	0	1.90	3.30	4.10	4.70	4.70
9	-	0	0	2.50	3.90	4.50	5.30	5.30
16	-	0	0	5.10	6.60*	6.40	7.90	7.90
23	-	0	0	8.30	9.70	9.70	11.00	11.00

Note 1: Headloss values with an asterisk have been ignored.

Note 2: For abbreviations see appendix.

Table 9.3.14 (Headloss)

Run No. 2/71-73

Headloss in inch, west filter						
Valve	W1	W2	W3	W4	W5	W6
Di / Td	0.5"	3.5"	9.5"	15.5"	21.5"	27.5"
1	0.30	2.10	3.00	4.40	4.50	4.50
3	-	-	-	-	-	-
6	0.90	3.50	4.20	5.10	5.30	5.50
13	2.10	4.90	5.70	6.70	6.90	7.20
17	5.40	8.40	9.40	10.60	10.70	11.50
20	7.40	10.60	11.70	13.00	13.30	13.70

Table 9.3.15 (Headloss)

Run no. 14/71-73

Mode of filtration: Regulae

Both filters covered

Headloss in inch, east filter						
Valve	E1	E2	E3	E4	E5	E6
Di / Td	0.5"	0.5"	6.5"	12.5"	18.5"	24.5"
0	-	-	-	-	-	-
4	2.10	2.10	4.90	6.50	7.30	8.50
11	3.00	3.00	7.30	9.00	10.30	11.20
18	4.90	4.90	9.90	11.00	13.10	14.00
26	6.80	7.20	12.40	14.20	15.40	16.20

Exp. No. 9.3.16 (Honduras)

Exp no. 14/71-73

Headloss in inch, west filter					
Valve	W2	W3	W4	W5	W6
Di / Td	2.5"	8.5"	14.5"	20.5"	26.5"
0	1.3	1.4	1.90	3.50	4.00
4	1.4	3.0	4.40	4.70	5.80
11	3.70	4.90	5.70	6.50	7.30
18	4.50	5.90	6.60	7.30	8.10
26	5.20	6.20	7.40	8.10	8.90

Note 1: For abbreviations.
Note 2: Numbers values with (**) are extrapolated

TABLE 9.3.17 (Contd. Experiment)

Run Time Days	Run No. 1 Tf	Cf	Run No. 2 Tf	Cf	Run No. 3 Tf	Cf	Run No. 4 Tf	Cf	Run No. 5 Tf	Cf	Run No. 6 Tf	Cf
0	7.50**	5.00**	7.00	4.50**	4.80	4.00**			3.00**	-		
1							3.10	-				
2												
3			12.30	5.50**								
4	8.80	5.50			5.70	4.90	3.30	-	3.50	3.30	2.80	3.60
6							4.20	1.60				
7			39.60	9.50							3.70	4.70
8												
9									6.40	4.40		
11	10.40	5.90					4.40	5.50**			4.70	5.30
12									6.80	4.60		
14					14.00	7.10	4.90	6.90				
16									14.10	5.10		
18	40.60	6.60			38.70	7.80	5.40	8.30			7.40	7.90
19							6.00	9.40				
23									9.30	7.70		
24											15.90	11.00
31							8.30	20.40				
34							11.60	41.00				
37							12.90	41.90				
39							13.60	41.30				
44							15.90	41.70				
							18.50	-				
							No Phenol				No Phenol	

TABLE 9.4.1 (Turbidity F.T.U.)

Run No. 1

Test (east) filter, dosed at 10 mg/l (phenol) pH (average) of the inlet sample: 8.0

Time in days	Probe Di m/h	E8 0	E1 0	E2 0	E3 1.5	E4 7.5	E5 13.5	E6 19.5	E7 under drainage	C ÷ Co Percent E8 0	E1,E2 0	E3 1.5	E4 7.5	E5 13.5	E6 19.5
4	0.22	0.98	0.98	1.80	0.78	1.60*	0.80	0.58	0.58	100	100	79.60	-	81.60	59.20
18	0.02	1.10	0.83	1.10	0.78	0.68	0.63	0.62	0.34	100	100	70.90	61.80	57.30	56.40

TABLE 9.4.2 (Turbidity F.T.U.)

Run No. 1

Control (west) filter, without dosing tracing solution pH (average) of the inlet sample: 8.0

Time in days	Probe Di m/h	W8 0	W1 0	W2 1.5	W3 3.5	W4 9.5	W5 15.5	W6 21.5	W7 under drainage	C ÷ Co Percent W8 0	W1 0	W2 1.5	W3 3.5	W6,W7 under drainage
4	0.21	-	-	-	-	-	-	-	-	-	-	-	-	-
18	0.2	0.91	53.0	0.92	0.73	-	-	-	0.44	100	-	98.90	78.50	47.30

Di = Distance from inlet surface; inch. m/h = filtration rate

Note: Turbidity with asterisk indicate inconsistant reading (ignored).

TABLE 9.4.3 (Turbidity F.T.U.)

Run No. 2 Filtration rate = 0.2 m/h

Test (east) filter, dosed at 10 mg/l (phenol)

Time in days	Turbidity F.T.U.									C ÷ Co Percent						
	Probe Di m/h	E8 0	E1 0	E2 0.5	E3 1.0	E4 7	E5 13	E6 19	E7 under drainage	E8 0	E1 0	E2 0.5	E3 1	E4 7	E5 13	E6 19
0	0.21	1.40	5.50	1.60	3.50	0.67	0.58	0.55	1.10*	100	393	114	250	47.90	41.10	39.30
3	0.19	1.00	1.10	0.60	0.68	0.36	0.34	0.32	2.30*	100	110	60.00	68.00	36.00	34.00	32.00
7	0.08	0.95	1.10	0.96	0.92	0.66	0.58	0.56	0.52	100	116	101	96.80	69.50	61.00	59.00

TABLE 9.4.4 (Turbidity F.T.U.)

Run No. 2 Filtration rate = 0.2 m/h

Control (west) filter, without dosing phenol solution

Time in days	Turbidity F.T.U.									C ÷ Co Percent						
	Probe Di m/h	W8 0	W1 0	W2 1	W3 3.0	W4 9	W5 15	W6 21	W7 under drainage	W8 0	W1 0	W2 1	W3 3	W4 9	W5 15	W6 21
0	0.30	1.30	7.60	1.10	1.10	0.83	1.00	0.80	1.50*	100	585	84.60	84.60	63.80	76.90	61.50
3	0.23	1.00	2.40	0.95	0.60	0.56	0.56	0.42	0.42	100	240	95.00	60.00	56.00	56.00	42.00
7	0.46	0.88	1.80	0.70	0.68	0.53	0.38	0.38	0.38	100	205	79.50	77.30	60.20	43.20	43.20

Di = Distance from inlet surface: inch. m/h = filtration rate

Note: Turbidity with asterisk indicate inconsistant reading (ignored).

TABLE 9.4.5 (Turbidity F.T.U.)

Run No. 3

Filtration Rate = 0.2 m/h

Test (east) filter, dosed at 10 mg/l (phenol)

Time in days	Turbidity F.T.U.									C + Co Percent					
	Probe Di m/h	E8 0	E1 0	E2 0	E3 0.5	E4 6.5	E5 12.5	E6 18.5	E7 u.d.	E8 0	E1,E2 0	E3 0.5	E4 6.5	E5 12.5	E6 16.5
2	0.24	0.70	0.80	0.85	0.72	0.46	0.43	0.28	0.64	100	118	103	65.70	61.40	40.60
4	0.23	0.95	0.72	0.74	1.10	0.48	0.33	0.25	0.32	100	76.80	116	50.50	34.70	26.30
12	0.18	0.70	0.66	1.10	0.87	0.52	0.52	0.40	0.53	100	126	124	74.30	74.30	57.30
16	0.01	0.57	0.55	0.50	0.95	0.45	0.39	0.40	0.45	100	92.10	167	78.90	68.40	70.20

TABLE 9.4.6 (Turbidity F.T.U.)

Run No. 3

Filtration Rate = 0.2 m/h

Control (west) filter, without dosing phenol solution

Time in days	Turbidity F.T.U.									C + Co Percent					
	Probe Di m/h	W8 0	W1 0	W2 0-0.5	W3 2.5	W4 8.5	W5 14.5	W6 20.5	W7 u.d.	W8 0	W1,W2 0	W3 2.5	W4 8.5	W5 14.5	W6 20.5
2	0.26	0.80	1.30	0.76	3.50*	3.20*	0.45	0.41	0.62	100	129	438*	400*	56.30	51.30
4	0.20	0.93	1.10	1.00	0.38	0.74*	0.53	0.31	0.48	100	113	40.90	79.60*	57.00	33.30
12	0.20	0.73	1.20	0.98	1.60*	0.47	-	0.43	1.10*	100	149	219*	64.40	-	58.90
16	0.20	0.55	0.67	0.63	0.20	0.39	0.65	0.30	0.15	100	118	36.40	70.90*	118	27.30

Note: Turbidity with asterisk indicate inconsistant reading (ignored).

TABLE 2.4.7 (Turbidity F.T.U.)

Run No. 4.

Filtration Rate = 0.2 m/h

Test (east) filter, without dosing phenol solution

Time in days	Turbidity F.T.U.										C + Co Percent				
	Probe	E8	E1	E2	E3	E4	E5	E6	E7		E8	E1,2,3	E4	E5	E6
	Di m/h	0	0	0	0-0.5"	6"	12"	18"	u.d.	SW 0	0	0	6	12	18
1	0.18	0.73	0.56	0.56	0.65	0.41	0.25	0.90*	0.27		100	80.80	56.20	34.20	37.00
4	0.16*	0.60	0.58	0.51	0.53	0.27	0.13	0.14	0.12	0.15	100	90.00	45.00	21.70	23.30
6	0.20	0.62	0.70	0.67	0.62	0.28	0.27	0.12	0.15	0.11	100	107	45.20	43.50	19.35
9	0.20	0.57	0.72	0.67	0.60	0.28	0.42*	0.15	0.15	0.13	100	116	49.10	73.70*	26.30
12	0.20	0.60	0.60	0.68	0.60	0.31	0.48*	0.33	0.29	0.11	100	104	51.70	80.00*	55.00
16	0.20	0.67	0.65	0.68	0.62	0.34	1.80*	0.25	0.26	0.11	100	97.00	50.70	269*	37.50
18	0.20	0.62	0.72	0.63	0.60	0.40	0.60*	0.25	0.1[illegible]	0.10	100	108	64.50	96.80*	40.50
24	0.20	0.57	0.86	0.70	0.75	0.33	0.37	0.10	0.11	0.12	100	135	57.90	64.90	17.50
31	0.20	0.55	0.67	0.67	0.50	0.25	0.29	0.09	0.10	0.10	100	112	45.50	52.70	16.40
34	0.20	0.53	0.60	0.55	0.55	0.25	0.11	0.08	0.09	0.09	100	107	47.20	20.80	15.10
37	0.20	0.62	0.60	0.62	0.63	0.12	0.12	0.08	0.09	0.06	100	99.50	19.30	19.30	12.90
39	0.20	0.73	0.64	0.67	1.00	0.12	0.37	-	0.14	0.07	100	105	16.40	50.70	19.20
44	0.20	0.60	0.75	0.72	0.73	0.44	0.12	0.10	0.10	0.07	100	122	73.30	20.00	16.70

Note: Turbidity with asterisk indicate inconsistent reading (ignored).

TABLE 9.4.8 (Tw[illegible] [illegible] F.T.U.)

Run No. 4

Control (west) filter, without dosing alum solution

Filtration Rate = 0.2 m/h

Time in days	Turbidity F.T.U.									C + Co Percent					
	Probe	W0	W1	W2	W3	W4	W5	W6	W7	W8	W1,2	W3	W4	W5	W[illegible]
	Di m/h	0	0	3	2	3	14	20	[illegible]	1	0	2	5	14	[illegible]
1	0.26	0.55	1.60	1.30	0.70	0.53	0.43	-	0.37	100	263	127	105	78.20	[illegible]
4	0.13	0.67	0.67	0.67	0.25	0.16	0.36	0.37	0.16	100	100	37.30	23.90	53.70	[illegible]
6	0.03	0.67	0.67	0.65	0.15	0.28	0.77*	0.49	0.11	100	90.50	22.40	41.30	115*	[illegible]
9	0.21	0.58	0.80	0.75	0.29	0.13	0.10	0.10	0.11	100	139	50.00	25.90	17.20	[illegible]
12	0.20	0.58	0.80	0.72	0.35	0.34	0.36	0.29	0.26	100	131	60.30	58.60	62.10	[illegible]
16	0.20	0.64	0.74	0.72	0.27	0.37	0.15	0.32	0.27	100	114	42.20	57.80	23.40	[illegible]
18	0.20	0.75	0.72	0.80	0.33	0.36	0.16	0.36	0.13	100	103	44.00	48.00	21.30	[illegible]
24	0.20	0.53	0.76	0.86	0.23	-	0.27	1.10*	0.25	100	155	43.40	-	51.00	[illegible]
31	0.06	0.53	0.88	0.80	0.38	0.84*	0.54	1.50*	1.15	100	158	71.70	158*	102*	[illegible]
34	0.03	0.63	2.30*	1.90*	0.28	0.25	0.27	0.77*	0.13	100	333	84.40	89.70	87.90	[illegible]
37	0.04	0.58	0.85	0.78	0.27	0.28	0.15	0.36*	0.11	100	142	46.60	48.30	25.90	[illegible]
39	0.04	0.63	0.72	0.70	0.10	0.13	0.10	0.40*	0.08	100	113	15.90	20.60	15.90	[illegible]
44	-	-	-	-	-	-	-	-	-						

Note: Turbidity with asterisk indicate inconsistent readi[illegible] (ignored).

TABLE 9.4.9 (continued) F.T.U.)

Run No. 5

Fast (east) filter, dosed at 10 mg/l phenol

Filtration Rate = 0.2 m/h

Time in days	Turbidity F.T.U.										C ÷ Co Percent				
	Probe	E8	E1	E2	E3	E4	E5	E6	E7	E10	E8	E1,2,3	E4	E5	E6
	DR E9	0	0	0	0-0.5	5.5	11.5	20.5	n.a.		0	0	5.5	11.5	17.5
0	0.20	0.71	0.78	0.78	1.50*	0.76	0.95	0.80	0.43	0.18	100	110	107*	134*	59.8
4	0.20	0.45	0. 47	0.48	0.61*	0.35	0.13	0.12	0.10	0.08	100	105	77.80	28.90	26.70
8	0.20	0.53	1.10	1.10	0.78	0.98*	0.95	0.83	0.83	0.08	100	208	185*	179*	157
11	0.20	0.52	1.40	1.50	1.50	0.86*	0.93	0.85*	0.85*	0.63	100	279	165*	179*	283
14	0.18	0.50	2.00	2.00	1.50	0.54	0.47	0.53	0.40	0.45	100	400	108	94.00	300
19	0.15	0.45	1.50	1.50	1.40	0.47	0.37	0.53	0.41	0.42	100	333	104	82.20	113
25	0.20	-	-	greasy	-	-	-	-	-	0.05					

Note: Turbidity with asterisk indicate inconsistent loading (ignored).

TABLE 9.4.2 ([illegible] F.T.U.)

Run No. 5.

Test (east) filter, dosed at 10 mg/l phenol

Filtration Rate = 0.2 m/s

Time in days	Turbidity F.T.U.										C + Co Percent				
	Probe D1 m/h	E8	E1	E2	E3	E4	E5	E6	E7	M/ϕ	E8	E1,2,3	E4	E5	E6
		0	0	0	0-0.5	5.5	11.5	17.5	n.d.		0	0	5.5	11.5	17.5
0	0.20	0.71	0.78	0.78	1.50*	0.76*	0.95*	0.40	0.43	0.14	100	110	107*	134*	56.3
4	0.20	0.45	0.47	0.48	0.61*	0.35	0.13	0.1*	0.10	0.08	100	105	77.80	28.90	26.7
8	0.20	0.53	1.10	1.10	0.78	0.98*	0.95*	0.83*	0.83*	0.08	100	208	185*	179*	157
11	0.20	0.52	1.40	1.50	1.50	0.86*	0.93*	0.85*	0.85*	0.63	100	279	165*	179*	163
14	0.18	0.50	2.00	2.00	1.50	0.54	0.47	0.53	0.40	0.45	100	400	108	94.00	88.8
19	0.15	0.45	1.50	1.50	1.40	0.47	0.37	0.52	0.41	0.42	100	333	104	82.20	113
25	0.20	-	-	greasy	-	-	-	-	-	0.05					

Note: Turbidity with asterisk indicate inconsistant reading (ignored).

TABLE 2.4.10 (Turbidity F.T.U.)

Run No. 5

Filtration Rate 0.2 m/h

Control (west) filter, without dosing phenol solution

Turbidity F.T.U.										C + Co Percent					
Time in days	Probe Di m/h	WS 0	W1 0	W2 0	W3 1.5	W4 7.5	W5 13.5	W6 19.5	W7 u.d.	W8 0	W1,2 0	W3 1.5	W4 7.5	W5 13.5	W6,7 19.5
0	0.20	0.70	0.87	1.20*	0.76	0.52	0.75*	1.10*	0.50	100	124	109	74.30	107*	157*
4	0.20	0.53	0.55	1.30*	0.37	0.50	0.10	-	0.14	100	104	69.80	94.30	18.90	26.40
8	0.21	0.53	0.50	1.00	0.22	1.30*	0.13	0.41	0.10	100	94.30	41.50	245*	24.50	48.10
11	0.20	0.48	0.45	1.10*	0.30	0.60*	0.09	0.25*	0.08	100	93.80	62.50	125*	18.80	16.70
14	0.19	0.53	1.50	0.72	0.14	0.13	0.11	0.11	0.08	100	136	26.40	24.50	20.80	20.80
19	0.20	0.52	0.68	0.95	0.35	0.35	0.09	0.14	0.09	100	131	67.30	67.30	17.30	17.30
25	0.20	0.44	0.53	-	0.19	0.44	0.33	0.20	0.08	100	120	43.20	100	75.00	45.50

Note: Turbidity with asterisk indicate inconsistant reading (ignored).

...ble: Unsuitable, with ...
inconsistent readin...

TABLE 9.4.11 (... TU)

Run No. 6

Filtration Rate = 0.2 m/h

Test (west) filter, no phenol dosed

	Turbidity F.T.U.										C ÷ Co Percent				
Time in days	Probe Di m/h	E8 0	E1 0	E2 0	E3 0-0.5	E4 .5	E5 11	E6 17	E7 u.d.	W0	E8 0	E1,2,3 0	E4 5	E5 11	E6 17
3	0.20	0.47	0.47	0.67	0.70	0.42	0.26	0.46	0.13	0.13	100	130	89.40	55.30	97.8...
6	0.20	0.53	0.66	0.70	0.60	0.44	0.33	0.53	0.12	0.05	100	123	83.01	62.30	100
9	0.20	0.55	0.67	0.68	0.72	0.33	0.46	0.40	0.12	0.05	100	125	60.00	83.60	72.9...
16	0.20	0.54	0.65	0.78	0.65	0.30	1.00*	0.35	0.08	0.05	100	128	55.60	185*	64.8...
23	0.16	0.67	0.88	0.92	0.92	0.43	1.30*	1.40*	0.10	0.0...	100	135	64.20	194*	20...

TABLE 9.4.12 (Turbidity F.T.U.)

Run No. 6

Filtration Rate = 0.2 m/h

Control (west) filter, without dosing phenol solution

	Turbidity F.T.U.									C ÷ Co Percent					
Time in days	Probe Di m/h	W8 0	W1 0	W2 0	W3 1	W4 7	W5 13	W6 19	W7 u.d.	W8 0	W1,2 0	W3 1	W4 7	W5 13	W6 ...
3	0.26	0.47	0.55	0.50	0.37	0.16	0.12	0.15	0.11	100	111	78.70	34.04	25.50	31.9...
6	0.21	0.63	1.00	0.65	0.31	0.60*	0.12	0.22	0.14	100	133	49.20	95.20*	19.04	34.9...
9	0.20	0.62	0.71	0.60	0.15	0.16	0.70*	0.10	0.15	100	106	24.20	25.80	113*	16.1...
16	0.20	0.53	0.80	0.70	0.12	0.30	0.07	0.09	0.06	100	142	22.64	56.60	13.20	17.0...
23	0.20	0.58	0.72	0.80	0.25	0.40	0.09	0.93*	0.08	100	131	43.10	69.00	15.5...	

[illegible] Delivery

Rate of Application: 0.2 m/h

Observations: (a) Mud cake in W filter; (b) 1 mm algae in W filter; (c) E and W both covered

	Residual Turbidity FTU (Neat)							C ÷ Co Percent (E)						
Valve	E8	E1	E2	E3	E4	[illegible]	E6	E8	E1	E2	E3	E4	E5	[illegible]
D1 / T8	0	0.5	2	8	14	20	26	0	0.5	2	8	14	20	[illegible]
8	0.59	0.80	0.75	0.64	0.47	0.30	0.34	100	136	127	108	79.7	54.2	[illegible]
11	0.64	0.43	0.42	0.25	0.23	0.39	0.13	100	67.18	65.6	39.1	35.9	29.7	[illegible]
14	0.67	0.41	0.40	0.25	0.26	0.18	0.16	100	61.2	59.7	37.3	38.8	25.9	[illegible]
18	0.50	0.25	0.32	0.21	0.15	0.11	0.11	100	50.0	64.0	42.0	30.0	22.0	[illegible]
21	0.47	0.23	0.36	0.15	0.13	0.13	0.11	100	48.9	76.6	31.9	27.7	27.7	[illegible]
Av.dy 0-21								100	72.7	78.6	51.7	42.4	32.1	[illegible]
25	0.56	0.25	0.82	0.21	0.22	-	0.14	100	44.6	146.4	37.5	39.3	-	[illegible]
28	0.59	0.34	0.58	0.34	0.10	-	0.12	100	57.6	98.3	57.6	30.5	-	[illegible]
35	1.03	0.34	0.56	0.24	0.23	0.13	0.12	100	33.0	54.4	23.3	22.3	12.6	[illegible]
Av.dy 21-35								100	45.1	99.7	39.5	30.7	-	[illegible]
56	1.06	0.40	0.63	0.27	0.14	-	0.21	100	37.7	59.4	25.5	13.2	-	[illegible]
63	1.00	0.26	0.34	0.15	0.22	-	0.15	100	26.0	34.0	15.0	22.0	-	[illegible]
71	0.94	0.29	0.44	0.23	0.13	-	0.18	100	30.9	46.8	24.5	13.8	-	[illegible]
Av.dy 35-71								100	31.5	46.7	21.7	16.3	-	[illegible]
77	-	0.36	0.89	-	-	-	0.15	100	-	-	-	-		[illegible]

Rate of filtration: 0.2 m/h

Observations: (a) New sand in W filter; (b) E filter sand 3 month ripe; (c) E and W both covered.

Valve	Residual Turbidity FTU (West)							C ÷ Co Percent (W)						
	W8	W1	W2	W3	W4	W5	W6	W8	W1	W2	W3	W4	W5	
Di / Td	0	0.5	4	10	16	22	28	0	0.5	4	10	16	22	
8	0.59	0.81	0.70	0.81	0.63	0.30	0.50	100	137	119	137	107	84.7	
11	0.58	0.58	0.41	0.40	0.36	0.35	0.35	100	100	70.7	69.0	62.1	60.3	
14	0.53	0.44	0.55	0.45	0.31	0.31	0.34	100	83.0	104	84.9	58.5	58.5	
18	0.52	0.42	0.35	0.88*	0.28	0.35*	0.24	100	80.8	67.3	-	53.8	-	
21	0.54	0.45	0.31	0.36	0.26	0.31	0.29	100	83.3	57.4	66.7	48.1	57.4	
Av. dy 0-21								100	96.8	83.7	89.4	65.9	65.2	
25	0.52	0.49	0.33	0.31	0.27	0.36	0.33	100	94.2	63.5	59.6	51.9	69.2	
28	0.61	0.61	0.38	0.30	0.30	0.36	0.28	100	100	62.3	49.2	49.2	59.0	
35	1.10	0.61	0.41	0.40	0.38	0.31	0.36	100	55.4	37.3	36.4	34.5	28.2	
Av. dy 21-35								100	83.2	54.4	48.4	45.2	52.1	
56	1.10	0.86	0.46	0.36	0.34	0.30	0.30	100	78.2	41.8	32.7	30.9	27.3	
63	0.90	0.59	0.28	0.23	0.14	0.21	0.23	100	65.6	31.1	25.6	15.6	23.3	
71	0.89	0.57	0.19	0.20	0.17	0.31	0.22	100	64.0	21.3	22.5	19.1	34.8	
Av. dy 35-71								100	69.3	31.4	26.9	21.9	28.5	
77	-	-	-	-	-	-	-	-	-	-	-	-	-	

Rate of filtration: 0.2 m/h

Observations: (a) E and W both uncovered; (b) Ozonization in W.

	Residual Turbidity FTU (E)							C / Co Percent (E)						
Valve	E0	E1	E2	E3	E4	E5	E6	E0	E1	E2	E3	E4	E5	E6
Di / Td	0	0.5	1.5	7.5	13.5	19.5	25.5	0	0.5	1.5	7.5	18.5	19.5	25.5
0	2.00	1.5	2.4*	1.9	1.1	1.3	0.30	100	75.0	-	95.0	55.0	65.0	15.0
5	0.76	0.39	0.38	0.31	0.33	-	0.26	100	51.3	50.0	40.8	43.4	-	34.2
11	0.86	0.34	0.50	0.20	-	0.24	0.12	100	39.5	58.1	23.3	-	27.9	14.0
18	0.72	-	0.69	-	0.49	0.14	0.14	100	-	95.8	-	68.0	19.4	19.4
Av. dy 0-18								100	45.4	68.0	32.0	55.7	23.7	22.5
32	4.70	0.41	0.49	0.34	0.37	0.22	0.11	100	8.7	10.4	7.2	7.9	4.7	2.3

Run no. 22/73-73

Rate of filtration: 0.2 m/h

Observations: (a) E and W both uncovered; (b) Ozonisation in W.

	Residual Turbidity FTU (W)							C ÷ Co Percent (W)						
Valve	W3	W1	W2	W3	W4	W5	W6	W3	W1	W2	W3	W4	W5	W6
	0	0.5	3.5	9.5	15.5	21.5	27.5	0	0.5	3.5	9.5	15.5	21.5	27.5
0	0.80	0.61	0.46	0.39	0.21	0.19	-	100	76.3	57.5	48.8	26.3	23.8	-
5	1.6	0.34	0.20	0.11	0.15	0.15	0.15	100	21.3	12.5	6.9	9.4	9.4	9.4
11	1.0	0.35	0.29	0.13	0.12	0.10	0.10	100	35.0	29.0	13.0	12.0	10.0	10.0
18	1.4	0.51	0.20	0.20	0.24	0.15	0.19	100	36.4	14.3	14.3	17.1	11.4	13.6
Av. dy 0-18								100	31.0	18.6	11.4	12.8	10.3	11.0
32	5.0	-	0.24	0.16	0.15	0.13	-	100	-	4.8	3.2	3.0	2.6	-

Table 9.6.1 (River Turbidity)

Run no. 1

Rate of filtration = 0.2 m/h

Phenol dose in test filter = 1 10 mg/l

	Turbidity (Removal) Gradient Percent						
Probe	B3	B4	B5	B6	W2	W3	W5
Di / Td	1.5	7.5	13.5	19.5	1.5	3.5	21.5
4	13.60	-	(-)0.17	3.73	-	-	-
18	19.60	1.52	0.74	0.16	1.27	10.20	5.20

Table 9.6.2 (River Turbidity)

Run no. 2

Rate of filtration = 0.2 m/h

Phenol dose in test (east) filter = 10 mg/l

	Turbidity (Removal) Gradient Percent							
Probe	B4	B5	B6	W2	W3	W4	W5	W6
Di / Td	7	13	19	7	3	9	15	21
0	7.44	1.08	0.35	15.40	0	3.47	(-)2.18	2.57
3	9.14	0.33	0.33	5.00	17.5	0.67	0	2.33
7	6.36	1.42	0.33	20.50	1.10	2.85	2.83	0

Table 9.6.3 (Raw Turbidity)

Run no. 3

Rate of filtration = 0.2 m/h

Phenol dose in test (cent) filter = 10 mg/l

Turbidity(Removal) Gradient Percent							
Probe	D4	D5	D6	W3	W4	W5	W6
D1 / W2	6.5	12.5	18.5	2.5	8.5	14.5	20.5
2	5.27	0.71	3.56	(-)	6.34	3.70	0.83
4	7.61	2.63	1.40	23.64	(-)6.46	3.76	3.95
12	3.95	0	2.86	(-)	5.93	-	0.45
16	3.34	1.75	0.20	25.44	(-)5.75	(-)7.85	12.25

Table 9.6.4 (Same Turbidity)

Run No. 4

Rate of filtration = 0.2 m/h

No Phenol dosed

Probe / Di / (2)	Turbidity (Removal) Gradient Percent						
	B4	B5	B6	W3	W4	W5	W6
	6	12	18	2	8	14	20
1	7.30	3.67	(-)0.47	(-)13.50	3.67	4.30	1.82
4	9.17	3.88	(-)0.27	31.35	2.23	(-)3.98	4.97
6	9.13	0.28	3.22	38.80	(-)3.23	(-)12.20*	16.43
9	8.48	(-)4.10	7.80	25.00	4.02	4.02	0
22	8.68	(-)0.72	4.17	19.85	0.20	(-)0.58	2.60
25	8.22	(-)36.33*	2.20	28.90	(-)2.60	5.73	(-)4.43
28	5.92	(-)5.38	9.42	28.00	(-)0.67	4.45	0.67
24	7.02	(-)1.12	7.75	28.30	-	(-)1.27	0.63
31	9.08	(-)1.20	6.05	14.15	(-)14.38*	9.33*	12.28
34	8.80	4.40	0.95	27.80	0.78	(-)0.53	3.72
37	13.45	0	1.07	26.70	(-)0.28	3.73	1.15
39	13.93	(-)5.72	5.25	42.05	(-)0.78	0.78	0.53
44	4.45	13.88	0.55	-	-	-	-

Table 9.6.5 (Layer Turbidity)

Run No. 5

Rate of filtration = 0.2 m/h

Depth / Di	Turbidity Gradient Percent						
	E4	E5	E6	W3	W4	W5	W6
	5.5	11.5	17.5	1.5	7.5	13.5	19.5
0	(-)1.27	4.50	12.95	(-)1.50	5.78	(-)5.45	(-)8.33
4	4.04	8.15	0.37	20.14	(-)4.08	12.57	(-)1.25
8	(-)15.45	1.00	3.67	39.00	(-)33.92*	36.75	(-)0.72
11	(-)11.82	(-)2.33	2.67	25.0	(-)10.42*	3.64	(-)5.53
14	(-)1.45	1.00	2.00	49.07	0.32	0.62	0
19	(-)0.73	2.97	5.63	21.80	0	6.66	(-)1.60
25	-	-	-	37.87	(-)9.47	(-)4.17	4.92

Table 9.6.6 (Layer Turbidity)

Run No. 6

Filtration rate = 0.2 m/h

Alumol dose in test (east) filter: 10 mg/l

	Turbidity Gradient Percent								
	E1	E4	E5	E6	W1	W3	W4	W5	W6
	0	5	11	17	0	1	7	13	19
3	1.3	8.12	5.68	(-)7.10	1.11	32.30	7.44	1.42	1.05
6	1.23	8.00	3.45	(-)6.28	1.33	83.30	(-)7.66	12.69	(-)2.64
9	1.25	13.00	(-)3.94	1.81	1.06	81.80	(-)0.26	(-)14.53	(-)15.15
16	1.28	14.48	(-)21.60	20.03	1.42	119.36	(-)5.66	7.23	(-)0.63
20	1.35	14.16	(-)21.57	(-)2.50	1.31	87.90	(-)4.31	8.91	(-)24.09

CHAPTER X

EXPERIMENTAL RESULTS ON PHENOL DEGRADATION

(M.W.B. WALTON)

In this chapter, the experimental data on phenol degradation and phenol formation in a slow sand filter, are analysed and presented in graphical form. The presentation is divided into three parts: phenol degradation in the filter depth, phenol degradation in the filter with time, and the formation of phenol in the filter. The tests on these phenomena were the last phase of this research. Phenol was dosed in run nos.1, 2, 3, and 5 and its formation was studied in run nos.4 and 6 when no phenol was dosed in the test filter. These tests were carried out to ascertain biodegradability in slow sand filters as mentioned earlier. A total of seven tables (10.1.1-10.1.7) have been prepared and used for this purpose.

10.1 Phenol Degradation in the Filter Depth

Graphs (10.1.1-10.1.4) illustrate curves for the degradation of phenol in the depth of the filter. The test (east) filter was chosen to be dosed at 10 mg/l of phenol, when test and control filter rates were 0.2 m/h. The depth of the filter bed is plotted in inches along the abscissa of each graph, and the ordinate represents P/Po, i.e. the phenol concentration in filter depth on a particular day of the run, as a percentage of the incoming (applied) phenol concentration in the raw water at the ball valve. The results are normalised to minimise the effect, due to unavoidable variation of phenol concentration at the inlet.

While interpreting the data, it is assumed that the degradation in a slow sand filter is related to the depth of the bed, as well as to the time of the run. In graphs (10.1.1-10.1.4) typical curves are drawn for runs 1, 2, 3 and 5, for the test filter, illustrating the residual phenol at any valve depth, for a particular time of the run. Curves in these graphs show a great fall for the top layer, demonstrating

indicate a large degree of degradation of phenol in the top layer of sand (about 5 cm thick). This behaviour is similar to that of headloss development in section 9.3, and turbidity removal in sections 9.4 and 9.6. There is substantial degradation in the top 15 cm (6 inch) (B3-B4) and some in the middle six inches (B4-B5) of bed. A close inspection of the curves reveals that in the majority of the cases the lowest point on the curve is B5 and not B6, thus indicating a phenol formation phenomenon in the bottom six inches of bed. The upward trend of the curve in the bottom six inches becomes more interesting in view of the discovery of pressure as reported in section 9.3. Inspection of the curves with respect to the length of the run reveals that the best degradation is achieved in the middle period of the run.

10.2 Phenol Degradation with Time

Graphs (10.2.1-10.2.4) show curves for the degradation of phenol with time, as the run proceeds. The analysis is for the data collected from phenol-dosed runs 1, 2, 3 and 5. The ordinate of the graphs is labelled C/Co, the phenol concentration in the filter depth for a particular day of the run, as a percentage of the incoming phenol.

Curves in graphs (10.2.1-10.2.4) show an increasing degradation of phenol during three fourths of the run, but in the last quarter of the run the trend continues only in two of the four graphs, the other two graphs indicate an increasing phenol concentration in the last quarter of the run, indicating appearance of phenol, which may be because of dislodgement of bacteria due to insufficient supply of oxygen and food.

10.3 Phenol Movement in Slow Sand Filters During no Phenol Dosing

In short below a set of curves were drawn by plotting the results of phenol transfer obtained from experiments during undosed runs, nos.4 and 6. Graphs (10.3.1-10.3.6) illustrate the curves on semi-logpaper for phenol transfer to the flowing water in the test and control filters.

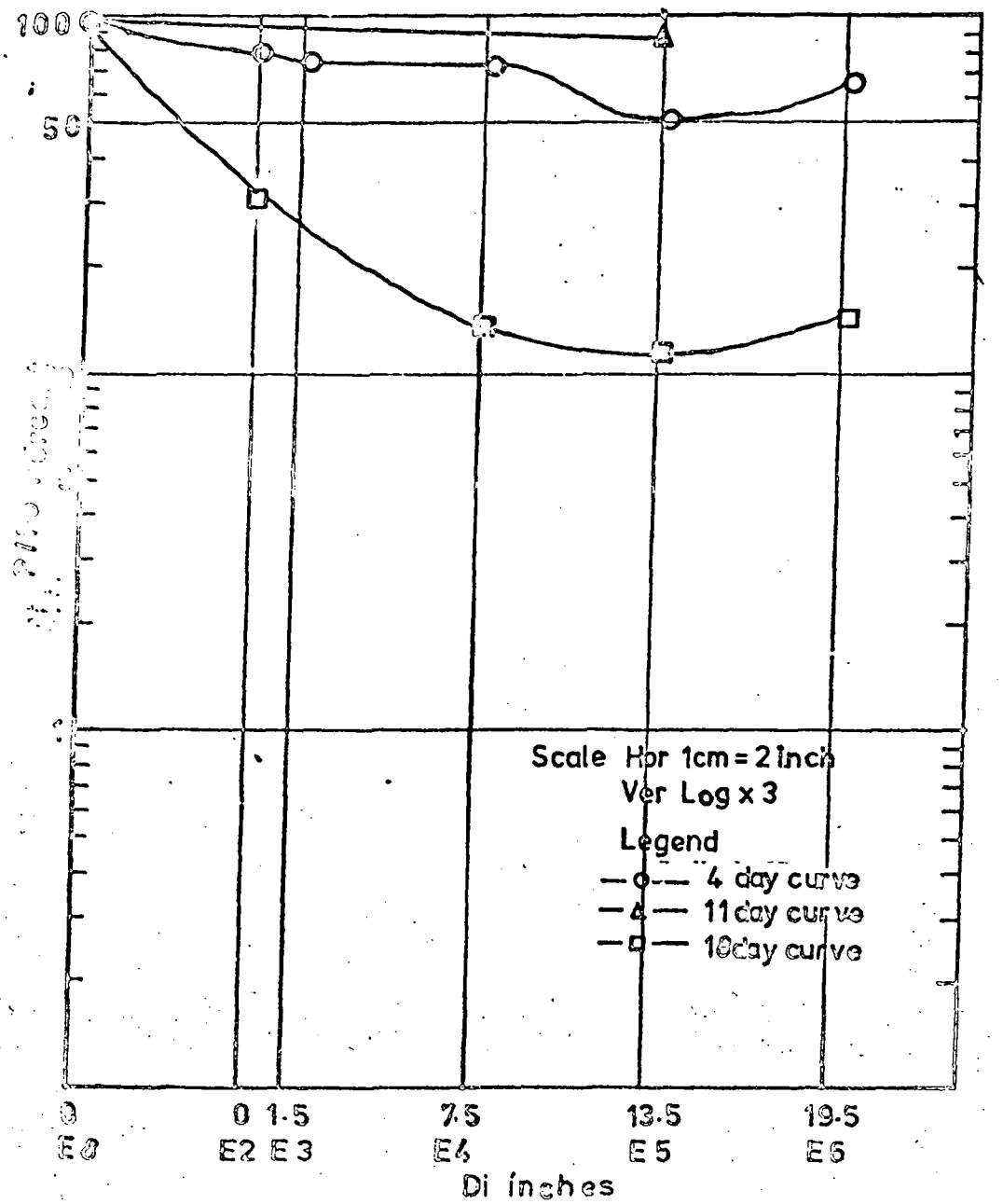
Curves in graphs (10.3.1-10.3.2) show concentration of phenol

[illegible] to the flowing water in the depth of the filters, abscissa [illegible] filter depth in inches and ordinate showing desorbed phenol in µg/l. Results in tables 10.1.5 and 10.1.6 are based on Chloroform Extraction Method and Direct Photometric Method for the determination of phenol. The curves in the above graphs (10.3.1-10.3.2) reveal a substantial quantity of phenol formed by the filter. It shows presence of formed phenol throughout the depth of the bed. In graph (10.3.2) the phenol measured in the control filter makes these results even more exciting. Close scrutiny of the curves for the test filter indicate W5 as the depth of maximum phenol formation, which is also the depth of maximum phenol degradation, during phenol dosed runs, as reported in section 10.1. In curves for the control filter (graph (10.3.2), however, the depth of maximum phenol formation appears to be W6.

Curves (10.3.3-10.3.4) illustrate concentration of such transferred phenol in the two beds as the run proceeds. Abscissa indicate T- [illegible] of the run in days and ordinate represents P - the phenol concentration [illegible] at a particular depth. Graph 10.3.3 shows curves for the test [illegible] with phenol concentration determined by Chloroform Extraction [illegible] by Direct Photometric Method being plotted separately for [illegible]. Graph 10.3.4 illustrates curves for both the test and the [illegible] filters based on phenol concentrations determined by the Chloroform Extraction Method only. Curves in graph 10.3.3 exhibit a general downward trend as the run proceeds, suggesting a higher rate of phenol transfer in the beginning and a lower rate of phenol transfer in the latter part of the run. The same pattern does not seem to be repeated by the curves of graph 10.3.4. In both these graphs, the position of the curves for B0/W8 is lower most generally, indicating higher phenol concentration at any other depth in the filter, thus suggesting strongly the process of phenol transfer occurring in the filter. It is difficult to tell the true reason of this phenomenon with any degree of certainty, but it is assumed that phenol is decayed by the cells of bacteria [illegible], and not by the surface of sand particles.

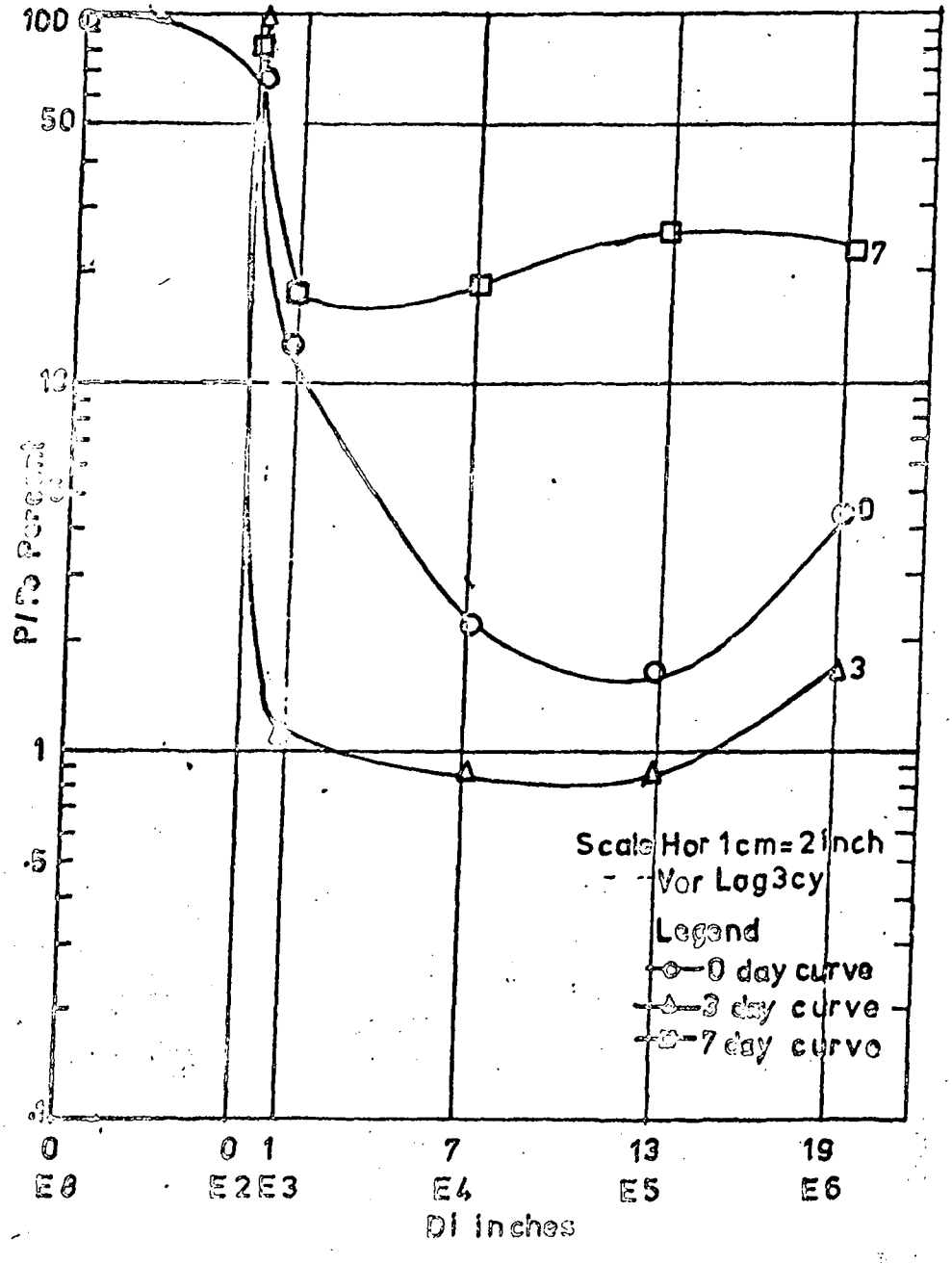
Curves in graph 10.3.5 illustrate the performance of the filter with respect to the phenol desorption for the undosed runs, nos.4 and 6, abscissa representing the time of the run in days and ordinate representing phenol concentration in µg/l, at the inlet and outlet of the filter. Terms '[illegible]O' and '6[illegible]O' in graph 10.3.5 are for the mixed filtered water

outlet exp. for all the filter beds of the Walton Water Works, at the [illegible] as experimental undosed runs 4 and 6. Curves 4W3 and 6W3 are for inlet water of experimental filter during undosed runs 4 and 6. Curve 6W7 is for the outlet of (control) experimental filter during undosed run 6. Comparing curves 4W8 and 4WWO it is clear that Walton Water Works Outlet curve is generally always higher than the experimental filter inlet curve. Assuming that the concentration of phenol was the same in the two inlet waters of the experimental filter and the Walton Works main slow sand filters (being the same source of primary filtrate for both) it is quite clear that some phenol is produced even by the main slow sand filter beds of Walton Works. Looking at curves 6W7, 6W8 and 6WWO for run no.6, the upper position of outlet curves for experimental and the main works, further strengthens this view. This important finding is supported by the description of phenol transfer curves, earlier in this section.

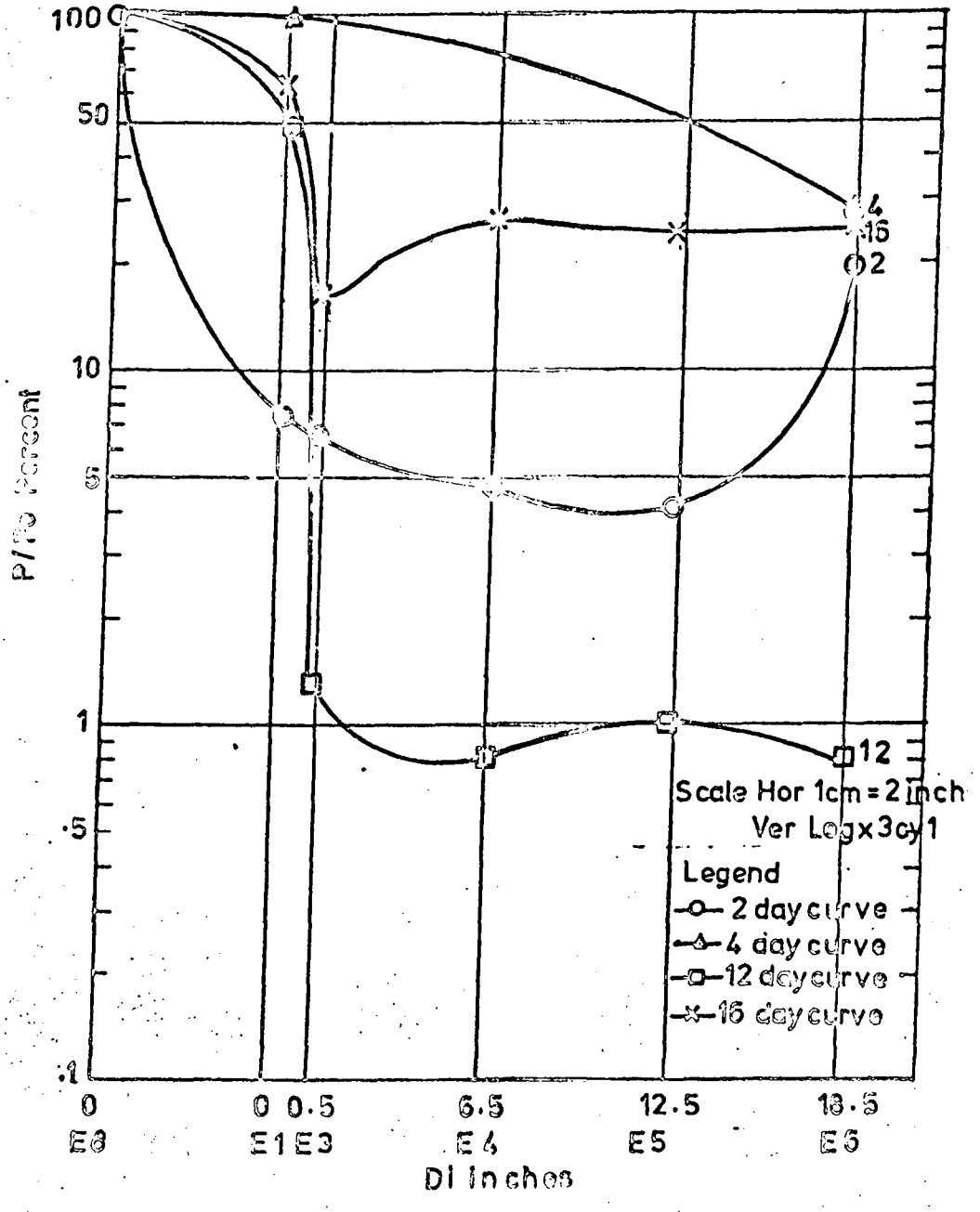


GRAPH 1011 (Run no 11)

Phenol Degradation with Depth Curves

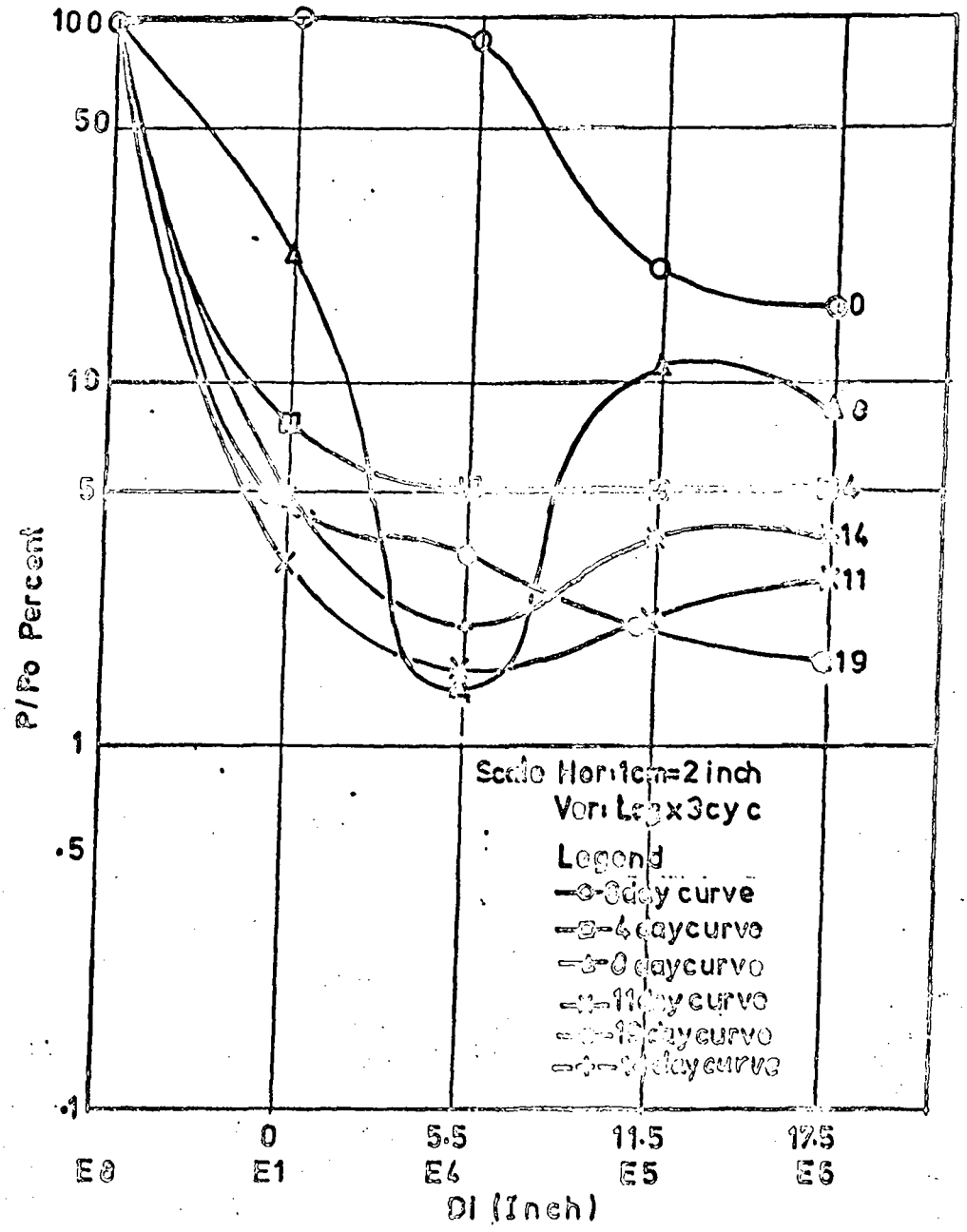


GRAPH 10.1.2 (Run no 2)
Phenol Degradation with Depth Curves



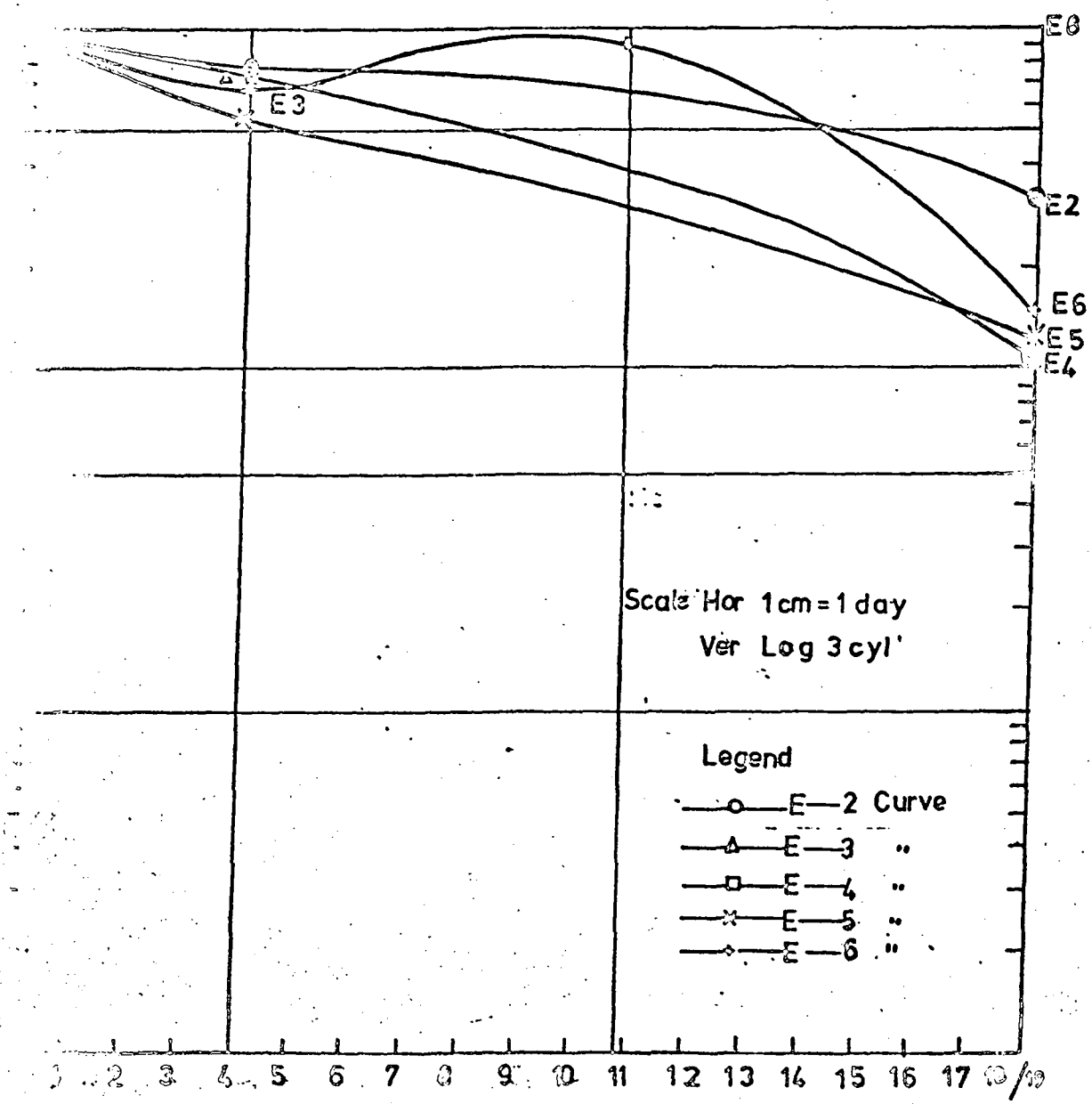
GRAPH 10.13 (Run no 3)

Fungal Degradation with Depth Curves



GRAPH 10.14 (Run no 3)

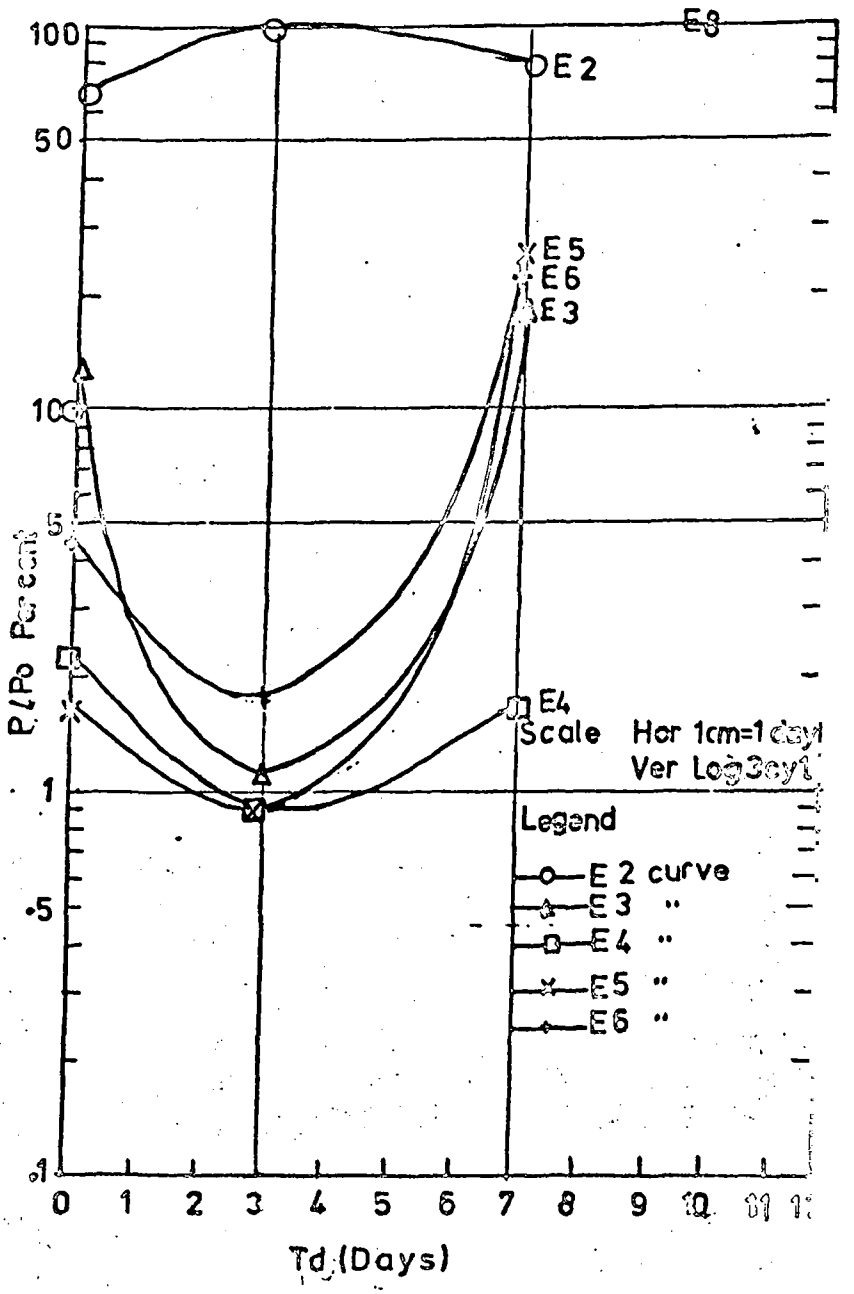
Phenol Degradation with Depth Curves



Td (Days)

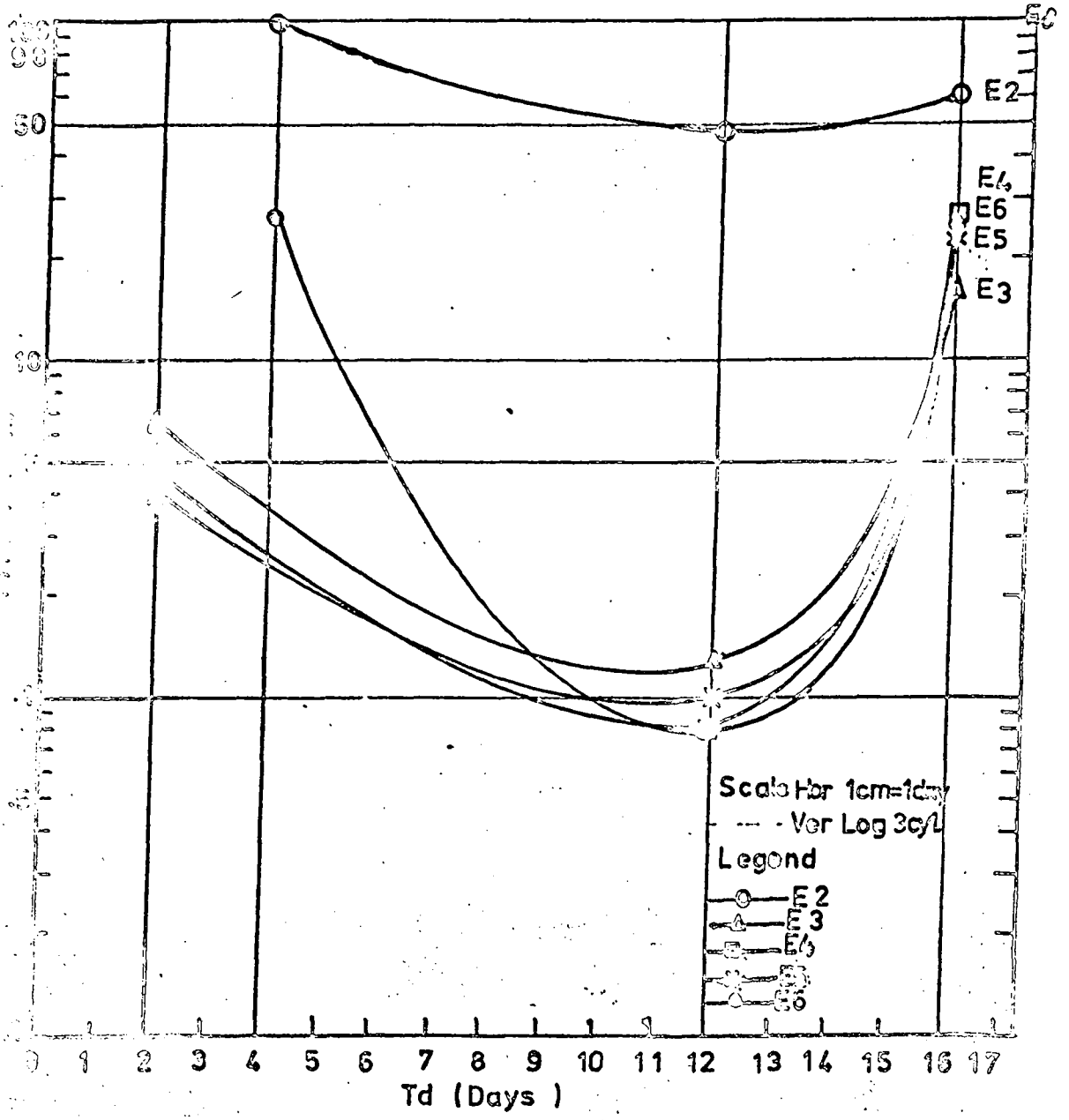
GRAPH 10.21 (Run no 1)

Phenol Degradation with Time Curves

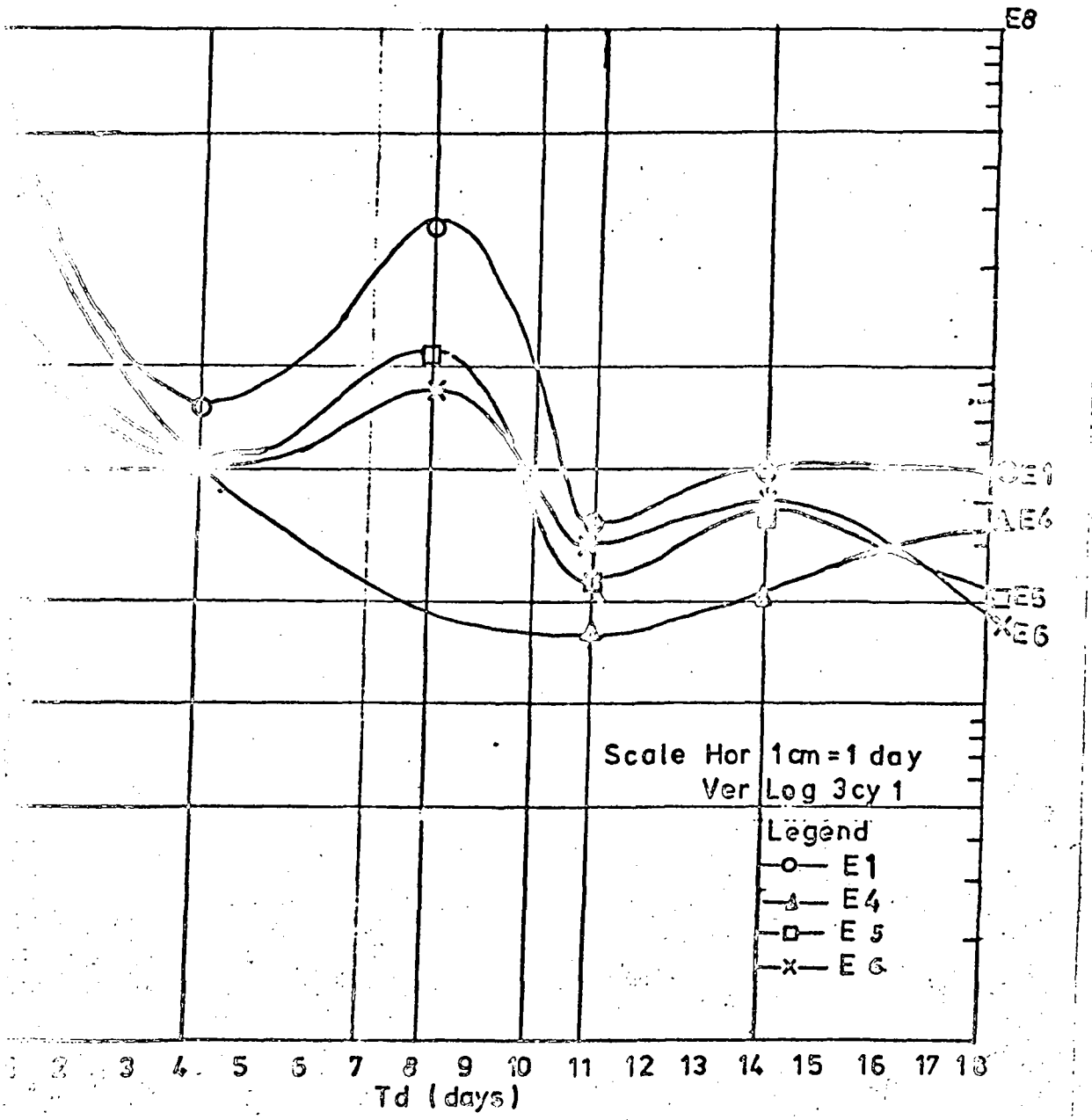


GRAPH 10.2.2 (Run no 2)

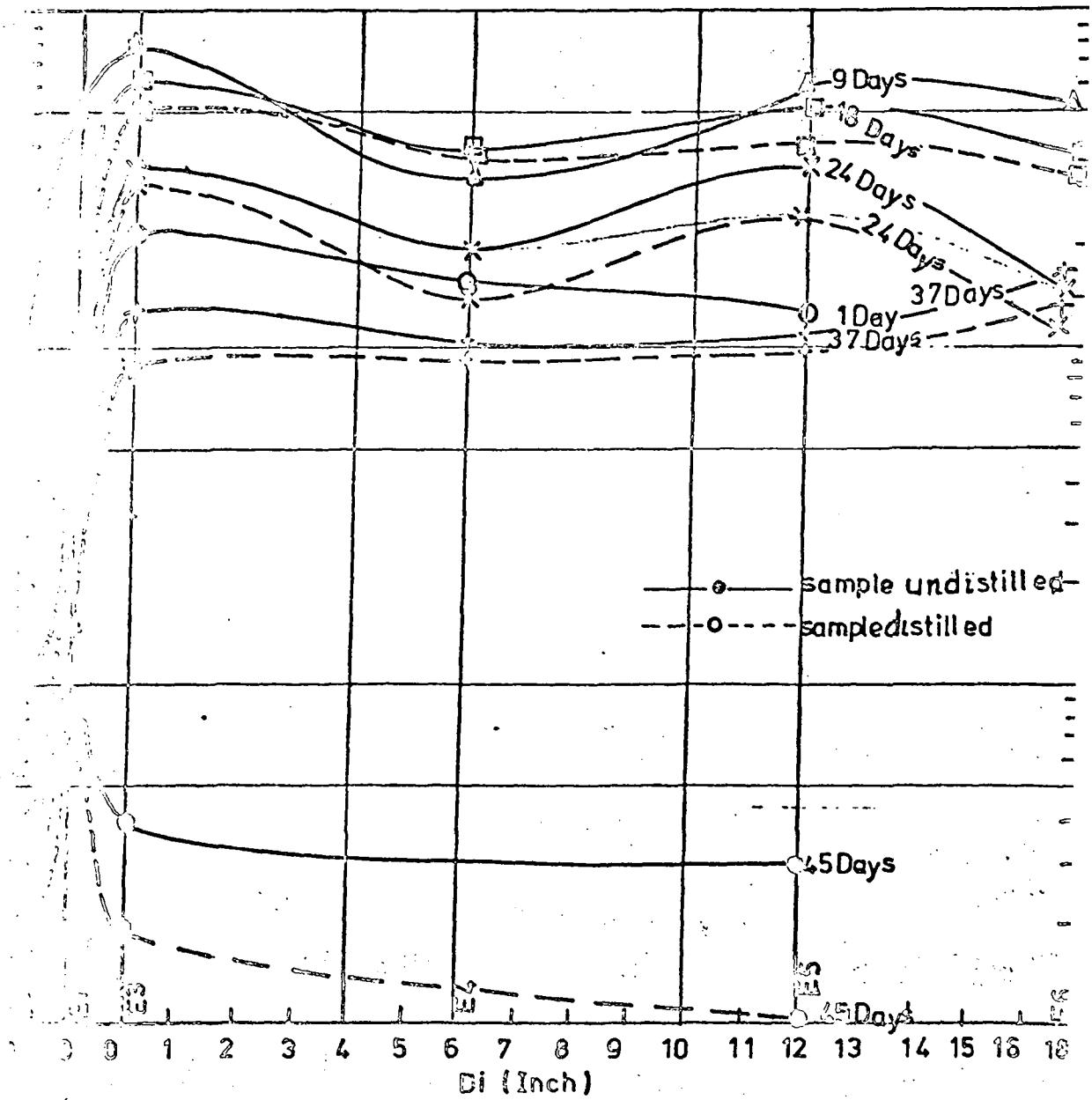
Phenol Degradation with Time Curves



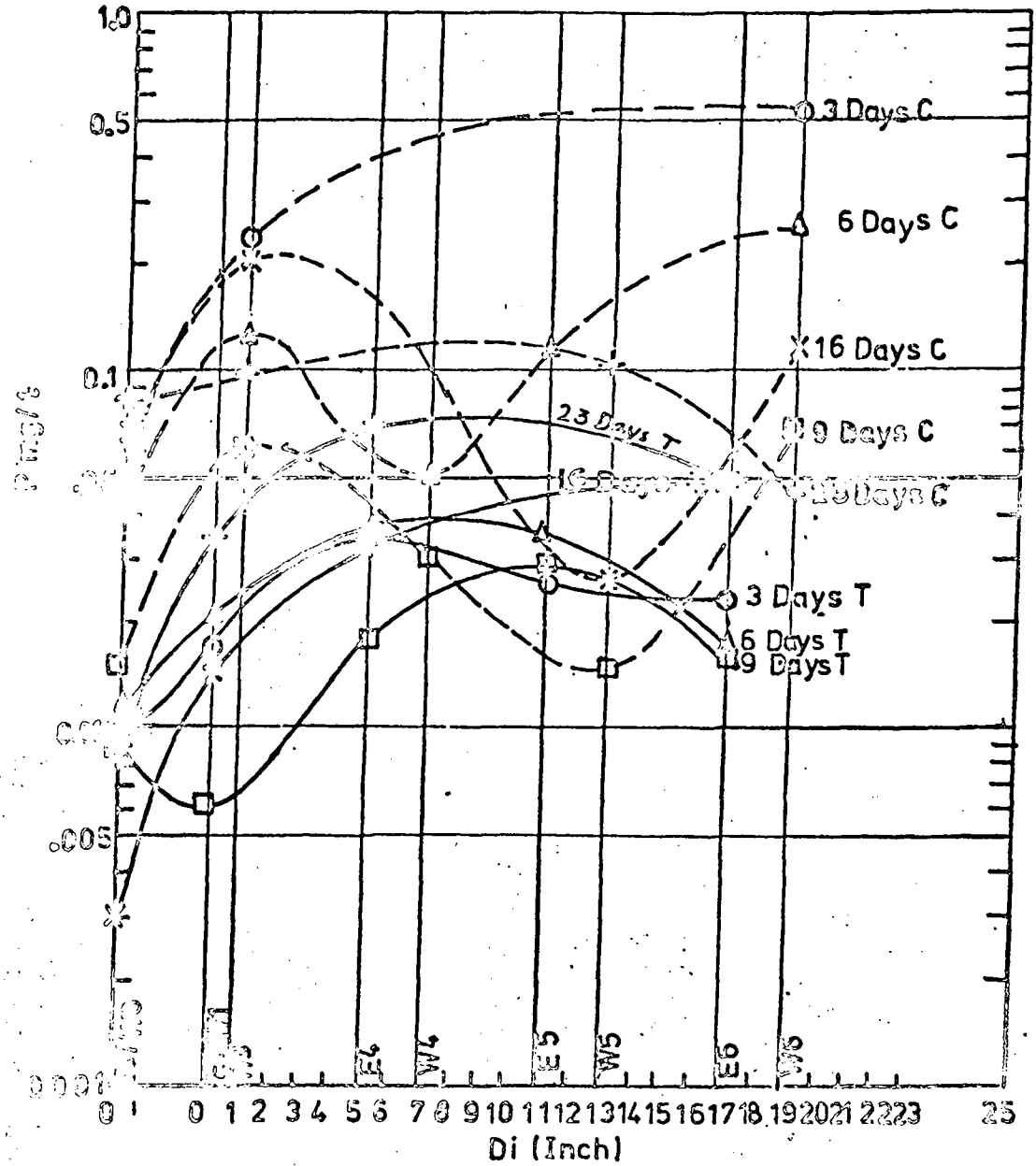
GRAPH 10.2.3 (Run no 3)
Phenol Degradation with Time Curves



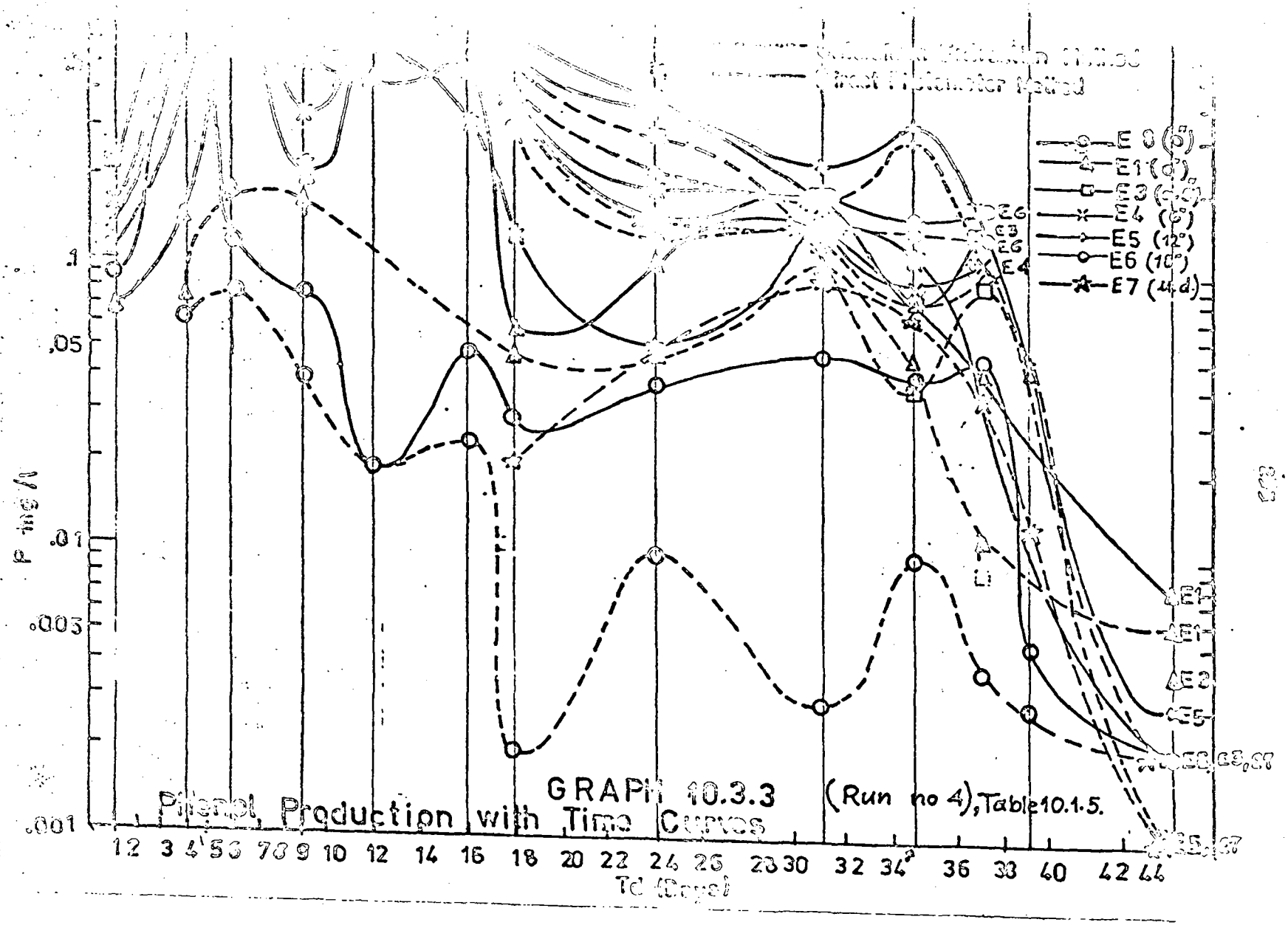
GRAPH 10.2.4 (Run no 5)
Phenol Degradation with Time Curves



GRAPH 10.3.1
(Run no 4)
Phenol production with depth curves

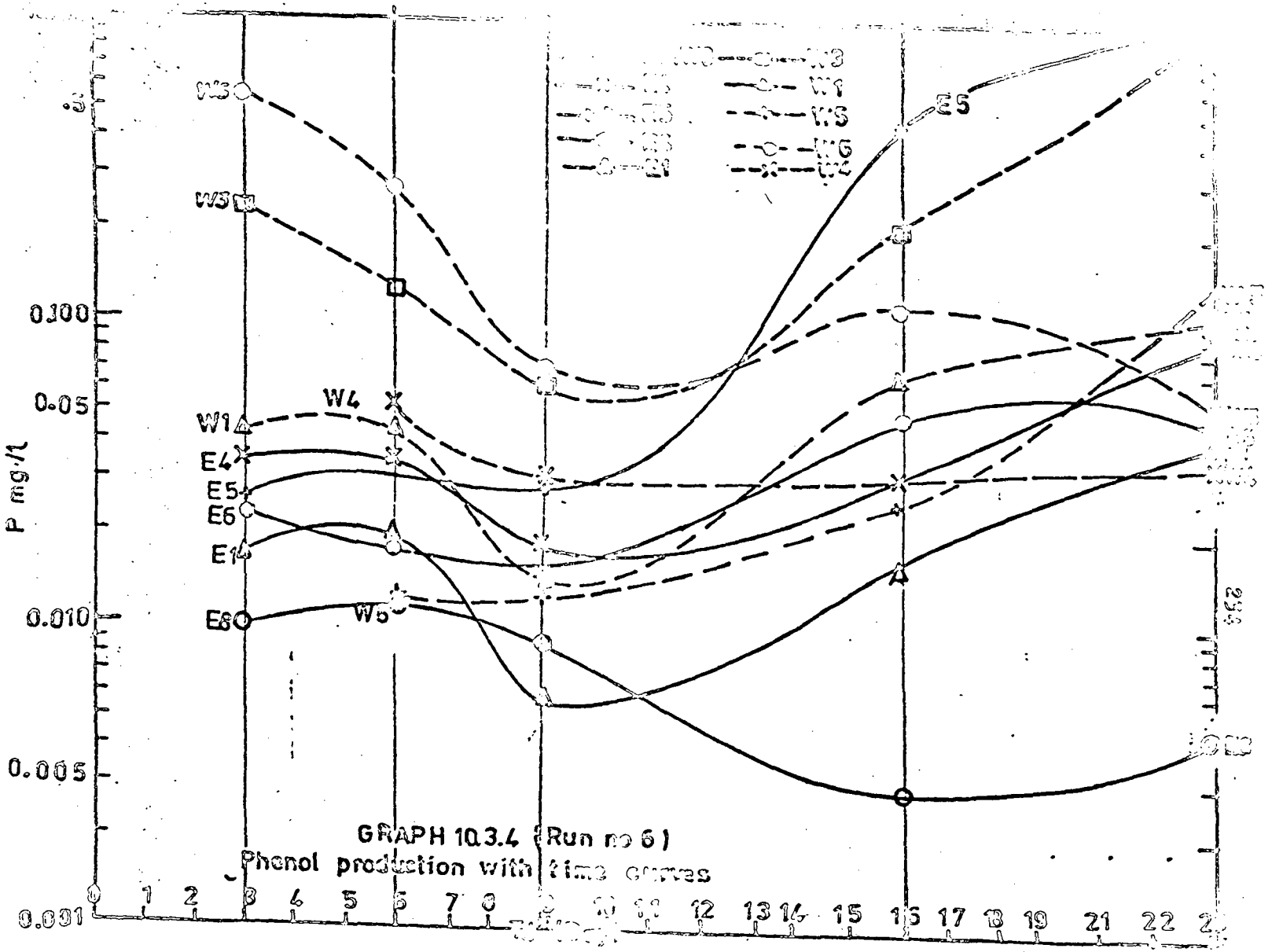


GRAPH 10.3.2
(Run no 3)
Phenol Production with depth curves



GRAPH 10.3.3 (Run no 4), Table 10.1.5.

Pilerdol Production with Time Curves



GRAPH 10.3.4 (Run no 6)
Phenol production with time curves

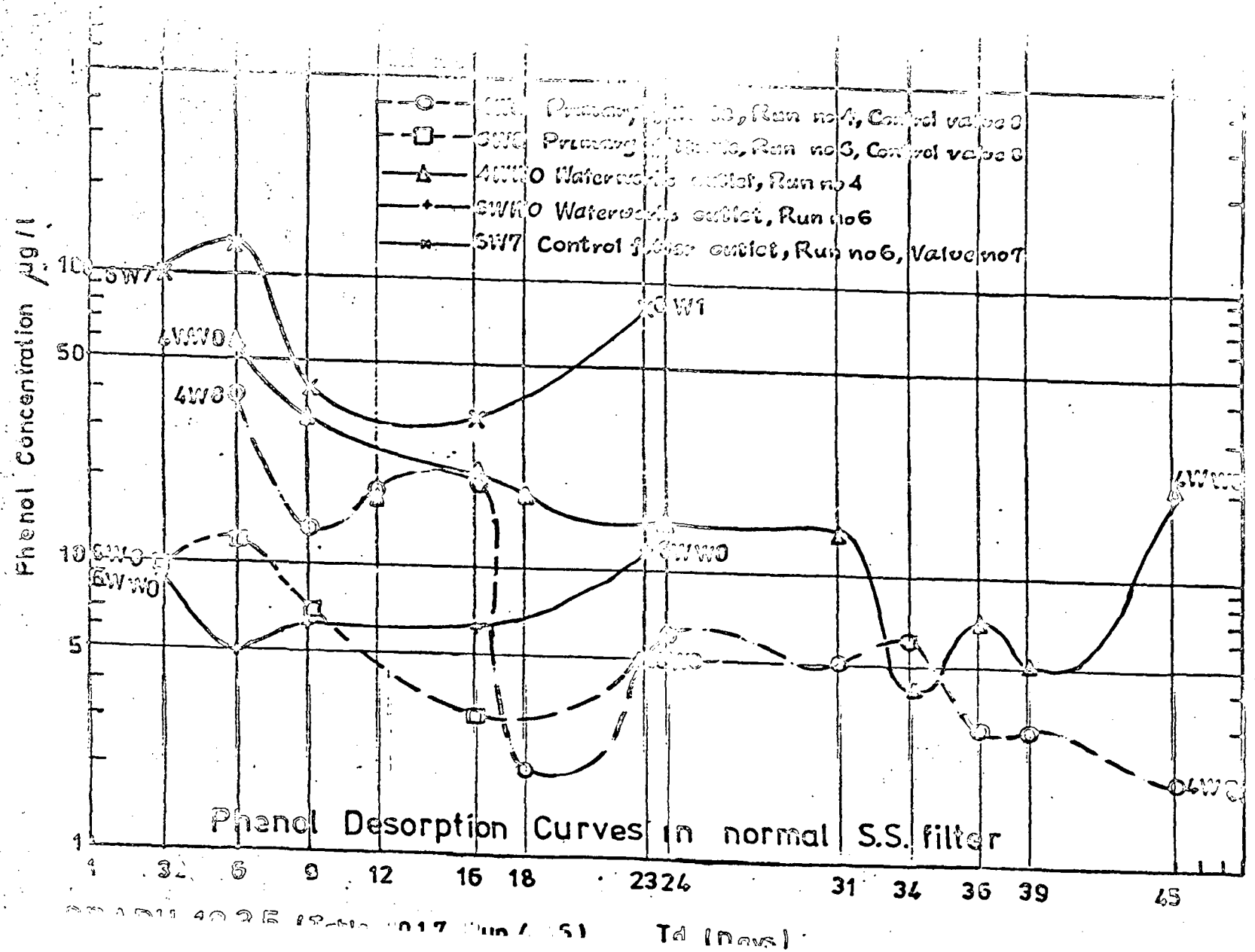

Phenol Concentration /µg/l
Td (hours)
Phenol Desorption Curves in normal S.S. filter
4WW0 Waterworks outlet, Run no 4
6WW0 Waterworks outlet, Run no6
SW7 Control filter outlet, Run no6, Valve not
6W1
4WW0
4W3
6WW0
6W0
4W0
1
5
10
50
100
1
3
6
9
12
16
18
23
24
31
34
36
39
45

TABLE 10.1.1

Run No. 1. Test (east) Filter : Phenol dosed. (Phenol concentration) Filtration rate = 0.2 m/h

	Residual Phenol mg/l							P ÷ Po Percent					
Probe / Td \ Di	E8	E2	E3	E4	E5	E6	E7	E8	E2	E3	E4	E5	E6
	0	0	1.5	7.4	13.5	19.5	u.d.	0	0	1.5	7.5	13.5	19.5
4	2.5	2.00	1.90	1.90	1.35	1.70	0.65	100	80.00	76.00	76.00	54.00	68.00
11	14.2	-	-	-	-	-	13.60	100	-	-	-	-	95.60
18	67.0	21.00	-	7.00	8.00	10.00	10.00	100	31.30	-	10.40	11.90	14.90

TABLE 10.1.2

Run No. 2. Test (east) Filter : Phenol dosed. (Phenol concentration) Filtration rate = 0.2 m/h

	Residual Phenol mg/l							P ÷ Po Percent					
Probe / Td \ Di	E8	E2	E3	E4	E5	E6	E7	E8	E2	E3	E4	E5	E6
	0	0	1.0	7.0	13.0	19.0	u.d.	0	0	1.0	7.0	13.0	19.0
0	7.9	5.3	1.000	0.170	0.130	0.350	0.500	100	67.10	12.70	2.20	1.65	4.43
3	9.0	9.0	0.100	0.080	0.080	0.150	-	100	100	1.10	0.890	0.890	1.70
7	17.6	14.7	3.100	3.300	4.50	4.000	1.100	100	83.50	17.60	18.70	25.60	22.70

Table 10.1.3

Run No. 3 Test (cast) Filter : Phenol dosed. (Phenol concentration) Filtration rate = 0.2 m/h

Probe	Residual Phenol mg/l							P ÷ Po Percent					
Td \ Di	E0	E1	E3	E4	E5	E6	E7	E8	E1	E3	E4	E5	E6
	0	0	0.5	6.5	12.5	18.5	u.d.	0	0	0.5	6.5	12.5	18.5
2	3.7	0.260	0.240	0.170	0.150	*0.720	*0.460	100	*7.02	6.48	4.59	4.05	-
4	5.7	5.7	*11.3	*12.0	*24.0	*11.8	1.5	100	100	-	-	-	26.30
12	10.0	4.8	0.130	.080	0.100	.080	16.8	100	48	1.30	0.80	1.00	0.80
16	46.0	29.0	7.6	12.3	11.1	12.5	12.6	100	63	16.50	26.70	24.0	27.10

TABLE 10.1.4.

Run No. 5. Test (east) Filter : Phenol dosed. (Phenol concentration) Filtration rate = 0.2 m/h

	Residual Phenol mg/l						P ÷ Po Percent				
Probe	E0	E1	E2	E5	E6	E7	E0	E1	E2	E5	E6
Td Di	0	0	5.5	11.5	17.5	u.d.	0	0	5.5	11.5	17.5
0	0.150	0.250	0.220	0.050	0.40	0.050	100	100	68.0	20.00	16.00
4	0.390	0.030	0.020	0.020	0.020	*0.040	100	7.70	5.10	5.10	5.10
8	10.0	2.30	*0.150	1.10	0.850	0.140	100	23	*1.50	11.00	8.50
11	7.0	0.240	0.110	0.160	0.200	0.090	100	3.40	1.60	2.30	2.90
14	8.7	0.430	0.180	0.320	0.340	0.110	100	4.90	2.10	3.70	3.90
19	10.7	0.520	0.360	0.230	0.180	0.060	100	4.90	3.40	2.10	1.70

TABLE 10.1.5

Run No. 4. Test (cont) Filter : No Phenol dosed. (Phenol concentration desorption) Filtration rate = 0.2

	Residual Phenol mg/l (P)							P (mg/l) After Distillation						
Probe / Td \ Di	E8	E1	E3	E4	E5	E6	E7	E8	E1	E3	E4	E5	E6	E7
	0	0	0 - 0.5	6.0	12.0	18.0	u.d.	0	0	0 - 0.5	6.0	12.0	18.5	u.d.
1	.090	.070	.220	.160	.130	4.7	0.110	-						
4	.850	.150	1.6	0.850	0.850	1.5	-	0.072cu	0.080cu					
6	.120	2.9	1.7	1.0	1.4	1.2	0.000	0.080cu	0.180cu					
9	.080	0.530	0.800	0.330	0.630	0.550	0.200	0.040cu	0.170cu					[illegible]
12	.020	0.470	0.690	0.620	0.650	0.630	0.040	0.020cu	-					-
16	.050	0.500	1.5	0.830	1.030	0.740	0.300	0.024cu	-					-
18	.030	0.060	0.640	0.390	0.520	0.370	0.130	0.002cd	0.050	0.520	0.360	0.410	0.330	0.020
24	.040	0.105	0.350	0.195	0.350	0.150	0.050	0.010cd	0.050	0.300	0.145	0.255	0.130	0.010
31	.050	0.150	0.185	0.185	0.230	0.185	0.170	0.003cd	0.110	0.125	0.140	0.180	0.160	0.100
34	.043	0.080	0.080	0.090	0.330	0.160	0.110	0.010cd	0.050	0.040	0.090	0.300	0.140	0.080
37	.050	0.045	0.130	0.110	0.130	.170	0.035	0.004cd	0.015	0.090	0.095	0.110	0.135	0.015
39	.005cu	-	-		.050cd		-	0.003cd				0.050cd		0.010cd
45	.002cu	.008cu	.004cu		.003cu		.002cu	.002cd	0.006cd	0.002cd		0.001cd		0.001cd

cu = chloroform extracted of undistilled sample

cd = chloroform extracted after distilling the sample

TABLE 10.1.6

Run No. 6 Test (east) Filter : No Phenol dosed. (Phenol concentration desorption) Filtration rate = 0.2 m/h

	Residual Phenol* P (mg/l)						P (mg/l) (Control filter)						
Probe	E8	E1	E4	E5	E6	E7	W1	W3	W4	W5	W6	W7	W10
Td \ Di	0	0	5.0	11.0	17.0	u.d.	0	1.0	7.0	13.0	19.0	u.d.	
3	0.010	0.017	0.034	0.026	0.023	0.018	0.043	0.236	-	-	0.531	0.100	0.009
6	0.012	0.021	0.036	0.036	0.018	0.019	0.045	0.130	0.052	0.012	0.270	0.205	0.008
9	0.009	0.006	0.018	0.029	0.016	0.018	0.015	0.063	0.031	0.015	0.070	0.039	0.007
16	0.003	0.016	0.032	0.450	0.050	0.037	0.068	0.210	-	0.026	0.118	0.033	0.006
23	0.006	0.035	0.072	3.2	0.052	0.032	0.086	0.100	0.310	0.107	0.047	0.082	0.012

* Chloroform extraction method

A.W.J. 10.1.7

(Phosphate concentration) Filtration rate = 0.2 m/h

Run Nos. 4, 5, and 6 Control (West) Filter, and Walton Meadows effluent considered.

Td	Run No. 4	
	P µg/l	
	W8	WWO
6	38	58
9	13	32
12	18	18
16	20	22
18	2	18
24	6	15
31	5	14
34	6	4
37	3	7
39	3	5
45	2	21

Td	Run No. 5	
	P µg/l	
	W8	WWO
0	11	20

Td	Run No. 6		
	P µg/l		
	W8	W7	WWO
3	10	100	9
6	12	125	5
9	7	39	7
16	3	33	6
23	5	82	12

CHAPTER XI

DISCUSSION OF RESULTS AND CORRELATION OF BIODEGRADATION

11.1 Discussion on Initial Headloss

The downward movement of water in a slow sand filter is so small that it can safely be considered a laminar flow throughout the bed. For determining the initial headloss when a filter is clean we can use the Kozeny Carman equation.

$$H = \frac{5\mu\, Vf\,(1-f)^2}{\rho g\, f^3}\left(\frac{6}{\delta o}\right)^2 Di \qquad 11.1.1$$

Where H is the headloss

μ is the dynamic viscosity, 10^{-3} Kg/m s at 20 °C

ρ is the mass density of the fluid, 10^3 Kg/m^3

Vf is the approach velocity of filtration, m/s

g is the gravitational acceleration, 9.81 m/s^2

f is the porosity ratio of clean filter bed

δo is the effective diameter of grain of filter sand, m

Di Distance into filter from inlet surface, m.

For 0.2 m/h filtration velocity, 40% porosity, 0.25mm effective size and 0.50m depth of bed.

$$H = \frac{5 \times 10^{-3}}{10^3} \times \frac{0.2}{3600 \times 9.81} \times \frac{(0.6)^2}{(0.4)^3} \times \left(\frac{6}{0.25 \times 10^{-3}}\right)^2 \times 0.5$$

$$= 0.007 \text{ m} \quad (7.81 \text{ mm})$$

Table 11.1.2 shows the actual and theoretical initial headloss for the runs with which relevant data. The Kozeny Carman equation used widely for rapid filters, has failed to produce wholly satisfactory results in this case of slow sand filters. Actual headloss is significantly higher (about twice to four times) than the one based on equation 11.1.1.

The plot runs as shown in Table 11.1.1 show a decreasing initial headloss

TABLE 11.1.1 ACTUAL AND THEORETICAL INITIAL HEADLOSS (H)

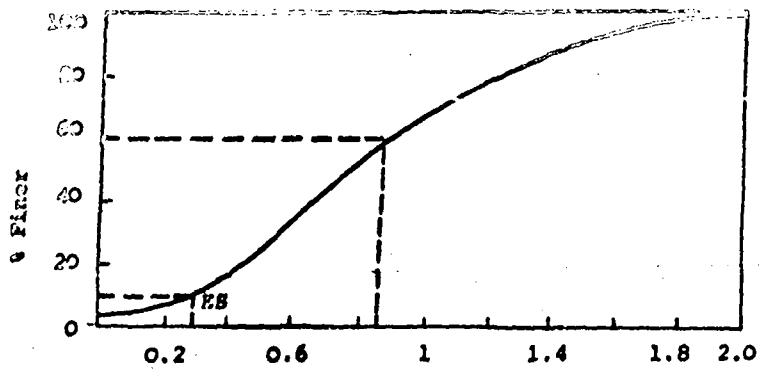
Run No.	Duration Day	From	To	Test Filter			Control Filter			Remarks
				Di inch	H (inch)		Di inch	H (inch)		
					Actual	Theor.		Actual	Theor.	
1	18	21.2.74	11.3.74	19.5	7.5	1.8	21.5	5.0	2.0	Phenol dosed
2	7	18.3.74	25.3.74	19.0	7.0	1.7	21.0	5.5	1.9	Phenol dosed
3	16	6.4.74	22.4.74	18.5	4.8	1.7	20.5	4.4	1.9	Phenol dosed
4	41	27.4.74	10.6.74	18.0	3.1	1.7	20.0	3.0	1.8	No Phenol dosed
5	25	20.6.74	15.7.74	17.5	3.0	1.6	19.5	2.5	1.8	Phenol dosed
6	23	23.7.74	15.8.74	17.0	2.8	1.6	19.0	3.6	1.7	No Phenol dosed
2/71 -73	21	20.5.71	10.6.71	27.5	5.3	2.3	27.5	5.5	2.5	No Phenol dosed
14/71 - 73	26	30.4.73	29.5.73	24.5	8.5	2.2	26.5	5.8	2.4	No Phenol dosed

[illegible] as in the control filter. These were conducted during the [illegible] May to August 1967 covering spring and summer months, which [illegible] the biological activity in the filters and ensuing bolf purification of slow sand filters by degrading the clogged organics in the pores.

The high initial headloss can be discussed from two angles:- If the porosity of the bed is considered 31%, due to some residual clogging material, instead of 40%, then the headloss by equation 11.1.1 is raised to thrice its previous value. So scraping half inch layer for cleaning the bed has not produced the desired result, a thicker layer 1.5cm or even 2.5cm should be [illegible] to produce a cleaner bed thus reducing the initial headloss and lengthening the run. There may also be some silt penetration. The builders sand used in the filters had a high uniformity (or actually non uniformity) coefficient of 3.5, and an effective size 0.25. Graph 11.1.1 shows the effect on sand size distribution with 3.5 U

Graph 11.1.1.

Effective size and Uniformity Coefficient



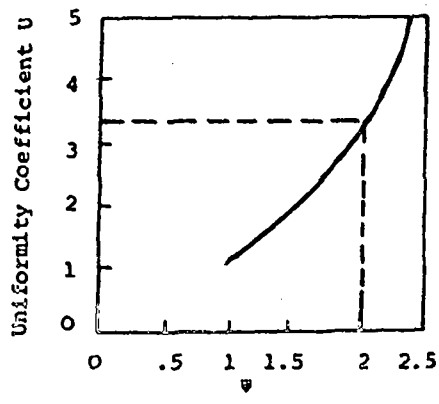
In the grain size distribution there exists a significant fraction of [illegible] grains (>1mm), indicated by the high uniformity coefficient (3.5) - [illegible] Fig. 11.1.1. The presence of these grains mixed into the depth of the filters (bearing in mind that a slow sand filter does not straddle, as does a rapid filter), causes a higher permeability, with consequent possibility of [illegible] in suspension penetrating well into the depth of the sand. This [illegible] the cleanliness of the sand layers below the schmutzdecke.

Graph 11.1.2 showing curve of the ratio Ψ versus uniformity coefficient (U) has been drawn based on formula (Huisman, 1974)

$$D_s = d_e (1 + 2 \log U) = \Psi d_e \qquad 11.1.2$$

Graph 11.1.2.

Uniformity v/s Ψ Curve



where D_s is the specific diameter* of sand grain in mm,

d_e is the effective size of the grain in mm,

U is the uniformity coefficient, and

Ψ is the ratio between the specific diameter and the effective diameter.

* Specific diameter is defined (Huisman, 1974) as the size of an imaginery grain from a uniform sand of which a certain weight has the same gross surface area as an equal weight of the filtering medium under consideration.

In Graph 11.1.2, when the uniformity coefficient is raised from 2.4 to 3.3, the Ψ increases from 1.75 to 2.0 and the value of $(D_s)^2$ increases from 3 to 4, thus affecting k in Darcy's law,

$$H = \frac{Vf}{k} Di \qquad 11.1.3$$

where H is the headloss

Vf is the velocity of filtration,

Di the depth of filter, and

k is a coefficient of permeability

$$k = 150\,(0.72 + 0.023\,T)\,\frac{\varepsilon^3}{(1-\varepsilon)^2}\,\psi^2 D_0^2 \quad m/h \quad \text{(Huisman, 1974)} \qquad 11.1.4$$

The favourable impact expected theoretically did not happen in the slow sand filter, because of the high permeability constant working out to be 8.4 m/h. High permeability is good for the rapid filter but bad for the slow sand filter, as it allows fine particles to escape into the bed, which deposit on the sand surface and remain there for as long as there is no back washing.

In Carman-Kozeny equation (11.1.1), the porosity function is inverted compared to the permeability constant equation (11.1.4), and thus positive variation in ψ has negative effect on the initial headloss, similar to its effect in Darcy's equation (11.1.3).

Initial headloss curves with depth as shown in Graph 9.2.1. are not linear as expected by Carman Kozeny or Darcy's equations, but are exponential, more so for the test filter, indicating progressive clogging of the filter from bottom to top, probably as a result of silt penetration and the bacterial growth, due to higher U^1 and phenol dosing respectively, and inadequate cleaning by surface scraping only.

11.2. Headloss Development in the Filter

Pressure curves (Graphs 9.3.1 - 9.3.8) clearly exhibit an overwhelming build up of headloss in the top 5cm of the slow sand filter, suggesting correspondingly almost entire suspension removal, plus vigorous micro-organism growth, in the top layer. There is no indication of a negative head developing at the end of any of these runs. This can be attributed to ample depth (1.52 m) of water over the filter. Thus a reasonable depth of overlying water has helped in two ways:- firstly in lengthening the filter run by increasing the total energy, and secondly in better phenol degradation by increasing the contact time. It is presumed that the organic matter growing in the sand pores and the organic matter in suspension in raw water is highly compressible and due to the increase in headloss the solids get compressed causing reduced permeability of the bed, especially the top layer.

The curves in graph 9.3.9 are similar to an exponential curve, and the hydraulic gradient curves for the top layer in graphs 9.3.10 - 9.3.17 show almost the entire headloss in the top layer. It is also clear from these graphs that the length of run for the test filter was considerably shorter when the phenol was dosed. Phenol-induced biological activity in the top layer and within the filter caused faster headloss development in

[illegible]. Therefore, it may be concluded that the headloss development in the top layer of a slow sand filter is more of a biological phenomenon and clogging biological growth principles. It is apparent that a totally new correlation for defining the headloss in a slow sand filter is needed to be evolved. Iwasakis (1937) fundamental formulation

$$\frac{dc}{dDi} = -\lambda C \qquad 11.2.1$$

(where C = concentration of suspended particles in volume per volume of water, Di = depth of filter layer, and λ = filter (or impediment) coefficient).

and

$$\frac{dc}{dDi} = -\frac{1}{v}\frac{d\sigma}{dt} \qquad 11.2.2$$

[illegible] σ = specific deposit, and t is the filtration time), even though [illegible]ally based on the slow sand filter, only accounts for the physical [illegible] hydraulic aspects of filtration. The widely used Kozeny Carman (1937) equation

$$\frac{H}{Di} = \frac{5\mu Vf\,(1-f)^2}{\rho g\, f^3}\left(\frac{6}{de}\right)^2$$

and the Rose's (1945) equation do not have a great deal to offer and suffer from the same shortcomings, even though these largely agree with rapid filter headlosses. Even recent mathematical models presented in the [illegible]ation, for example (Ives 1960)

$$\frac{H}{Ho} = \frac{k_1'}{k_1}\,\frac{r_1}{r_o}\,\frac{(1-f+\sigma)^2\, f^3}{(f-\sigma)^3\,(1-f)^2}$$

cannot be applied to the biologically developing headloss in the top layer of slow sand filter.

Accounting of pressure curves in graphs 9.3.1 - 9.3.8 indicates an insignificant amount of headloss development in the rest (below the top 15cm) of the bed. In the hydraulic gradient curves, for layers below the top 15cm in graphs 9.3.10 - 9.3.17, there is actually a tendency towards recovery of head in the middle of the run. As a slow sand filter is not back washed, the intention is that no suspension should penetrate it, and

Therefore, no headloss in the deeper layers, because of suspension in the incoming water should theoretically develop. And the depth of a slow sand bed (below top 15cm) should always be free from clogging and the only headloss occurring there should be the initial headloss. However, the hydraulic gradient curves for lower layers indicate recovery of head in the middle of the run. This phenomenon can be explained by considering the remaining bed as a biological reacter. After scraping the top 1cm layer, when the slow sand filter is started, the schmutzdecke and top 5cm of bed are only partially capable of dealing with organic impurities of water, and thus a part of those impurities penetrate into the bed. This supply of food and oxygen in the beginning of the run activates bacterial growth within the filter, so the slow sand filter becomes a biological reacter with new bacterial growth. The bed is at its peak biologically when these bacteria have adapted and are growing exponentially, usually about 0.2 - 0.5 of the way through the run, and oxidises any organic impurity either coming through the water to be filtered or present in the filter as a result of bacterial metabolism. This growth may proceed beyond the exponential phase, into the endogenous growth phase, leading to depleted bacterial numbers and at that time recovery of head is witnessed. Near the end of the run, schmutzdecke itself takes care of most of the incoming impurities and the bacteria within the filter are starved of normal food and oxygen, thus dying out and getting dislodged and maintaining the recovery of head. Thus, the kinetics of purification within a slow sand filter are quite dissmilar to that of a rapid filter.

Thus, a slow sand filter can be divided into three regimes from the headloss development point of view. The top 5cm, between top 5cm and 15cm, and the rest of the bed. In the top 5cm, the rate of headloss development is very fast, exponential with time and is highly affected by temperature and organic contnet of incoming water. In the middle zone (below 5cm but above 15cm of the bed), there is development of headloss at a much slower rate, it is nearly exponential. The third zone, that is the rest of the bed (below the top 15cm) maintains more or less constant porosity, as the biological effect is self adjusting, self cleansing. The headloss development in the third zone is significant only when there is great fluctuation in the organic contnet of the incoming water.

Foltman and Wachs (1970) experimented on filtering Chlorella through 3m deep dune sand at Vf 0.04 to 0.25 m/h. Sand size was not given, but based on permeability rate of 27.3 to 37.5 m/day, the dune sand decalculates to be around 0.2mm. The experiments approximated to slow sand filtration, though these were not identified as such. Rapid filter theory did not fit their results as such, but it adequately described the results when

modified to allow for an exponential headloss rate with time in the surface layer, and may be useful in formulating a mathematical theory.

Vloed has described the biological purification in terms of autotrophe zone and heterotrophe zone; Huisman in terms of upper layer and lower layer, but this view has not been expressed by either Huisman (1974) or Vloed (1955), who have dwelt on using the existing mathematical models appropriate for rapid filters. The nearest chord, in the form of a protest is struck by Ridley (1967) who doubted if living algal cells could be regarded as merely particles, and fitted into hydrodynamic equations.

11.3. Turbidity Penetration

For measuring particle concentrations in water before, during and after the filtration, several techniques like radioactive tracers (Stanley 1955, Ives 1962), chemical constituent measurements (Mohanka 1969, Miller 1971) and the organic particle penetration (Folkman et al 1970) have been tried, but the most natural and practical is the turbidity measurement, especially after the introduction of quick (90° scattered light nephelometer) and fine turbidity measuring (0.01 FTU) Hach turbidimeter (Jeffery 1971), based on formazin standard (FTU) proved to be the most satisfactory of the artificial standard (Ives et al 1968). Turbidity in a water supply source must be considered from the poit of view of discharges of industrial wastes, and growths of micro-organisms in addition to the normal clay and silt.

The rise in turbidity of overlying water by 44% in the test filter and by 39% in the control filter can be attributed to the growth of algae and other biological growths, which is a normal phenomenon in the open filter tanks in the presence of sunlight. Some of the turbidity may be due to the increased growth of phenol degrading bacteria. The growth of algae contributes to the increase of turbidity, but the increase of turbidity should check the growth of algae by cutting the penetration of sunlight in the overlying water. One interesting result that may be deduced is that there is no significant effect of the phenol on the algae growth of the test filter, even though there is 49% phenol degradation there.

Graphs (9.6.1 - 9.6.6, 9.5.1 - 9.5.8., 9.4.1.- 9.4.8) show substantial turbidity removal (by about half) in the schmutzdecke and the top layer. Also, in the same zone graphs (10.1.1 - 10.1.4, 10.2.1 - 10.2.4) show a great deal of phenol removal (87% of the residual incoming phenol). Therefore, contact time between incoming solids and this vital

[illegible] (schmutzdecke and the top 5cm of slow sand filter bed) is of great significance. In terms of filtration velocity, influents with higher total solids (especially organic solids) can be treated equally well by lowering the filtration velocity and increasing the corresponding contact time (or the residence time). In terms of sand characteristics, sand with higher 'de' (equivalent diameter) will provide a greater permeability, enabling the deeper penetration of micro-organisms which form the schmutzdecke in the top layer of the filter, resulting in higher contact time, but this will cause permanent damage to the cleanliness of the rest of the filter resulting in higher initial headloss. The variation of 'U' should not significantly affect the porosity or headloss, as according to the observation of Allen Hazen (1892) (quoted in Fair et al, p.665, 1959), the resistance to the passage of water offered by a bed of sand within which the grains are distributed homogeneously remains almost the same, irrespective of size variation (up to a U of about 5.0), provided that the 'de' remains unchanged.

These graphs also suggest a continual filtrate improvement with depth, indicating that the whole bed is active for turbidity removal. This behaviour of the slow sand filter is interesting when compared with the biological pattern of the filters. While there is insignificant biological development in the rest of the bed, there is distinct turbidity removal within the same depth of bed, which can be attributed to the biological purification of a slow sand filter in degrading the turbidity-causing particle.

To check the distribution of removals and the variation of filtrate turbidity along the depth of bed, curves for the test and control filters are drawn in graphs (9.4.1 - 9.4.8). From these graphs it is observed that the effluent contained little or insignificant turbidity almost from the start of the filter run. The turbidity of incoming water varied between 1.4 FTU and 0.44 FTU, and that of the effluent between 0.8 FTU and 0.03 FTU. So it may be concluded that the turbidity of incoming water is very low, and probably consisting of very fine particles, bearing in mind that it has passed through coarse primary filtration. It may be argued that the sand size in the slow sand filter should not normally be finer than necessary to avoid unduly short filter runs, and the margin of safety obtained by increasing the bed thickness rather than decrease 'de'. This may even seem more logical for clear incoming water to be able to filter fast. But in such clear raw waters, the great majority of turbid particles would be colloids and very fine suspended particles, which would penetrate deep into the bed causing clogging of the entire bed, and making surface scraping ineffective as a cleaning procedure, and therefore, the

necessity of using finer grained medium than is strictly necessary may not be undermined. However, the evidence that a part of the colloidal impurity is removed in the slow sand filter can be attributed not only to the interfacial forces which are present, but also the gelatinous surfaces of the bacteria and biological growths within the filter, phenomena which are evident in coagulation and responsible for removing dissolved colour and colloidal turbididty.

Graphs (9.4.1 - 9.4.8) show better clarification in the test filter. This can be attributed to the increased bacterial activity due to phenol dosing. The enhanced biological activity within the filter was able to degrade the suspended organics more extensively, and led to the removal of inorganic colloids and fine suspensions by the interfacial forces and to mineralisation. Thus the chemical constituents of the incoming water have an important direct bearing on the clarification, and the length of the run due to the level of biological activity in the slow sand filter. This is a strong reason for the inappropriateness of mathematical models which do not take into account the concentration and proportion of organic constituent of the incoming water, for the determination of headloss development in the slow sand filter. Considering the analogy of trickling filters, the liquid there is only 20 - 30 seconds in contact with micro-organisms to bring about biogradation of the dissolved, colloidal and the suspended organic impurities in the waste water. In a slow sand filter, the total number of organisms are comparatively much smaller but the contact time is much longer (about 100 times) for bringing about adsorption and stabilisation, the maximum rate of stabilisation occurring at the micro-organism/liquid interface since diffusion of organics through the biological film is slow.

Most of the curves in graphs (9.5.1 - 9.5.8) can be interpreted as 'V' shaped curves, more so in the case of test filter, indicating better clarification in the first and the last quarter of the run. The same trend of lower turbidity gradient during the middle period of the run is evidenced in the layer turbidity gradient curves of graphs (9.6.1 - 9.6.6). It is most interesting to mention here the discussion of section 10.1 where it was seen that the best degradation of phenol was achieved in the middle period of the run. Section 10.2 dealing with phenol degradation with time also outlines a better phenol degradation during the first three fourths of the run. Additionally, when scrutinising the headloss curves in graphs (9.3.1 - 9.3.8, 9.3.10 - 9.3.17), it is of great interest to find the recovery of head in the bottom layers of the filter with the progress of the run time (Section 9.3).

Combining these findings together from three directions of the headloss, the turbidity removal, and the phenol degradation, it emerges that the maximum phenol degradation takes place in the middle of the run, because there is maximum level of bacteria and biological growth within the filter at that time , and there is recovery of head with corresponding deterioration of effluent turbidity due to dislodging of bacteria and its metabolic products due to shortage of oxygen and other bacterial food. This view is further strengthened by the results of increased turbidity in the bottom most layer and by the shortening of the dosed runs in the test filter with corresponding increase in the effluent turbidity. The turbidity increase of effluent in a slow sand filter at times is similar to the effect in a trickling filter, wherein fairly high concentration of suspended solids in the form of displaced biological film appears in the effluent, requiring sedimentation. In the end it may be summed up that turbidity removal and phenol degradation are good attributes of slow sand filtration.

11.4 Phenol Degradation

The microflora and microfauna in a slow sand filter, biodegrade the phenol and other organic compounds in solution, into simple salts, water and carbon dioxide, while using the chemical compounds as nutrients for cell growth or as source of energy. It has not been proved that pure cultures of members of the Pseudomonas and Achromobacter and some other groups, utilise phenol as the sole carbon source (Tabak et al, 1964; Davey and Turner, 1961; Czeknlowski and Skargynski, 1948). Some other genera such as Bacillus, Micrococcus, Alcaligenes, Streptococcus and Flavobacterium who also colonise slow sand filters have been identified as phenolics-consuming (Shoots et al 1954, Lynn, Powers, 1955). Recently the Water Pollution Research Laboratories (Jones and Carrington, 1972) and the Metropolitan Water Board (Windle Taylor, 1971 - 73) have reported encouraging results on degradation of phenols by mixed cultures.

The phenol degradation results for the present work are shown in graphs (10.1.1 - 10.1.4, 10.2.1 - 10.2.4).

The acclimatisation period of ten days was longer than expected, for satisfactory removal of 10 mg/l phenol. About 65% of the phenol dosed at 2.5 mg/l was removed after 4 days. Phenol removal started almost immediately after application, and therefore relatively low concentrations (<1 mg/l) of phenols expected in a slow sand filter should be removed on the first application. However, a model rapid filter inoculated with a

[illegible] of Pseudomonas species took 1½ days to bring down the effluent level of phenol to 1 µg/l or below, from influent concentration 10 µg/l (Cleasby, 1959). The poor performance of this filter in the initial stages can be attributed to the inadequate contact period at the filtration rate of 4.5 m/h (2 gal/ft^2 - min).

In an acclimatised run 96a of a phenol dose of 10 mg/l was removed (at 20 °C) at a filtration rate of 0.2 m/h. At 0.2 m/h of filtration rate it was not possible to degrade phenol completely, so for effective degradation of such high doses of phenol in the influent, a lower rate of filtration must be used. In most of the runs, a state of instability occurred in the latter half of the run, and the phenol concentration would fall below its previous level, presumably either due to variations of phenol utilising bacteria in the filter, or resulting from differences in rate of oxidation of phenol due to the lower concentration of phenol. This behaviour of mixed culture bacteria is in contrast to that of pure culture bacteria. The results compare well with those of Dow Chemical's pilot scale activated sludge treatment plant (Lynn and Pojasek, 1955), which achieved 99.76% phenol removal in influent with 2.6 mg/l phenol (at [illegible] days of detention).

It is expected that for well adapted species of bacteria, the biochemical oxygen demand is 2 mg/l for every 1 mg/l of phenol concentration (Nicholson and Gellman, 1951). Based on the results of residual phenol, an average of 7 percent of phenol dose was going to the bed after the schmutzdecke (and top 5cm bed). So on an average there was a demand load of oxygen by about 1.5 mg/l of oxygen, in the bed. It can also be assumed that higher concentration of phenol could be transfered to the bed at times intermittently causing larger oxygen demand, resulting in anerobic conditions in the bottom layer of the bed. Even though the biochemical oxygen demand of the bed was not determined specifically, there was no evidence of aseptic conditions in the bed.

Rate of degradation per hour, and the real progress of degradation with cumulative contact time, in the pilot filter, have been shown in graph 11.3.3. The rate constants k_t, k_0 and k_b in the three regions of [illegible], as evaluated later in Section 11.4 for the degradation equation, have been utilised

Kinetics of Degradation

The inherent source of organic matter in a slow sand filter system are the waste organic substances that find their way into inflowing water, and the organisms themselves, in their metabolic cycle, that make the

matter and the bed itself their habitat. The organisms utilise organic matter and their mineral portions as a source of energy through a series of biochemical reactions. Specific enzymes, which are large protein molecules and produced by the living cells, synthesise organic matter into living cells and eventually to a more stable mineral level. The organisms convert the organic nitrogen, into ammonia nitrogen initially, into nitrite nitrogen afterwards and finally into nitrate nitrogen, and this progression is capable of chemical determination. Oxygen dissolved in water, or released by aquatic plants during photosynthesis is used by the organisms for respiration, during the process of decomposition. In the first stage of aerobic decomposition, which is applicable to phenol degradation, largely carbonaceous matter is oxidised, and the amount of BOD exerted in a unit of time relative to the remaining to be exerted, is substantially constant (Fair and Geyer, 1959) and appears to be sufficiently constant to be generalised in mathematical terms.

Formulation of the Degradation Equation

The phenol degradation reaction in a slow process like aeration, BOD removal, disinfection and sludge digestion, and the reaction kinetics are time dependent operations varying with conditions. In the type equation $\phi dc/dt = k\phi(R)$ for reaction kinetics, c represents the concentration of the material of interest, $\phi(R)$ is some function of the concentration of the substances concerned in the reaction, and k the specific reaction rate constant, is independent of the substances covered by $\phi(R)$, but may depend on temperature, time and other factors. Simple rate processes can be classified according to the mathematical order of this differential rate equation. The phenol degradation reaction in a slow sand filter is a complex consecutive reaction where the rate of reaction is largely independent of the concentration of phenol, within the limits of usual influent concentrations and therefore it can be considered that phenol does not participate in the rate determining step, thus the rate of phenol degradation is independent of the concentration of phenol in water. The phenol degradation reaction can also be interpreted as a first order reaction, dependent on the contact time, but independent of phenol concentrations (but not more than 10 mg/l usually), similar to the first stage BOD curve, or similar to the basic law of Velz (1948) for biological filters, who assumed depth of medium as the time function, and formulated sewage purification mathematically in terms of 1st order kinetics. First order kinetics have been subsequently used successfully (Eden, 1964), relating fraction of remaining BOD to the liquid residence time,

As the phenol degradation is a time dependent slow reaction, the contact time is of fundamental consideration. Moreover, rate of filtration, depth of overlying water in the filter tank, and the depth of filter bed could all be interpreted in terms of contact time. Contact time implies that there is no rate limiting step set up by phenol diffusion at the bacterial-water interface. The degradation rates in water, schmutzdecke and the filter bed are different, presumably because of the bacterial population concentrations. Different rates are also expected because some bacteria are fixed on sand surfaces and some are free in the water, whereas sand particles provide a good surface to which the bacteria can attach and grow.

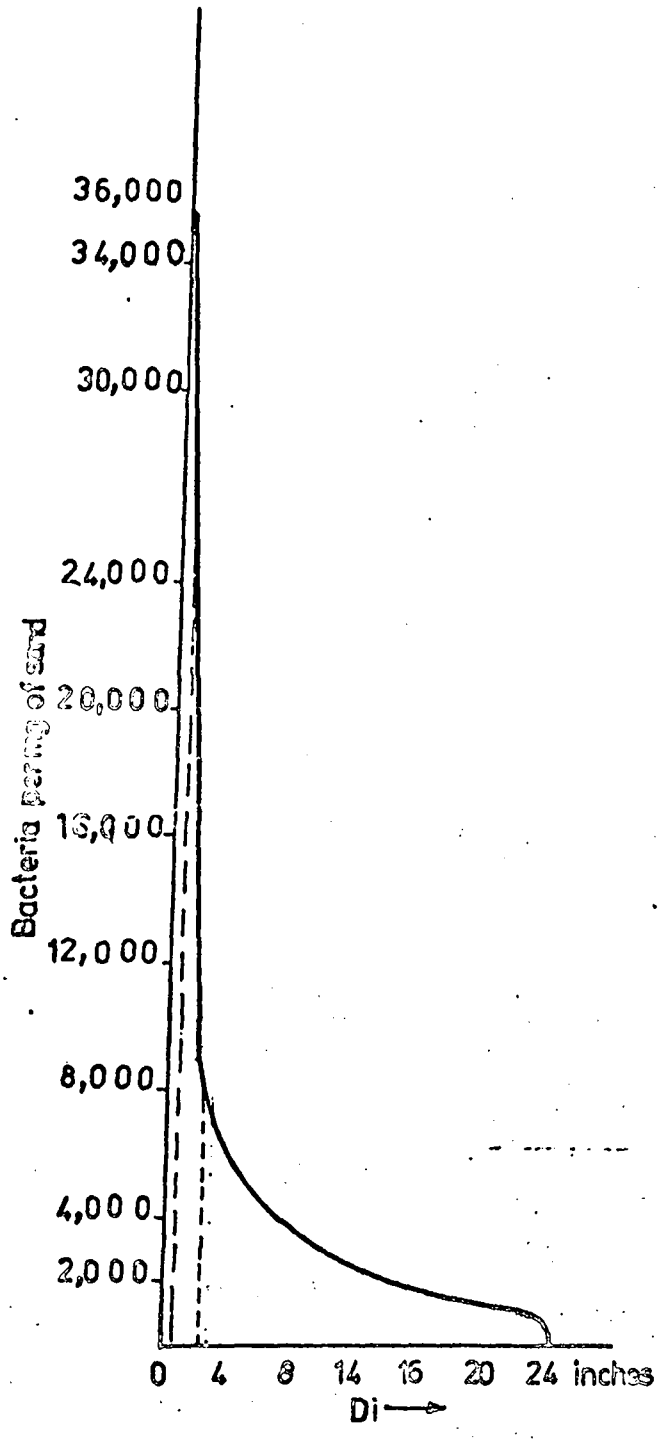
In the formulation of the degradation equation it is desirable to consider the overlying water also, as suggested by the results. In the aeration tank of an activated sludge treatment plant, 39% of the bacteria were known to degrade phenol (Lynn and Powers, 1955). In view of the results on the phenol removal, and the headloss development in the top layer of the filter bed, top of the bed up to 5cm depth has been considered [illegible] with schmutzdecke for finding out the contact time in schmutzdecke. [illegible] is highly supported by the very heavy concentration (about [illegible]) of the bacteria in the top 5cm of bed, and then quickly decreasing with depth below that level, as is clear from graph 11.4.1., based on table 11.4.1.

TABLE 11.4.1

BACTERIA CONCENTRATION VERSUS DEPTH (bacteria per milligram of sand)

Depth Di	Run No. 4*	Run No. 5*	Run No. 6*	Average
0" - 1"	38,000	38,000	24,000	33,500
2" - 3"	22,000	35,000	16,500	24,500
10"	3,400	2,900	2,300	2,900
17"	2,500	1,300	1,100	1,600
23"	1,000	900	700	1,200

Based on Cavalier, 1969. (* his run numbers)



GRAPH 11.4.1
(Table 11.4.1)

Bacteria Concentration V/S Filter Depth Curve

The following pages are devoted in establishing quantitative relationships between the principal variables and observed performances, as experienced on the pilot experimental filter. It is believed that the probable relationship, even though based on the performance of phenol, could be advantageously used for the performance of normal organic impurities coming across a slow sand filter.

Degradation Equation

The Degradation Equation can be considered a balance equation, therefore,

Total removal = removal (tank) + removal (schmutzdecke) + removal (depth)
= removal (tank) + residual x removal rate (schmutz)
+ residual x removal rate (depth).
= input x rate (tank) + residual (schmutz) + residual x rate (bed depth).

$$P_o - P = P_o\left[dt\,Ht + ds\,Hs\,(1 - dt\,Ht) + db\,Hb\,(1 - \{dt\,Ht + ds\,Hs(1 - dt\,Ht)\})\right] \qquad 11.4.1$$

$$\text{or} \quad P_o - P = P_o\left[X + Y\,(1 - X) + Z\,(1 - \{X + Y\,(1 - X)\})\right] \qquad 11.4.2$$

$$= P_o\left[X + Y\,(1 - X) + Z\{1 - (X + Y - XY)\}\right]$$

$$= P_o\{X + Y\,(1 - X) + Z\,(1 - X - Y + XY)\}$$

$$= P_o\,(X + Y - XY + Z - ZX - YZ + XYZ)$$

$$\text{or} \quad \frac{P_o - P}{P_o} = X + Y + Z - (XY + YZ + ZX) + XYZ \qquad 11.4.3$$

Equation 11.4.3 could be further derived to another form,

$$1 - \frac{P}{P_o} = X + Y + Z - (XY + YZ + ZX) + XYZ$$

or $P/P_o = -(X + Y + Z - XY - YZ - ZX + XYZ - 1)$

or $P/P_o = 1 - Z - Y + YZ - X + XZ + XY - XYZ$

or $P/P_o = (1 - X)(1 - Z - Y + YZ)$

or $P/P_o = (1 - X)(1 - Y)(1 - Z)$ 11.4.4

where P_o = Phenol concentration at the inlet (E8)

P = Phenol concnetration at the effluent (E6)

X = dt Ht

Y = ds Hs

Z = db Hb

dt = Degradation rate constant in the top water, determined empirically, 0.065 h^{-1}

Ht = Contact (or detention) time in hour in the top water

ds = Degradation rate in schmutzdecke and top .05m bed, constant determined empirically = 8.66 h^{-1}

Hs = Contact time in hour in schmutzdecke and top 5 cm bed

db = Degradation rate constant in the (rest of) depth of sand bed, determined empirically, 0.58 h^{-1}

Hb = Contact time in hour in the depth of (rest of) filter bed

Using above degradation rate constants, equation 11.4.4 could also be written as,

$P/P_o = (1 - 0.065\ Ht)(1 - 8.66\ Hs)(1 - 0.58\ Hb)$ 11.4.5

Calculate dt, ds and db (Reference Tables 10.1.1 - 10.1.4)

dt : Average residual phenol (%) at E1(or E2)

$$= \frac{759.00}{15} = 50.6\%$$

Average degradation in filter tank

$$= 100 - 50.6 = 49.4\%$$

Ht = 7.6 hr (1.52 m @ 0.2 m/hr)

$$dt = \frac{49.4}{7.6} = 6.5\% \text{ or } 0.065\ h^{-1}$$

ds : Average residual phenol at E3(or E4)

$$= \frac{67.88}{10} = 6.79\%$$

Average degradation in top 5 cm bed (including schmutzdecke) 50.6 - 6.79

$$= 43.81\% \text{ (if } P_o) \text{ or } \frac{43.81}{50.6} = 86.58\%$$

Hs = 0.1 hr (Di = .05 m, f = 40%, Q = 0.2 m hr^{-1})

$$ds = \frac{86.58}{.1} = 865.8\% \sim 8.66\ h^{-1}$$

db : Average residual phenol at E6,

$$= \frac{33.28}{9} = 3.69\%$$

Average degradation in the rest of filter

$$= 6.79 - 3.69 = 3.10\%$$

$$\text{or } \frac{3.10}{6.79} = 46\%$$

$$Hb = \frac{0.4}{0.5} = 0.8 \text{ hr} \quad (Db = 0.45 - .05 = .40 \text{ m}, \ f = 40\%)$$

$$db = \frac{46}{0.8} = 57.5\% = 0.575 \sim 0.58\ h^{-1}$$

Example 11.4.1

Total Phenol Removed,

Q = (.05 to .35 m/h) T = 20 °C, Dw = 1.52 m, Db = 0.45 m,

dt = 0.065 h^{-1}, ds = 8.66 h^{-1}, db = 0.58 h^{-1}

Using equation 11.4.4,

$P/P_o = (1 - X)(1 - Y)(1 - Z)$

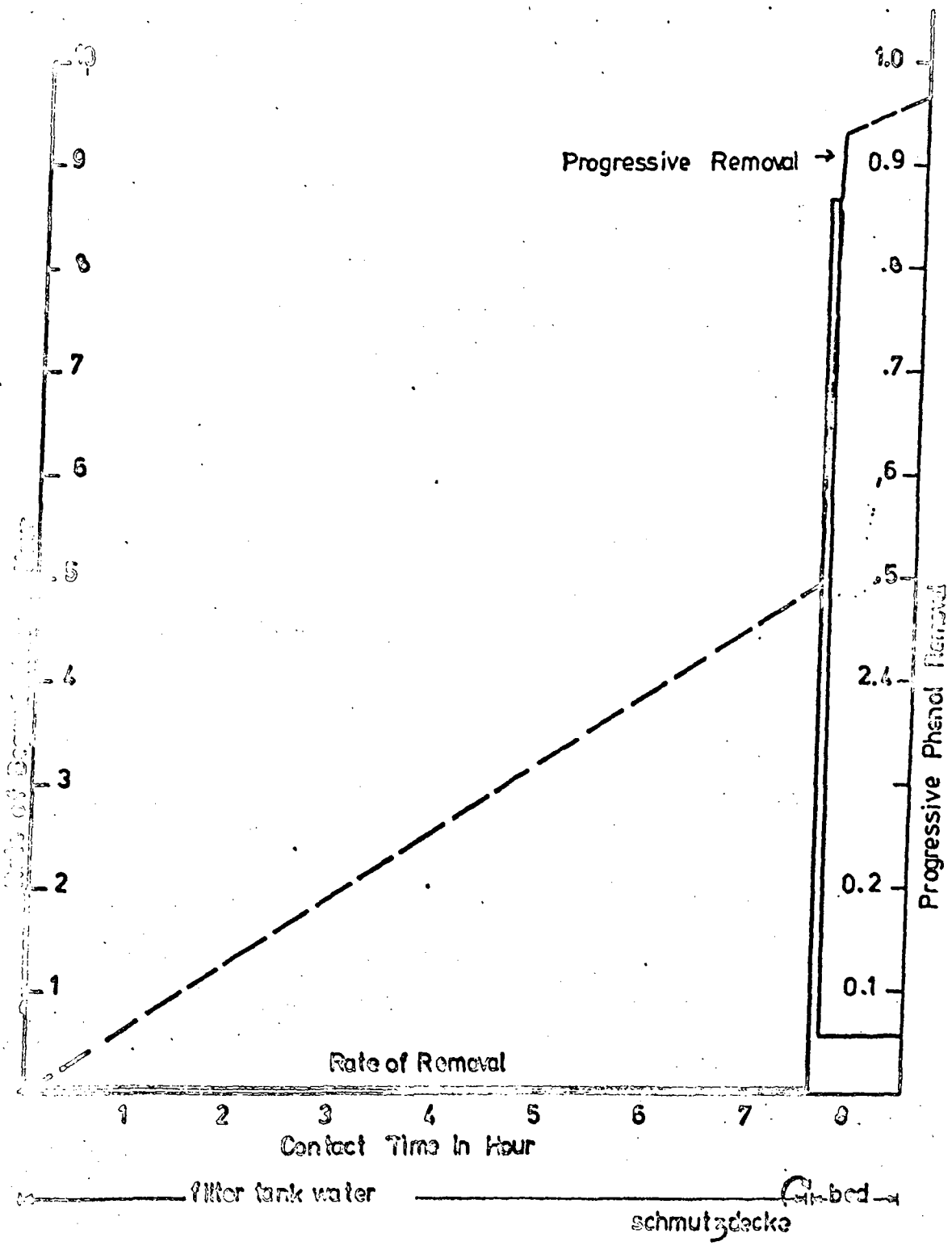
Q m/h	Ht hr	Hs hr	Hb hr	X	Y	Z	P/P_o	$\frac{P_o - P}{P_o}$
0.05	20.4	0.4	3.2	1.976	3.464	1.856	-2.058	3.058
0.1	15.2	0.2	1.6	.988	1.732	.928	-.001	1.001
0.15	10.133	0.133	1.067	.659	1.152	.619	(-).020	1.020
0.20	7.6	0.1	0.8	.494	0.866	.464	.036	.964
0.25	6.08	0.08	0.64	.395	.693	.371	.116	.884
0.30	5.067	0.067	0.533	.329	.580	.309	.195	.805
0.35	4.343	0.057	0.457	.282	.494	.265	.267	.733

Temperature Effect

No attempt was made to evaluate the complete temperature effect on phenol degradation in view of the difficulty of maintaining temperature control on open pilot filters. The following discussion is useful when trying to correlate degradation with temperature.

With the increase in temperature, the rates of reaction dt, ds and db, and the resultant total phenol removal should increase. A very approximate rule, (Vant Hoff Arrhenius) accepted in connection with BOD measurement is that the rate doubles for each rise in temperature of 10 °C, expressed in mathematical terms as

$$k/k_o = 1 + Ck\ (T - T_o) \qquad 11.4.6$$



GRAPH 11.42
Phenol Removal Kinetics

(where T is the temperature and the subscript zero denotes the reference value of k, the rate constant). From about 15 to 30 °C, the values of Ck = .046 per degree C. (Fair and Geyer, 1959).

Another approximate rule is that biological oxidizability of polluted water increases in the vicinity of 20 °C by about 2% for each degree Centigrade (Theriault, 1927).

In a recent study, for the 10 °F difference in temperature, the times required to yield a suitable phenol free effluent varied by a factor of 4 (Cavalier, 1969).

Well known Streeter and Phelps (1925) empirical relationship, $K_T = K_{20}\, C^{(T-20)}$ could be considered to be used where K_T and K_{20} are values of rate constant at T and 20 °C, and C a temperature coefficient for biological filters.

Limitations

The degradation equation is used for finding the total phenol removal in the slow sand filter for the various rates of flow. It is also applicable to various depths, of the filter bed, and those of overlying water in the filter tank, or for determining the effect of these parameters in different combinations.

The degradation equation is however limited in application to the extent, when X or Y or Z is less than unity. When the product X is more than one, total degradation is expected to occur in the filter tank water. When the product Y is more than one, schmutzdecke (with 5cm of bed top) alone is indicative of total phenol removal capability. Similarly, more than unity product Z, suggests complete degradation in the depth of filter bed itself. The degradation equation is usable for the normal probable rises in future rates of slow sand filtration.

The test results exhibit some fluctuations in the values of dt, ds and db on different days of the run. There is no clear trend of fluctuation; and the rate constants based on mean magnitude, have been considered good enough for use in the degradation equation. Another complication noticed is state of inadequate flora and fauna to activate degradation in less mature filters in the beginning, and a lag period occurring during acclimatination phase of the filter for a particular concentration of the phenol. In some instances the value of dt, ds and db, diminish as the percentage of degradation increases, probably resulting from different rates as discussed previously in this section..

11.3 Phenol Measurement in Undosed Runs

Based on the analysis (Section 10.3) of graphs (10.3.1 - 10.3.5) for the runs immediately following the dosed runs, there was evidence of substantial levels of phenol (around .01 to .5 mg/l) in the test filter samples, and low but unwelcome levels (around .005 - 0.1 mg/l) of phenol in the samples from the control filter. In these runs, phenol was measured in the overlying tank water and in every layer of the test filter bed. It is also seen that the samples from valve E5 (6" above the bottom and about 14" below the top), contained the maximum phenol concentration in the bed, and this was the level which also caused maximum phenol degradation during the dosed runs. The reason for the appearance of phenol in the filter water samples, when none was dosed is not truly known. It may be that adsorption of phenol on sand grains took place while dosed, which was desorbed later. There is now good evidence in this respect for activated carbon (Pahl et al, 1973, Knickmeyer et al, 1973), and that Tebbutt (1971) has described the process of degradation of colloidal and soluble organics in a trickling filter, in terms of desorption and [illegible]. However, there is no evidence in the literature that sand [illegible], or silica surfaces have any adsorptive-desorptive properties for organic molecules such as phenol. It appears that the kinetics of phenol leaching are complex. It is possible that a part of the phenol solution which diffuses into the biological cell remains unutilised and reappears along with the biological cell as phenol. It is also possible that algae and the filter bacteria are transforming some other chemical constituent into hydroquinones or some phenol derivatives, which register as phenol in the determination. Or it could just be a case of decomposing cell leaching out plant phenol. The well-established 4-aminoantipyrine colorimetric method used by Ettinger et al (1951) and described as a classic technique by Baird (1974), is not without short comings. This procedure along with phenol, determines also, the ortho- and metasubstituted phenols and under proper PH conditions, those parasubstituted phenols in which the substitution is a carbonyl, halogen, methoxyl, or sulphonic acid group (Taras et al 1971). Formerly, to overcome this difficulty, GLC (gas liquid chromatography) technique was studied, compared (Baker 1966), reviewed extensively (Baker and Malo 1967), and used recently (Baird 1974). It was shown that the GLC technique was effective in identifying phenolic material isomers except m and p chlorophenol. But GLC is useful only for concentrations of phenol higher than 1 mg/l, and for fine phenol determinations (1 µg/l), 4 aminoantipyrine chloroform extraction procedure still appears to be the best in spite of its imperfections.

In conventional water coagulation treatment it is claimed that because of their spongy nature, floc particles have a very large surface area, capable of adsorption of dissolved matter from solution (Tebbutt 1971). Extending this theme into the slow sand filtration, it can be argued that the spongy nature of slimes, bacteria and other biological growths, over and within the filter adsorbed phenol while dosed, in addition to the probable overwhelming diffusion and its use by the bacteria for energy extraction, and desorbed it immediately afterwards during undosed run.

Phenol Presence in the Control Filters

The discussion in the latter part of section 10.3, based on the interpretation of graph (10.3.5), shows the production of phenol in the control filter. Considering that the working of the control filter was similar to that of the normal Walton Works slow sand filters, the detection of phenol in their effluents is intriguing and very interesting. There is evidence that decay of plant organic matter can cause significant concentration of phenolics in water. The Williamsburg-Penn Joint Water Authority has repeatedly found the characteristic medicinal odour of phenol after a heavy run off from rainfall. There are no industrial wastes entering the reservoir and the usual phenol concentration in the reservoir on the Allegheny river shed was 0 to 6 μg/l (Hoak 1960). Hoak also suspected the presence of tannins yielding phenols due to biochemical decay, and mentioned the Mellon Institute study, where oak leaves suspended in river water produced 1250 μ g/l phenol in 10 days. At Beaver Falls water treatment plant in Pennsylvania, phenol was persistently detected for all 197 days in the concentration range of 0 - about 100 μ g/l (Kinney 1960). Unfortunately, neither Kinney nor Hoak mentioned the method of phenol determination used, and did not differentiate between various phenols, quinones, etc.

The presence of a higher concentration of phenol in the effluent of the pilot control filter compared with that of the influent (graph 10.3.5) suggests production of phenol in the slow sand filters, or the production of a compound registering as phenol in the determination. The reasons for phenol production have already been discussed in this section earlier. Although quinones and hydroquinones are also reported to form on the surfaces of activated carbon (Rulim, 1974), this does not appear to account for any similar formation on biological surfaces on sand.

Recently the topic of plant phenolics has gained so much importance that a full book, 'The Biology of Plant Phenolics', by J.B.L. Walker, in

scheduled to be printed in 1975, by the Institute of Biology (Mellanby 1974).

Phenol Standard as a Parameter of Water Quality

Inspection of graph (10.3.5) and the foregoing discussion in this section indicate the concentration of phenol, in the effluents of test control filter (and possibly the main Walton Works effluent) in terms of tens of micrograms per litre, as against the International and European standards (WHO 1971, 1970) of 1 g/l, with no apparent evidence of undesirable taste and odour in the Metropolitan Water Boards water supply. This may be regarded as enough cause for introspection about the basis of this standard.

A limit of 1 g/l of phenol in drinking waters was set in 1946, because extremely low concentrations tended to react adversly with chlorine to form odorous components (U.S. 1962). The concentrations harmful to health are many times more than those which impart taste or odour. It was reported (Heller 1938) that 15 - 1000 mg/l of phenol had no observable effect on rats for extended periods. Up to 5000 mg/l concentration exerted no effect on their digestion, absorption or metabolism. However, 7000 mg/l caused still births. 1 mg/l was reported not to seriously affect most fish. The standard was set, not because of its ill effect on health, but due to a criterion established for aesthetic purposes. This does not appear to be based on strong evidence from literature. According to the Standard Methods (Taras et al 1971) chlorination of water supplies containing traces of phenols, may produce odoriferous and objectional tasting chlorophenols, like O-chlorophenol, p-chlorophenol, 2, 6, dichlorophenol, and 2, 4, dichlorophenol, and in phenol detection, phenol itself has been selected as a standard, and any colour produced by the reaction of other phenolic compounds is reported as phenol. The methods for determining phenols have been described as being among the most sensitive organic analyses available (Burttscholl et al 1953). The low limit has been justified in trying to avoid unpleasant tastes in chlorinated waters, and with a view that some phenolic compounds are capable of being toxic when ingested over a long period of time (WHO 1970). However, a year later (WHO 1971) described phenol as not constituting a hazard to health of the users, but its presence affecting acceptability for domestic supply. It appears that serious difficulty has been experienced in the determination of low phenol concentrations, and due to dissatisfaction with the acceptable methods, new techniques have been tried (Afghan et al 1974, Fountaine et al 1974).

It emerges from the foregoing discussion that not too strong evidence is available for the justification of such a low phenol concentration standard in drinking water. There is also an element of unreliability in its determination, and it is likely that many treatment works are already disregarding the allowable limits. There is a strong case for revising the phenol standards upwards, especially in view of the decision taken by the Technical Review Committee of the 1970 EPA (Environmental Protection Agency, USA) in dropping phenols from the standards, due to practical difficulty in analytical methods experienced by most water works.

11.6 Uprating the Slow Sand Filter

The turbidity removal results for the test and control filters have been presented in section 9.4 and discussed in section 11.3. A detailed study, of the several efforts made to improve the rate of slow sand filtration has been described earlier in Chapter 6, which reviews both sides of the argument.

Based on the results of test and control filters for the successful removal of turbidity (comparable to the main Walton Works effluent), and the substantial level of phenol degradation (96% degradation, of 10 mg/l phenol concentration, at 0.2 m/h filtration), it is felt that wherever influent turbidity is between 1 to 5 mg/l silica scale, a filtration rate of 0.2 m/h could be safely employed in the slow sand filters, with scope for even further uprating.

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CHAPTER XII

PRACTICAL APPLICATION AND CONCLUSIONS

12.1. Practical Application of This Research

This research having considered the processes and rates within slow sand filters is useful in justifying their applicability to three situations: rural communities, for developing towns and metropolitan cities. In addition it is useful when considering uprating and purifying organically polluted influent. It also contributes to the problem of a phenol stanard in drinking water, as explained later in this section.

Rural Communities

The rural scene has been considered for India, where except for 1.7% towns and cities (more than 5,000 and 100,000 population respectively), and the most of the communities, numbering over half a million are villages, with an average population of 900, needing a slow sand filter area of only 19 m^2 (at a filtration rate of 0.1 m/h, and 50 litres/cap/day consumption). So, for water filtration capcity design, in all cases for a village, and in great majority of the cases for a group of villages, it will not be the rate of filtration, but factors like the availability and the minimum size of a slow sand filter that will crucially affect the decision. The slow sand filter has been proved inherently suitable for reducing bacterial numbers, and is simple in operation and design. The recent strong doubts on the ability of chlorine to completely deactivate the hepatitis virus and the polio virus (Weber 1972, Shah et al 1972), and the doubtful proposition of using chlorination apparatus economically in a village, may be regarded sufficient reason to place more responsibility on filtration. The slow sand filter with proven record for dealing with bacteria efficiently, therefore, becomes an extremely attractive choice for rural areas based on reliability and simplicity.

Developing Towns

Recently, especially after the 1973 oil crisis, the concept of the

conservation of resources has developed. While addressing a gathering of engineers, on a British point of view of education and training of engineers, Prof. Coates (1974) emphasised the urgent need to find means of making bigger engineering systems which are more economical in the use of raw materials and natural resources. Bearing this in mind, it can be emphasised that the slow sand filter does not require chemicals, so that by avoiding coagulation processes, energy is saved due to less ultimate headloss, much less wash water is wasted, only 0.4% of the filtered water compared to 4.0% for a rapid filter (Fair et al 1959), less equipment and machinery is used, and better disinfection can be achieved with less chlorine (Huisman 1974). In the context of supplying potable water to towns in developing countries, in addition to savings on the resources as mentioned above, it permits the use of import finance, which would otherwise be diverted to technical requirements of rapid filtration, for essential commodities. The choice of a slow sand filter, to be able to save on natural resources, is the adoption of a design of high relevance to modern conditions.

[illegible]

Whether it is London on the Thames, New York on the Hudson, Tokyo on the Sumida or Calcutta on the river Ganges, the metropolitan cities are usually located on rivers which have travelled through industrial regions of the country, and are thus carrying heavy industrial and organic pollutional loads. To be able to use raw water from such deteriorated surface sources, it is imperative that strict and extensive treatment processes be employed. The turbidity and phenol degradation results from this research have shown the high efficiency of the slow sand filter, which forms an important part of the multiple barrier technique to deal with such grossly polluted raw water. The results of the examination of London waters, spread over several decades (Windle Taylor 1971-73, and the previous M.W.S. Reports) speak very highly of the validity of the multiple barrier purification with the slow sand filters as systems. The sparkling sand soft filtrate with less than 0.1 units of turbidity (silica scale) compared with 5.0 units (silica scale) as the acceptable limit of international standards (WHO 1971, US 1962), and 29,280 (1972 average) samples free of coliform organisms compared with 95% of acceptable international standard (WHO 1971) and the European standard (EWO 1970), are highly regarded throughout the world. The key to this, it seems, lies in the built-in versatile quality of biological purification of the slow sand filters, using a very low turbidity (about

[illegible] (Seelo) influent water from the rapid filters (or the intermediate), which are supplied from improved and biologically maintained bottled reservoir raw water. The results (Windle Taylor 1971-73) show that three storage reservoirs, the Walton, Queen Mary and Queen Elizabeth II Reservoirs, eliminate 92.6% E. Coli and 88.6% turbidity of the Thames water. Advances in limnological control can now help eliminate even the undesirable quality features due to the thermal stratification by providing inexpensive engineering installations (Bidley 1971).

These metropolitan cities, faced with the position of being situated on a heavily used river, but housing also the large concentrations of an industrialised affluent society, keen to have drinking water of a highly discriminating specification, and able to pay the due price to achieve this, can do so by making use of the unmatched biological purifying quality of the slow sand filter, necessary to produce a polished water, in a whole multiple barrier strategy.

[illegible] Degradation and the Phenol Standard

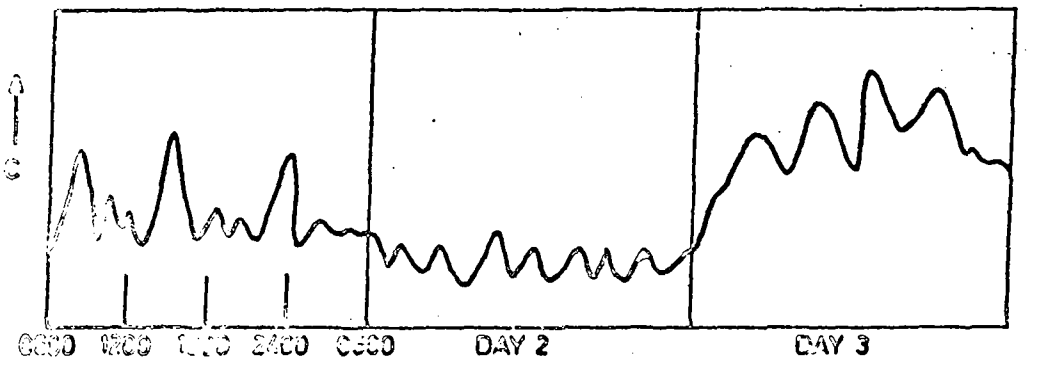
[illegible] velocity results of the test and control filters at a filtration [illegible] of 0.3 m/h as discussed in section 11.3, are comparable to those of the E.M.B., based on normal slow sand filters at a filtration rate of 0.07 - 0.13 m/h. There was apparently no untoward effect in the headloss development or the relevant length of the filter run at this higher velocity of filtration. It is, therefore, felt that there is a strong case for increasing the filtration velocity in slow sand filters to 0.3 m/h, as discussed in section 11.6, where the influent water is of low turbidity (< 5 FTU). This step reduces the filtration area and the cost of construction to almost half.

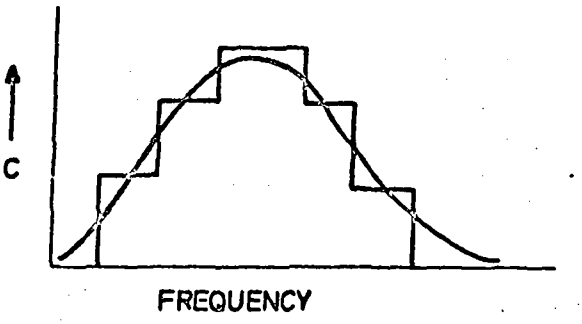
Raw water with high content of organic impurity can be suitably purified by slow sand filters without any chemical pretreatment. Phenol degradation results of this research are a witness to this fact and are discussed with detail in section 11.4.

The determination of phenol in water has limitations imposed by the analytical technique. In addition slow sand filters have been shown in this work to produce material which registers as phenol, by the standard Emerson determination. Therefore, reconsideration should be given to the WHO limit of 1 µg/ℓ of phenol, either to raise it, or to adopt alternative criteria (e.g. taste production after chlorination).

12.2 [illegible] for Future Research

(a) The sampling technique has been discussed in detail elsewhere (Khan 1967). However, it is felt that the present sampling technique needs further investigation. It would be interesting to see the improvement by trying composite sampling daily on a slow sand filter. From this it is easy to prepare graphs for concentration versus time for each sample tap as shown in graph 12.2.1, and a histogram of concentration frequency.





GRAPH 12.2.1

This method will remove any faulty concentration determinations at a particular time, which were in evidence, at times, during the conduct of the present experiments.

(b) The present study did not investigate the variation of the degradation constants for the top water (dt), for the schmutzdecke (ds), and for the bed (db), with temperature. Study of the effect of temperature is practicable in the laboratory, under controlled conditions, and could prove useful in correlating further, the degradation constants with velocity of flow (Vf), depth of tank water (dw) and the bed depth (Di).

(c) Apart from the Metropolitan Water Board of London, there is little evidence of fundamental research on the biological aspects of the slow sand filter. There is need for research on the capability of the slow sand filter to handle many other important organic compounds which are in wide use now, e.g. surfactants, pesticides, organic fertilisers and the petroleum oil etc, as discussed recently in the Loughborough Symposium (Jain 1973 a, b).

(d) The present methods of phenol determination as given in the Standard Methods (Evans et al, 1971) seem to be registering quinone and chlorinated other derivatives as phenol. There is need to develop a method which determines the concentrations of phenol exclusively with [illegible].

(e) The chief reason for limiting the amount of phenol in water supplies is the fear of phenol reacting with chlorine to form chlorophenolen resulting in bad tastes and odours. There appears to be a large element of speculation about the minimum phenol concentration which reacts to form undesirable chlorophenoles. Research on this aspect should be useful.

(f) Because of set backs in the successful operation of slow sand filters or rapidly operated slow sand filters (Kardile 1970), and of time occurrence of anaerobic conditions in the lower layers, and the production of sulphides, it appears that a study leading to better understanding of do, U and Di and their impact on Vf and the total and proportional organic constituent of raw water is desirable.

(g) Theoretical studies relating to the dominant biological mechanism and mathematical models governing the headloss development should be carried out to be able to improve the functioning of slow sand filters.

It is also desirable to make tests with phenol (or other organic [illegible] to isolate rate of oxidation with rate of flow. Presently at higher rates of flow there is less time for adequate oxidation.

This can only be achieved by multiple pilot filters (each at different rates), or very long research programme due to length of runs (several weeks) and need to establish steady conditions (phenol acclimatisation), and replicate runs.

12.3 Conclusions

Based on this study of two pilot scale slow sand filters at a waterworks near London, the following conclusions have been drawn.

1. There was overwhelming phenol removal (87% of incoming residual) in the schmutzdecke and the top 5cm of sand bed.

2. There was considerable phenol degradation in the rest of the filters (13% of the incoming residual).

3. There is considerable phenol degradation in the overlying tank water (by about 40%), therefore, increased depth of tank water affording more contact time may be conducive to the organic degradation in the filter.

4. The best phenol degradation was in the middle of the run, with recovery of head, and the corresponding increase of turbidity, probably due to the dislodgement of bacteria and other biological growths.

5. A mathematical model to describe the phenol degradation in these slow sand filters has been developed. The total degradation is the sum of degradation in the three regimes of the slow sand filter. One is the 'X' for the overlying water, the other is Y(1 - X) for the schmutzdecke and the top 5cm of bed, and the third is the $Z\left[1 - \left\{X + Y(1-X)\right\}\right]$ for the bed depth. The degradation in each regime is time variant and may be temperature dependent.

6. The results of phenol degradation led to the conclusion that the filter influents with high organic content (up to 10 mg/l) can be successfully treated with the slow sand filter.

7. When the dosing of phenol solution is stopped, the length of run in the test (dosed) filter was 2 - 3 times the average run, and there was evidence of the presence of phenol everywhere in the filters. Phenol in the overlying water (test filter) was around 100 µg/l, in the filter depth several hundreds µg/l, diminishing with time, in the primary effluent around 10 or less µg/l. However, there was also phenol at the main works outlet, at several tens µg/l. This significant concentration of phenol was detected in the control filter effluent, and several times more in the test filter effluent during runs immediatley following the dosed runs.

8. The international standard of phenol in drinking water at 1 µg/l needs upward revision, in view of the difficulty in maintaining filtrate at that low level and the practical difficulty in low phenol measurements, and the absence of any strong experimental documentation for fixing 1 µg/l phenol standard.

9. Almost the entire headloss occurs in the top layer of the filter, which [illegible] as an exponential function of time. There is insignificant [illegible] build up in the rest of the filter and whatever is built up during the first half of the run tends to recover in the later half of the run. The Kozeny-Carman equation can only describe the net effect in the lower layers but not the building up and recovery of headloss.

10. During phenol-dosed runs, the length of the run in the test filter was considerably shortened, due to rapid headloss increase. This can be interpreted as an increase in the biological activity within the filter, thus proving the inadequacy of the present mathematical models of filtration and the need for a new one incorporating the magnitude and proportion of organic compounds in the influent of the slow sand filter, with consequent biological productivity.

11. There was great turbidity removal in the top layer, similar to the headloss development and the phenol degradation. But the turbidity removal was continued with depth, similar to the degradation, but rather dissimilar to the net headloss.

12. The turbidity was best removed in the first quarter of the run and the phenol was best degraded in the middle of the run. The increase of turbidity in the middle of the run may be attributed to the

[illegible] of bacteria and biological growths preparing to enter the state of endogenous respiration.

13. From all the data and the graphs it emerges that the slow sand filter, from the point of view of phenol degradation (and possibly, therefore, from the point of view of organic degradation), and the turbidity removal, is not a surface filter but a depth filter.

14. Slow sand filters, with influent turbidity less than 5 fTU can be successfully operated at a filtration rate of 0.2 m/h, and possibly even higher.

15. Because of its reliability and simplicity, the answer to rural water supply problems in India is found in the slow sand filter. Considering the conservation of resources aspect, it is well suited for developing towns. As it is able to produce a high quality polished water from grossly polluted and reused river water for the affluent [illegible] of metropolitan cities, its unique biological purification makes the slow sand filter a suitable element of the multiple barrier technique.

APPENDIX

Brief Specification of Components

(a) Filter tanks: each measuring 3.20m x 1.82m x 2.72m deep, concrete wall thickness 0.75m tapering to 0.38m at the top, glass observation windows 0.45m x 2.1m deep.

(b) Sampling device: Aluminium pipe 13mm internal dia. with 3mm dia battery of holes, embedded in cone wall, fitted with brass sample taps 9mm dia.

(c) Pressure tappings: brass pipe 6mm internal dia tapped into 13mm sample pipe.

(d) Thermometer: range -10 °C to 110 °C.

(e) Dosing pump: Micro metering pump series II, 100 R.P.M. standard drive 3mm head and valve, short stroke 1,723, 690 N m^{-2}, 230 ml/h capacity, fitted with reduction capsule gear, max. pressure 689,476 N m^{-2} short stroke, capacity 45 ml/h, with variable speed 0-100%, supplied by Metering Pumps Ltd, 83 New Broadway, London W5 5Sd, England.

(f) Connecting pipes: flexible p.v.c. reinforced, semi-transparent 6mm, 13mm internal diameter, supplied by Gallenkamp and Co., Technico House, Sun Street, London E.C.2.

(g) Control valves: 5cm needle valves used for filtrate and recharge, 13mm for inlet flow and 25mm ball valve for influent control.

(h) Aspirator bottles: Pyrex, 10 litre capacity, rubber stopper, glass stopcock, supplied by Gallenkamp and Co., Technico House, Sun Street, London, E.C.2.

NOMENCLATURE

SYMBOL	DEFINITION	MLT UNITS
a	area of hole in the sample pipe	L^2
a1	Ives filter coefficient	L^{-1}
a2	Ives filter coefficient	L^{-1}
A	inlet surface area of filter	L^2
b	geometric constant relating to the grain packing	(-)
C	turbidity (FTU) at a certain depth	(-)
Cd	phenol concentration using Chloroform Extraction Method using undistilled sample	ML^{-3}
d	diameter of sample pipe hole	L^2
db	degradation constant for the filter bed	T^{-1}
de	effective size of sand grain, mm	L
dc	degradation constant for schmutzdecke	T^{-1}
dt	degradation constant for tank water	T^{-1}
D	grain diameter	L
Db	depth of sand bed	L
Di	distance into filter from inlet surface in inch	L
Dm	distance into filter from inlet surface in m	L
Do	grain diameter at inlet face	L
Ds	specific diameter of grain	L
Dw	depth of water in the filter tank	L
e	particle diameter	L^2
E	Stokes-Einstein diffusion coefficient	$L^2\ T^{-1}$
f	porosity ratio of clean filter bed (volvoid/unit vol.)	(-)
fo	porosity of clean filter medium	(-)
g	gravitational acceleration, 9.81 m/s^2	$L\ T^{-1}$
hd	headloss due to pore deposition, m	L
hL	headloss (at a certain pt in the filter	L
hLt	total headloss reached at the end of the run	L
ho	headloss due to surface deposition, m	L
H	headloss (total) through filter bed	L
Ho	headloss of clean filter	L
Hb	contact time (hour) in filter bed	T
Hc	contact time (hour) in schmutzdecke and the top 5cm layer)	T

$\bar{t}$	contact time (hour) in the filter tank water	T
I	force of interception	(-)
j	gradient of grain size/distance relationship	(-)
k	rate constant at T °C	(-)
ko	rate constant at O °C	(-)
ks	initial headloss at surface, m	L
kt	rate constant of surface headloss, l/s	T^{-1}
K	Boltmann's constant	ML^2T^{-2} deg^{-1}
K_1	Kozeny coefficient, variable with σ	(-)
l	length of filter tank	L
L	length of the sample pipe	L
m	exponent of velocity	(-)
n	inertial action	(-)
n_1	exponent of grain size	(-)
N	number of holes in the sampling probe	(-)
p	Peclet number	(-)
P_1	Dispersion filter coefficient constant	(-)
P_2	Dispersion filter coefficient constant	(-)
P	phenol concentration at a particular depth, mg/l	ML^{-3}
PO	phenol concentration at the inlet mg/l	ML^{-3}
q	sampling rate	$L^3 T^{-1}$
Q	flow rate or filtration rate volumetric	$L T^{-1}$
r_1	area/volume ratio of coated filter grains variable with σ	(-)
R	Reynolds number	(-)
s	specific surface	L^{-1}
s_o	specific surface of clean bed	L^{-1}
S	concentration of suspension, vol/vol	(-)
S_o	inlet concentration of suspension	(-)
t	absolute temperature °K	(-)
to	elapsed time of filtration, s	T
T	temperature in C	(-)
Td	time of the run in day	T
u	settling velocity	LT^{-1}
U	uniformity coefficient of sand	(-)
V_f	approach velocity of filtration, m/h	LT^{-1}
V_p	velocity through pores	LT^{-1}
V_s	velocity of sampling	LT^{-1}

w	width of filter tank	L
x	exponent of velocity term	(-)
X	dt Ht	(-)
y	exponent of spherical surface term	(-)
Y	ds Hs	(-)
z	exponent of capillary specific surface term	(-)
Z	db Hb	(-)
α	scour or detachment coefficient	T^{-1}
β	bulking factor for deposits	(-)
$\Delta\rho + \rho$	density of suspended matter	ML^{-3}
λ	filter or impediment coefficient	L^{-1}
λ_o	initial filter coefficient	L^{-1}
μ	dynamic viscosity at 20 °C	$ML^{-1}\ T^{-1}$
ν	kinematic viscosity	$L^2\ T^{-1}$
ρ	mass density of filtering liquid	ML^{-3}
ρ_s	particle density	ML^{-3}
σ	specific deposit, vol of deposited solid per unit filter vol.	(-)
σ_a	absolute specific deposit	(-)
σ_u	saturation value of specific deposit	(-)
$\phi(\Phi)$	shape factor of grains	(-)
ψ	ratio between specific diameter and effective diameter	(-)
*	inconsistant values of headloss (ignored)	(-)
**	extrapolated values of headloss	(-)

The above notation has been followed in the text. Some unavoidable differences from this nomenclature in the text are clearly noted as and when they occur.

Note:- The data in Chapters 9 and 10 on headloss, and depth of filter press in in inches because of existing facilities and relating the work with previous data.

w	width of filter tank	L
x	exponent of velocity term	(-)
X	dt Ht	(-)
y	exponent of spherical surface term	(-)
Y	ds Hs	(-)
z	exponent of capillary specific surface term	(-)
Z	db Hb	(-)
α	scour or detachment coefficient	T^{-1}
β	bulking factor for deposits	(-)
$\Delta\rho + \rho$	density of suspended matter	ML^{-3}
λ	filter or impediment coefficient	L^{-1}
λ_o	initial filter coefficient	L^{-1}
μ	dynamic viscosity at 20 °C	$ML^{-1}\ T^{-1}$
ν	kinematic viscosity	$L^2\ T^{-1}$
ρ	mass desnity of filtering liquid	ML^{-3}
ρ_s	particle denisty	ML^{-3}
σ	specific deposit, vol of deposited solid per unit filter vol.	(-)
σ_a	absolute specific deposit	(-)
σ_u	saturation value of specific deposit	(-)
$\phi(0)$	shape factor of grains	(-)
ψ	ratio between specific diameter and effective diameter	(-)
*	inconsistant values of headloss (ignored)	(-)
**	extrapolated values of headloss	(-)

The above notation has been followed in the text. Some unavoidable differences from this nomenclature in the text are clearly noted as and when they occur.

Note:- The data in Chapters 9 and 10 on headloss, and depth of filter probes is in inches because of existing facilities and relating the work with previous data.

ABBREVIATIONS

@	at the rate of
cm^3	cubic centimetre
cm^3/h	cubic centimetre per hour
cm^3/min	cubic centimetre per minute
CF	control (west) filter
dro/min	drop per minute
dro/sec	drop per second
E1, E2 ...E8	sampling valves cum pressure tappings in the test (east) filter
hr	hour
lit/h	litre per hour
m	metre
mg/l	milligram per litre
m/h	metre per hour
min	minute
ml	milli litre
mld	million litre a day
mm	millimetre
mV	millivolt
nm	nanometre
N/m^2	newtons per square metre ($1N/m^2 \approx 1.019 \times 10^{-5} kgf/cm^2$)
OR	overflow rate (filtration rate) inch per hour
p^H	hydrogen ion concentration
Ref	reference point for headloss measurement
sec	second
TF	test (east) filter
u.d.	under drainage
Vol	volume
W1, W2 ...W8	sampling valves cum pressure tappings the the control (west) filter
W.H.O.	World Health Organisation
W.W.O.	Walton waterworks outlet
μ	micron

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