Negative microfilm 65–5293
received from university

DAVIS, Eric, 1923–
SAND FILTRATION OF FLOCCULANT AND
NON–FLOCCULANT PARTICULATE MATTER.

The University of Michigan, Ph.D., 1964
Engineering, sanitary and municipal

University Microfilms, Inc., Ann Arbor, Michigan

SAND FILTRATION OF FLOCCULANT AND NON-FLOCCULANT PARTICULATE MATTER

Eric Davis

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
1964

Doctoral Committee:

Professor Jack A. Borchardt, Chairman
Doctor Alfred M. Beeton
Professor Lloyd L. Kempe
Assistant Professor Walter J. Weber, Jr.

ACKNOWLEDGEMENTS

The author acknowledges with gratitude the advice, cooperation and support of his Doctoral Committee during the execution of this research.

An expression of sincere gratitude is extended to my wife, Nancy, whose assistance and encouragement contributed to the completion of this work.

This research was supported in large part by the Department of Health, Education and Welfare, Public Health Service, Bureau of State Services Research Grant WP-00329.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
LIST OF TABLES.	vi
LIST OF ILLUSTRATIONS	vii
LIST OF APPENDICES.	x
I. INTRODUCTION	1
Proposed investigation	2
II. GENERAL ASPECTS	5
Historical Development of Filtration	5
The Effects of Algae on Filters	10
Filter Clogging	10
Filter Penetration	13
Factors Influencing Filtration	15
Spatial Arrangement of Sand Particles	19
Media Depth	20
Media Size	21
Porosity	24
Particle Shape	24
Ratio of Container to Particle Diameter	26
Mathematical Formulation of Filtration	31
Mechanisms of Removal	33
Surface and Interstitial Straining	34
Gravitational Sedimentation	35
Inertial Impaction	37
Interception	38
Brownian Movement	38
Electrokinetic Forces and Surface Charge	38
Molecular Forces	42
Fluid and Suspended Phases	43
Size of Particle in Suspended Phase	44
Concentration of Suspended Particles	45
Shape of Suspended Particles	46

Density of Suspended Particles 46
pH of Fluid Phase 47
Chemical Composition of Fluid Phase . . . 48
Coagulant floc Characteristics 49
Surface Properties of Suspended Particles 50
Rate of Flow of Fluid 56
Uniformity of Rate of Flow 59

III. APPARATUS AND PROCEDURES 60

General 60

The Filters 60
Rate of Flow and Liquid Level Control . . 69
Filter Bottom and Underdrains 72
Algae Culturing 76
Filter Sand 79

Experimental Procedures 81

General 81
Filter Run Criteria 82
Head Loss Readings 82
Frequency of Sampling 83
Iron Determination 83
pH Determination 83
Algae Determination 83

IV. EXPERIMENTAL OBSERVATIONS AND DISCUSSION 85

Algae Filtration Studies 85

Simultaneous Filtration of Flocculant and Non-Flocculant Particles 97

Organism Removal and Penetration of Old and New Coagulants at 435 ml/min 107
Removal of Organisms for Three Different Methods of Applying Coagulant 113
Organism Removal and Penetration Patterns for High and Low Application of Coagulant and Suspended Matter 120
Organism Removal Pattern 129

Pattern of Coagulant Penetration Study 144

The Effect of Algae on Penetration 144
The Effect of Activated Carbon on Penetration 152
The Effect of Hexametaphosphate on Coagulant Penetration 160

TABLE OF CONTENTS (Continued)

V. SUMMARY 165

VI. CONCLUSIONS 172

REFERENCES 178

APPENDICES 188

LIST OF TABLES

Table		Page
1.	Percentage Removal of Organisms Accomplished by Filters at Different Hydraulic Rates After Application of 7×10^9 Organisms per Filter . . .	95
2.	Organism Removal and Head Loss for 24" Beds of -30+40 Sand	105
3.	Summary of 24 Hour Removals Runs C-7 - C-9 . .	125
4.	Summary of 12 hour Removal Efficiencies	137
5.	Activated Carbon Passing Through 24 Inch Filters of -20+30 Sand Under Different Solution Coagulant Applications	154

LIST OF ILLUSTRATIONS

Figure		Page
1.	Schematic Diagram of Apparatus	61
2.	Model Filter	62
3.	Sample and Piezometer Port	65
4.	Constant Head Feed Apparatus	66
5.	Electric Rate Controller	73
6.	Schematic Diagram of Rate Controller Circuit .	74
7.	Filter Bottom	75
8.	Algae Removal Efficiencies of 24" Beds of various Sized Sands Filtering a Suspension of a Filamentous Organism Run A-1	87
9.	Organisms Remaining in Suspension at Various Depths Run A-1	88
10.	Organism Removal Efficiencies for 24" Beds of Various Sized Sands Filtering a Suspension of Selenastrum Run A-2	90
11.	Organism Removal Efficiencies for 24" Beds of Various sized Sands Filtering a Suspension of Selenastrum Run A-3	91
12.	Organism Removal Efficiencies for 24" Beds of Various Sized Sands Filtering a Suspension of Selenastrum Run A-4	92
13.	Algae Removal Efficiencies of a Mixed Culture of Organisms Filtered Through 24" Beds of Various Sized Sands.	94
14.	Organism Removal Efficiencies and Head Loss Increases Developed During Run C-1	101
15.	Organism Removal Efficiencies and Head Losses Developed During the Filtration of a Suspension of Filamentous Organisms Through Various Sized Sand	102
16.	Organism Removal Efficiencies and Head Losses Developed During Run C-3	104

LIST OF ILLUSTRATIONS (Continued)

Figure		Page
17.	Rate of Head Loss Increase Produced by Different Coagulant Dosages for Floc and Solution Feed of Coagulant	106
18.	Organism Removal Efficiencies and Head Losses Developed During Run C-4	109
19.	Organism Removal Efficiencies and Losses Developed During Run C-5	110
20.	Penetration of Preformed Floc During Run C-4	111
21.	Penetration of Solution Fed Coagulant During Run C-5	112
22.	Organism Removal Efficiencies and Head Losses Associated with Different Methods of Coagulant Application and Different Diameter Filters	115
23.	Organism Removal Efficiencies and Head Losses Developed During Run C-7	121
24.	Removal Efficiencies and Head Losses Developed During Run C-8	122
25.	Removal Efficiencies and Head Losses Developed During Run C-9	123
26.	Coagulant Penetration Occurring During Run C-7	126
27.	Coagulant Penetration Occurring During Run C-8	127
28.	Coagulant Penetration Occurring During Run C-9	128
29.	Removal Efficiencies and Head-Loss Increase Developed During Run C-10	130
30.	Removal Efficiencies and Head-Loss Increase Developed During Run C-11	131
31.	Removal Efficiencies and Head-Loss Increase Developed During Run C-12	132
32.	Removal Efficiencies and Head-Loss Increase Developed During Run C-13	134
33.	Removal Efficiencies and Head-Loss Increase Developed During Run C-X	135

LIST OF ILLUSTRATIONS (Continued)

Figure		Page
34.	Percentage of Organisms Removed as a Function of the Coagulant Dosage	138
35.	Coagulant Dose Employed as a Function of Organisms Removed per Unit of Coagulant	140
36.	Number of Organisms Removed as a Function of the Coagulant Application	142
37.	Organisms Removed for Two Different Dosages of Coagulant as a Function of the Concentration of Organisms in the Influent	143
38.	Pattern of Penetration of Preformed and Solution Fed Coagulant and Location of Algal Material Removed in Experimental Sand Filters	147
39.	The Effect of Varying Concentrations of Algae on the Penetration of Coagulant into Experimental Filters	148
40.	Location of Algal Material Deposited in Experimental Filters During Run P-2	149
41.	The Effect of Varying Concentrations of Algae on the Penetration of Coagulant into Experimental Filters	150
42.	Location of Deposit of Algal Material Deposited in Experimental Filters Run P-3	151
43.	The Effect of Varying Concentrations of Activated Carbon on the Penetration of Coagulant into Experimental Filters	155
44.	The Amount and Location of Deposited Coagulant and Activated Carbon in Experimental Filters	156
45.	The Effect of Increasing Concentrations of Activated Carbon on the Head Loss Developed in Experimental Filters	158
46.	The Effect of Varying Concentrations of Hexametaphosphate in the Filter Influent on the Location of Deposited Solution Fed Coagulant in Experimental Filters	162
47.	The Effect of Varying Concentrations on the Head Loss Increase and Amount of Coagulant Passing Through an Experimental Filter	163

LIST OF APPENDICES

Appendix		Page
I.	Synthetic Nutrients for Algae Cultures	188
II.	Specific Gravity of Sand	189
III.	Sand Size Determinations	189
IV.	Sampling and Testing Procedures	190

I. INTRODUCTION.

The penetration of non-flocculant particulate matter through rapid sand filters is a well-recognized but poorly documented occurrence.

Filter penetrating particulate matter may originate as an impurity in the water being treated, or as a result of the treatment processes. Finely divided fractions of soil, micro-organisms, and organic colloids may be representative of the former, and calcium carbonate crystals, activated carbon and coagulant material may be included in the latter category.

The fact that macroscopic as well as microscopic matter will penetrate a properly constructed and normally operated rapid sand filter and appear in the water being delivered to the distribution system is of vital significance to the sanitary engineer and others engaged in public health activities.

Depending upon the operation of an individual water treatment plant, filtration may be the last, or next to last, unit operation or process applied to water prior to its distribution. The removal by filtration of all particulate impurities is vital and disinfection should be regarded only as a major adjunct to the treatment of a high quality water produced after filtration rather than the ultimate process in quality protection.

With some justification, the major line of advance in water treatment has been toward better pre-treatment yielding a water low in suspended material to be applied to the filter. The majority of the suspended impurities in the raw water having been coagulated and settled out prior to filtration.

At times, however, suspended matter in the form of silt,

clay, algae and color may be present in the raw water in such quantities or states that the complete removal of these materials by normal treatment methods is impossible. Their occurrence in the filter influent is then inevitable and their presence in the filter effluent is probable. Continued induced eutrophication of natural waters will probably make itself felt in increased and widespread growths of aquatic microscopic plants. These organisms have already caused considerable difficulty in the practice of water treatment.

At times massive doses of activated carbon are required for taste and odor control. Evidence of this material in the treated water is dramatically attested to by the color it imparts and provides a clear indication of the passage of activated carbon through conventional sand filters.

In appreciation of the present limits of effectiveness for removal of non-flocculant particulate matter by rapid sand filters, studies have been outlined to (1) determine methods to improve removal efficiencies in rapid sand filters, and (2) to gain further insight into the mechanisms of filtration processes. The opinion is held by the author that these studies are required to further advance the scientific art of water purification and it is hoped that the information gained will indicate further profitable lines of endeavor.

PROPOSED STUDIES

Previous investigations into the mechanisms involved in filtration, on both experimental and plant scale bases, have generally been approached by one of the following methods:

A. The study of filtration of discrete non-flocculant particles without addition of a coagulant. This type of research was con-

ducted by Gosh (39) using Fuller's Earth, and by Ives (40) using algae which had been grown in a media containing radioactive Cesium-137. O'-Melia (41) also used algae for investigations of the effectiveness of filtration for removal of non-flocculant particulate matter.

B. The experimentation conducted in connection with the filtration of flocculant particulate matter only, without its being associated with organic or inorganic non-flocculant particulate matter. Stanley (42) used hydrated ferric oxide in conducting laboratory experiments on this type of filtration.

C. The studies of filtration of flocculant and entrapped non-flocculant particles carried over in the effluent from a sedimentation unit. Ling (43), in laboratory pilot plant studies, used water coagulated with hydrated ferric oxide floc. Gamet and Radamacher (29) have reported work based on actual plant operation. Robeck (37), operated a battery of two inch diameter filters in connection with an operationally flexible pilot plant in a program to evaluate modifications in water filtration. He studied the removal of virus and bacteria, as well as activated carbon, accomplished by various types of filters. With the exception of a limited amount of work done by O'Melia (41), utilizing controlled simultaneous application of flocculant material and suspensions of algae, no detailed information appears to exist on the removal mechanisms and relationships involved in the simultaneous removal of flocculant material and algae, or other non-flocculant particulate matter in rapid sand filters.

The object of the experimental work was to elucidate that area of the knowledge of rapid sand filtration dealing with removal of algae, and other particulate non-flocculant matter with a controlled amount of flocculant particulate matter.

To this end, it was proposed to institute a study employing a number of sand filters with control established on sand size, algae concentration, quantity of flocculant material, and rate of flow. Removal efficiencies were to be evaluated based on length of filter run, head loss, and penetration criteria.

It was further proposed to conduct a series of experiments to study the pattern of penetration of flocculant material, non-flocculant, or both, into, and through, a filter. In order to accomplish this it was planned to install plastic tubes within the filters which could be removed at the end of the filter run for analysis, these cores taken as being representative of the patterns established in the filter as a whole. It was believed that this method would result in obtaining undisturbed samples of the filter bed, and the deposits therein.

Knowledge thus obtained on the removal capacities and characteristics should result in practical plant scale methods of improving water quality and in development of filter plant design criteria to ensure higher quality water being produced even when a water heavy in non-flocculant particulate matter must be treated.

II. GENERAL ASPECTS.

HISTORICAL DEVELOPMENT OF FILTRATION

The treatment of water by passing it through a porous medium such as sand is a process with a history extending nearly four thousand years. It was not until about one hundred and fifty years ago that Paisley in Scotland became the first urban center to receive filtered water distributed by a network of pipes throughout the community. By 1829 slow sand filters operating at about two million gallons per acre per day were in use in London. By an Act of Parliament, all water supplied to the Metropolitan District of London, after 1856, was required to be filtered. An order similar in nature was issued by German authorities after the 1892 cholera epidemic in that country requiring filtration of all public water supplies in Germany having a river as their source.(1).

The European slow sand type of filter never came into general use in America. This was attributed by Fuller (2) to be due to (a) the high cost of construction, (b) the absence of governmental bodies in the United States with authority to enact regulations governing water supplies and (c) the fact that no severe epidemics of cholera occurred in the United States. Fuller (3) dates the interest in filtration in the United States from 1865. In that year the Cincinnati Common Council "acquired the services of the most eminent of engineers, John P. Kirkwood, ... to ascertain the most economical and practical mode of supplying pure water . . . . " (4). Kirkwood's report contained the recommendation of filtration of water from the Ohio river.

In the same year Kirkwood was instructed by the St. Louis Water Department to examine the European practice of filtration. For more than a quarter of a century his report was considered a leading work on the subject of filtration.

Bell (4), reviewing the water works facilities of fifteen major American cities for the year 1880, makes no mention of filtration being practiced, in contrast eight of fourteen European cities reviewed practiced this treatment process. During the 1890's, information was gained from the operation of slow sand filters at the Lawrence Experiment Station of the State Board of Health of Massachusetts.

The development of the "rapid sand" filter in America to treat water for industrial and manufacturing purposes led to interest being taken in this process by water supply companies. In 1884 patents were taken out to apply alum, iron, salt, or other coagulating chemicals to the water prior to filtration. The rapid sand filter is differentiated from the slow sand filter by (a) the addition of a coagulation chemical usually in a pretreatment unit, the carryover of floc making it possible for filtration to be carried on at higher rates with resulting reduction in surface area of the filter, and (b) the rapid sand filters are cleansed by reverse flow of water through the media which carries away the deposited material. The addition of coagulating chemicals to water was not a new concept. Hazen (5) pointed out that as "early as 1831 D'Arcet published . . . . . an account of the purification of Nile river water in Egypt by adding alum to the water, and afterwards filtering it through small household filters."

According to Fuller, writing in 1898, the first rapid sand filters were constructed in Somerville, New Jersey, in 1885, and "since that time, many towns and small cities have adopted systems of this general type. At the present time it is said over one hundred town and

municipal plants are in operation, but among that number there are none for larger cities." (2).

In the discussion of his report, Fuller stated, in reference to patented filters, "the capacity of filters of this type is considered to be one hundred million gallons of filtered water per acre daily. It is probable that this capacity - - - with satisfactory results could be raised fifty per cent." Fuller also emphasized the importance of pretreatment, surface agitation, backwashing, and judged it advisable to use thirty inches of sand, having an effective size of 0.35 mm (2). Experimental investigation and plant operation observations have led to some modification of the physical parameters of filters as set down above, but changes have been slow to be adopted, perhaps not without cause, by regulatory agencies and those responsible for filter design.

Beginning in the early 1930's, and continuing until the present, (6) the literature is liberally sprinkled with reports of experimental investigations and plant operation of filtration rates in excess of the accepted two gallons per minute per square foot. One journal lists over sixty such articles dealing with elevated rates of filtration during a twenty year period starting in 1932. Considerable weight to the argument for increasing the design rate of the filtration process was given by the work conducted at Chicago under Baylis (7, 8, 9, 10) which culminated in the operation of the entire South District Filtration Plant for over a year at a maximum rate of four gallons per minute per square foot (11). Ten of the eighty filters in this plant had been operated at four to five gallons per minute per square foot (12). This plant had been designed to operate at 3.5 gal-

lons per minute per square foot in summer, and two gallons per minute per square foot rate in winter (13). In summarizing the operation of the plant at a high rate, Baylis pointed out that only after evidence that high rate filtration will not decrease plant efficiency should it be introduced.

There is apparently general agreement among investigators of high rate filtration that the process can produce water of equal quality to that produced at normal rates, but high rate filtration should only be instituted after it has been justified by engineering study and precautions have to be taken for adequate supervision and control (14, 15, 16, 17).

Any advance in the rate of filtration necessitates use of coarser filter media to reduce the initial head loss across a filter bed, as well as that resulting from build-up of particulate matter in the bed. An effective size of 0.65-0.90 mm was used at Chicago (11). The trend toward larger sized media was followed in conventional plants (17). A study of the retention of floc in test filters of uniformly sized sand was conducted under the direction of Armstrong (18), and the results incorporated into American Society of Civil Engineers Manual of Practice #19 (19) where the advantages and disadvantages of the use of coarse grained media are outlined. The shearing forces exerted by the water on a coagulant floc increase with increased rate of filtration, and with an increase in viscosity (20) associated with reduced temperatures. In order for high rate filtration to be effective in periods of weak flocculation it is often necessary to add floc strengtheners in the form of clay, activated silica, polyelectrolytes, or recycled precipitated material (17, 20, 21, 22).

In order to increase the capacity of a plant with no increase in construction, in some cases replacement of filter sand by coal has been practiced. Longer filter runs, higher filtration rates and the use of less backwash water due to lower specific gravity and greater angularity of particles, are claimed.

Camp (143) and Baylis (144) both advocated the use of anthracite-sand filters at least twenty years ago. Conley and Pitman (145) reported the evaluation of sand, anthracite, and anthracite-sand filters at elevated filtration rates. The criteria imposed was the production of filtered water with a turbidity of .01 parts per million or less during a filter run of at least six hours under all raw water conditions and at a filtration rate of 6 g.p.m./sq.ft. after one hour's settling. A filter composed of twenty two inches of -6+18 mesh anthracite over eight inches of -30+40 sand was found to meet the criteria, provided a filter aid was utilized. Conley (146) reported that a number of filters were constructed of twenty four inches of 0.9 mm anthracite over size inches of 0.43 mm sand and that these filters gave excellent results when operated at 6-8 g.p.m./sq.ft. with a filter aid.

Loss of anthracite during back wash was not excessive, even with the use of surface wash equipment. Camp (143) contended that if the size ratio of the anthracite to the sand at the interface is less than three there will be very little mixing of the two types of media. It is believed this separation of media results in improved turbidity removal whereas beds in which the media becomes mixed due to a ratio greater than three, give a better head loss distribution pattern.

In both cases advantages are gained in capacity due tothe fact that turbidity is allowed to penetrate into the filter bringing about removal with a moderate increase in head loss.

Robeck et al (37), utilized pilot plant filters of eighteen inches of 1.05 mm anthracite on top of six inches of 0.45 mm sand (-30+40 sieve fraction). Results obtained indicated that these dual media filters were as effective as sand or anthracite alone in removal of bacteria, activated carbon, or polio virus. and in addition, allowed extended filter runs. With proper pretreatment filtration rates of 6 g.p.m./sq.ft. were obtained with equal removal as at rates of 4 and 2 g.p.m. Filter aids of polyelectrolytes and activated silica as a coagulant aid were employed.

THE EFFECTS OF ALGAE ON FILTERS

If algae are present in the water reaching a filter they may, depending upon the type of organism, tend to cause one of two problems. They may either (1) help to cause clogging of the filters or they may (2) penetrate the filter.

1. Filter Clogging - There are numerous references in the literature describing problems of varying complexity associated with the clogging of filters by algae.

In 1921, the algae Melosira was associated with minor filter clogging (23). In 1922, Baylis (24) reported the presence of a strong gelatinous colloid due to decaying algae which did not penetrate filters, but resulted in maximum head losses being reached in twelve hours or less. In 1935 the clogging of filters by diatoms was discussed, and Synedra was indicated as the major offender in water derived from the Ohio river (25). Palmer (26) reported on the diatom infestations

of the Potomac river in 1934, 1936, and 1938. It is reported that on one occasion the diatoms blocked the filters so completely they required backwashing every fifteen minutes, and in general, filter runs were reduced to less than one hour from an average of fifty hours. The nuisance organism in these infestations was Synedra and the concentration reached 4800 cells per milliliter. In 1936 (27) it was reported that plants treating water from large reservoirs on the Great Lakes had shorter filter runs than plants which obtained their water elsewhere. It was suggested that the presence of micro-organisms could be the cause of these short filter runs.

Baylis, in 1953, and again in 1958, reported on the effect of micro-organisms in Lake Michigan water which had caused runs to be shortened to five hours at the Chicago South District Filtration Plant. The organisms guilty in these cases were Tabillaria, Melosira, and Oscillatoria. In 1961 (28) Vaughn, discussing filtration problems at Chicago's South Filtration Plant, stated that "a new filimentous organism did appear and by January 1, 1961 was present in sufficient numbers to appreciably increase the number of filter washes. This organism has been tentatively identified as Stephanodiscus binderanus. In fact, the number of filter washes was fifty per cent higher than the usual figure for this time of year." In 1957 Baylis reported on the determination of the effects of algae on the operation of the Chicago South Filtration Plant. Water from Lake Michigan which normally contains a high concentration of diatomswas the source of supply. Coagulation and sedimentation precede filtration and fifty to eighty per cent of the algae were retained within this final unit. The presence of the algae resulted in lowered penetration of floc into

the filters and a concave upward type of head loss versus time curve developed. Gamet and Rademacher (29) conducted a nine month study of "short filter runs" at twelve water treatment plants located around Lake Michigan. This had as one of its objects identification of water quality and other conditions which contribute to poor sedimentation and short filter runs.

Tabellaria was found to be the most important of the Lake Michigan plankton that produced short filter runs. Average volumetric plankton concentrations in excess of 1700 standard units per milliliter were observed. Thirty seven per cent of all runs were considered to be "short", that is, less than twenty hours duration and about two per cent were five hours duration or less. It was determined that turbidity of the settled water was not a factor in short filter runs and it was suggested that nannoplankton and the activation of the silica shells of diatoms to form a silica gel may be, in part, responsible for short filter runs. This could also hold true for improperly generated or applied activated silica.

The subject of filter clogging algae has warranted a separate discussion in a publication by Palmer (30). He listed forty three of the most important filter clogging algae and gave illustrations of twenty two of these. In another work (31) the enumeration of algae in sixteen rivers, as well as the Great Lakes, indicated that "the same genera tend to be dominant in all rivers in the country, and that only a limited number of genera comprize the list of dominant forms." From highest to lowest in order of frequency are Cyclotella, Synedra, Melosira, Navicula, Asterionella, and Stephanodiscus. Other predominant algae are Anacystis, Chlorella, Chlamydomonas and Ankis-

trodesmus.

In a recent publication Palmer (32) stated that algae have been present in the Rio Grande river in such numbers that filter runs at Laredo have been as short as one hour.

2. Filter Penetration - Few documented reports of the penetration of algae or other particulate non-flocculant material are available. It is general practice to record plant effluent quality as "turbidity" a measure which is not nearly sensitive enough to detect microscopic particles in fairly large numbers and it is not a generally accepted test procedure as yet to subject the plant effluent to microscopic examination. It has been noted (30) that some of the algae which may cause filter clogging may also pass through a filter, the size and mobility of the organism playing a direct role in its penetration.

Perhaps the most well-documented and widely distributed report on algae penetration of filters arose from the re-use of water at Chanute, Kansas (33). A drought culminated in the cessation of flow in the river supplying the city with water. Treated sewage which was stored in the river channel was recirculated to the water treatment plant where the liquid was afforded conventional treatment in addition to softening. A heavy algae growth developed in the storage area, the predominant species being Ankistrodesmus with concentrations ranging from 2000 to 45000 per milliliter. Removal through the plant was poor, never reaching ninety per cent, with subsequent concentrations of algae in the filtered water of up to 7100 per milliliter. The presence of these micro-organisms together with amoeba cysts in the finished water pointed to the inefficiency of water treatment plants

in removing particulate matter of this type in the size range below twenty microns.

Passage of the algae Stephanodiscus hantzschii through filters has been reported from Chicago (28). At the time of the infestation of this organism the pH of the raw water rose and the filters were noticed to be passing trace amounts of turbidity which was determined to be cuboidal crystals of calcium carbonate, presumably precipitated from the bicarbonate due to the metabolic requirements of the algae.

The presence of bleached algal cells in the clear well water of a plant incorporating upflow clarification prior to filtration through anthracite during the time of a bloom of Anabaena and Aphanizomenon was reported by Dillenberg (34). Harwood indicated that membrane filtration of a plant effluent had always shown to some degree, the presence of the suspended matter found in the raw water or that added or produced in the treatment plant (35). Most of the forms of algae found in the raw water appeared in the filter effluent, and counts ranged from 0-1000 per gallon when raw water counts were 1000 to 50,000 organisms per milliliter. It was also noted that when activated carbon was used, and when it reached the filters without sufficient coagulation, the carbon would appear in the filter effluent, and its presence "will be obvious before it is detected by the laboratory turbidimeter."

Penetration of rapid sand filters by poliomyelitis virus has been demonstrated if the virus arrives at the filter associated with insufficient floc or with aged floc (36). Removal of polio virus in the filters was enhanced by the application of a fresh floccul-

ant material.

The presence of bacteria and activated carbon in a filter effluent has been associated with effluent turbidity at times of weak flocculation (37).

Riddick (38) states "all suspended matter in raw water has historically been considered as turbidity regardless of particle size. It consists of finely divided silt and clay and organic matter undergoing microbial decomposition. Included in the latter category are algae, plant proteins, and domestic and industrial wastes discharged to a watercourse." The author points to the necessity of reappraising the present concept of turbidity if plant effluents of the highest quality are to be produced from raw water sources which are subject to periods of strong growths of algae. He stated that turbidity is electronegative and must be regarded as consisting of two distinct and separate fractions. (1) A coarse fraction with particle diameter of 1 mm to 1 micron and (2) a fine (colloidal) fraction with particle diameter of 1 micron to 10 Angstrom units. The latter is very difficult to remove from water as the zeta potential of the colloids approximates that of hydrated metal oxide floc resulting in mutual repulsion.

FACTORS INFLUENCING FILTRATION

A study of rapid sand filtration must, of necessity, be based first on the laws of fluid flow through porous media, and then be expanded to take into account the removal mechanisms at work within the media. At the rates at which rapid sand filters operate, two to three gallons per minute per square foot, and the size of sand used, the overall flow rate through a filter is demonstrably laminar (39), at least at the start of filtration, and complies with the Darcy

formula for flow through porous media.

$$H = \frac{v\ L}{K} \qquad (1)$$

where H = head loss
v = velocity
L = depth of bed
K = coefficient of permeability

Theoretical and experimental methods have led to the evaluation and refinement of this basic flow equation. The following formula for flow of water through a bed of sand was based on experimental work involving sands with a uniformity coefficient less than five and an effective grain size of 0.1 to 3.0 mm (45).

$$H = \frac{L\ v}{C\ d^2}\ \frac{60}{T+10} \qquad (2)$$

where H = head loss - meters
L = depth of bed - meters
v = velocity of water - meters/day
C = a Constant - the value of which approximates 1000
d = effective size of sand - 10% size - mm
T = water temperature degrees F.

Thus, head loss was shown to be proportional to velocity of the water and depth of sand and inversely proportional to the temperature and the square of the effective grain size of the sand. Hulbert and Feben (46) working with model filters with eight different sands of uniform size, ranging from the -20+30 sieve fraction to the -40+60 fraction, at flow rates up to three hundred million gallons a day and at temperatures of from thirty five to seventy degrees Fahrenheit evaluated rate of flow, depth of sand, temperature, sand size and porosity. An equation of head loss due to flow of water through clean sand of any shape within one sieve fraction and within the porosity range of thirty five to forty eight per cent was proposed to be of the following form (47)

$$H = \frac{27}{10^5} \frac{L\ Q}{d^{1.89}} \frac{(73-P)}{(T+20.6)} \qquad (3)$$

where H = head loss in feet
L = depth of bed in inches
Q = Flow rate m.g.a.d.
P = Porosity % voids
d = sand size in mm (median sieve size)
T = water temperature ^{o}F

Fluid flowing under laminar conditions in circular tubes may be described by the Hagen-Poiseuille equation, which is a refinement of the Darcy equation (58).

Starting with the Hagen-Poiseuille equation $H = 32 \frac{\mu\ L\ v}{\rho\ g\ d^2}$ and working on the assumption that flow within the pores in a porous media is analagous to flow in a large number of hydraulically equal pipes, two different investigators (48, 49) by introducing hydraulic radius, porosity, interstitial velocity and shape factor terms, arrived at the same flow expression referred to interchangeably as the Kozeny or Fair-Hatch equation.

$$H = f \frac{L}{g} \frac{\mu}{\rho} v \frac{S^2}{d^2} \frac{(1-P)^2}{P^3} \qquad (4)$$

in which f = a constant with a value of 5 for spheres
L = depth of bed
μ = absolute viscosity
v = superficial velocity
S = shape factor - 6 for spheres
P = porosity
g = gravity constant
ρ = mass density
d = diameter of particles

Fair and Hatch determined the value of S for sands of varying degrees of sharpness. Carman (52) cited various investigators who have evaluated f and from his own work he concluded that the variation in f for changes in sand shape is small.

Equation 4 is consistent with observed facts of flow through

porous media (50) in that head loss is:

1. Proportional to depth.
2. Proportional to rate of flow.
3. Inversely proportional to size of sand grains.
4. Related to the coefficient of viscosity.

Rose (52), by the application of the method of dimensional analysis, determined the head loss through porous media to be a function of eight dimensionless groups. Rose started with the following expression, where each term within the bracket was raised to some power:

$$H = F\left[v^a h^b d^c \rho^d D^e \mu^f g^g e^h p^i Z^j U^k\right] \qquad (5)$$

where H = head loss
F = function
v = velocity
h = depth of bed
d = particle diameter
ρ = mass density
D = bed diameter
μ = absolute viscosity
g = gravity constant
e = height of surface roughness
P = porosity
Z = shape of particles
U = size distribution

Equation 5 was resolved by dimensional analysis into:

$$\frac{H}{d} = F\left(\frac{\rho dv}{\mu}\right)^{\alpha}\left(\frac{dg}{v^2}\right)^{\beta}\left(\frac{h}{d}\right)^{\gamma}\left(\frac{D}{d}\right)^{\delta}\left(\frac{e}{d}\right)^{\varepsilon} P^{\xi} Z^{\eta} U^{\theta} \qquad (6)$$

Experiments to evaluate the five remaining relationships were conducted employing smooth spherical shot of uniform size. This eliminated the terms Z U and $\frac{e}{d}$. This work led to an expression similar to the Fair-Hatch equation but in which the head loss is proportional to one over the porosity raised to the fourth power $\left(\frac{1}{P^4}\right)$.

Equality may be obtained by introducing a coefficient, itself a function of the Reynolds number and numerically equal to 1.067 times the coefficient of drag (53). Thus, the Rose equation becomes

$$H = 1.067 \; C_D \frac{L V^2}{g d p^4} \qquad (7)$$

In the laminar range $C_D = \frac{24}{R} = \frac{24u}{pdv}$

otherwise $C_D = \frac{24}{R} + \frac{3}{R} + .03$

When dealing with a stratified bed containing different sieve fractions the total head loss may be obtained in the application of both equations 4 and 7 by the summation of increments proportional to weight fractions of sieve analysis assuming a constant porosity from top to bottom of the entire bed.

It becomes apparent that the following physical characteristics of the solid phase affect the flow of fluid through a porous media and are of importance in rapid sand filtration:

1. Spatial arrangement of media.
2. Media depth.
3. Media size.
4. Porosity.
5. Media shape.
6. Ratio of container to particle diameter.

In addition to the purely physical factors listed above, surface properties of the media may play an important part in the filtration process.

A study of each of the factors as they have been developed will lead to a wider understanding of the modifications they might be expected to produce in the process of filtration.

SPATIAL ARRANGEMENT OF MEDIA PARTICLES

Slitcher (54) suggested that regardless of the complexity of a porous media there is justification in representing it in terms of an ideal sample which would be hydraulically identical to the complex media, the ideal sample being composed of spherical

grains of the effective size of the grains of the complex sample.

Geometric arrangements of spheres produce ten spatial variations of four basic patterns. The loosest pattern is Cubic, in addition three each of Orthorhombic, Tetragonal. Sphenoidal, and Rhombohedral variations also may be encountered. Respectively, the porosity of these patterns is 47.65, 39.54, 30.19 and 25.95%. The pressure drop through a column of spheres stacked in the arrangements indicated above has been determined and it is different for each pattern, and for some variations within a certain pattern (55). Spatially oriented beds are obtainly only by hand packing. This is not a normal arrangement for media which has been introduced in a rapid manner into a container. In such dumped beds the packing is random and the bed acts hydraulically similarly to a Rhombohedrally packed bed. Channelling is reduced in dumped beds by having $\frac{D}{d}$ ($\frac{\text{diameter of bed}}{\text{diameter of particle}}$) greater than eight (56).

MEDIA DEPTH

At the start of a filter run, when the filtering material is clean and is of uniform particle size, the loss of head due to flow through the media is directly proportional to the depth of media as indicated by the Darcy equation (43). Discrepancies from this linear relationship were noted by Gosh (39) who suggested that losses due to sudden enlargement and contraction and end effects may be responsible for the deviations. Others (57, 59) ascribed the deviation from linearity to size stratification within the sand fraction within one sieve range. Rose (52) found a perfectly linear relationship between depth of the bed and head loss for h/D

values of from nearly unity to more than 300.

In a perfectly stratified bed of mixed sized particles the total head loss is equal to the sum of the individual head losses developed across the individual layers of the media which are, in turn, directly proportional to the weight of the individual fractions. Thus, the head loss versus depth relationship is not constant, but decreases with increasing depth (increasing particle size). Methods for computing initial head loss are available (53, 60).

As the filtering process continues, the influence of depth of the bed is often overshadowed by other factors such as size and nature of the substance being removed. Strongly flocculant material tends to clog the upper fine layers of a filter causing a very rapid increase in head loss (7). In such a case the lower layers of sand act only as a support mechanism (46) and head loss considerations govern the length of filter run.

When a weak or non-flocculant material is filtered, penetration into the bed is increased and the bed depth is then of primary importance in determining length of filter runs (39, 41). In this case effluent quality may be the governing factor.

MEDIA SIZE

In general, the head loss due to a fluid flowing through a porous media is inversely proportional to the diameter of the particles in the media raised to some power.

When dealing with a bed of uniformly sized particles, the value of the diameter is that of each particle. In media composed of grains of a single sieve fraction, the average diameter has been taken as the arithmetic average of the screen openings (52). The

geometric average, that is the square root of the sum of the squares of the diameters of openings in adjacent sieves has been utilized (60, 53) for single sieve fractions.

For beds of mixed sand sizes use of equation 2 is restricted to the effective size or ten per cent by weight size. This size, according to Hazen "has as much influence upon the action of a material in filtration as the coarser ninety per cent."

For use in flow equations of the Fair-Hatch or Rose type, the diameter of the particle may be obtained from expressions such as the following:

1. $$D_p = \sqrt{\frac{\sum \frac{Mi}{Di}}{\sum \frac{Mi}{Di^3}}}$$

where D_p = average particle diameter
Mi = the mass fraction of a given particle fraction
Di = arithmetic mean of sieve openings (52)

2. $$D_p = \sqrt[3]{\frac{\sum d^3 n}{\sum n}}$$

where D_p = average particle diameter
n = number of grains
d_s = arithmetic mean of sieve openings.

3. $$D_p = \sqrt{\frac{\sum d^2 n}{\sum n}}$$

where D_p = average particle diameter
n = number of grains
d = average grain diameter

Method number one for determining the particle diameter was preferred by Brownell and Katz (61) over number two, the diameter based on average volume per particle method of Fancher and Lewis (62),

or number three, the average surface area of the average particle method of Blake (63), as it brought the data with which they worked into agreement with that of beds of uniformly sized particles.

Attempts have been made to determine relationships of the size of the particle employed in the solid phase to the length of filter runs obtained. Baylis reported that the length of filter runs in hours, terminating after the development of eight feet of head loss, was directly proportional to the diameter of the effective size particle raised to the 2.15 power. His experiments were conducted mainly on twenty-four inch deep beds of mixed sized materials and the effective size was determined by an improved method which yielded results usually lower than Hazen's ten per cent size (7).

Work by Stanley (42) indicated filter runs to eight feet loss as being proportional to the 2.46 power of the geometric mean size of the uniformly sized particles used. His work was conducted on filters seventeen and three quarter inches in depth.

Ling's (43) study of filtration yielded evidence that the length of a filter run necessary to develop a head loss of seven feet was proportional to d to the 2.37 power, where d equals the geometric mean of the openings of sieves, delineating the fraction used for the twenty two inch deep beds of uniform sand particles. Ling stated that the relationship appeared to hold true for other loss of head values.

Baylis's work was conducted using water which had received alum coagulation treatment on a plant scale. Stanley directed iron floc directly to the sand surface of his filters, and Ling's filters were part of a model water treatment plant employing iron and lime coagulation.

POROSITY

It is agreed by a number of investigators (63, 64, 65), that the equation for fluid flow through a bed of porous material is described in part by the term $(1-P)^{3-n}/p^3$ as in equation 4. Where P is the porosity of the bed and where n is a state of flow factor ranging from 1 for laminar flow to 2 for fully developed turbulent flow (66).

A theoretical determination employing the analogy of free fall of a sphere in a fluid yielded a porosity group of $1-P/p^2$ (65). This formulation has been rejected as being contradictory to experimental results by Carman (64) who cited evidence that between porosities of twenty six and ninety per cent. the first function accurately represents the relationship between the volume of the voids. and the permeability of the bed. The porosity of beds of randomly packed granular materials have been found to vary between thirty and forty five per cent (61).

It was contended by Rose (52) that a given percentage change in porosity brings about a much greater change in resistance to flow through a bed of porous material than a similar percentage change in any of the other variables, due to the resistance varying as a high power of the porosity. He cited porosity functions proposed by a number of authors with indices ranging up to the sixth power of P (67). His own experimental work, resulting in Equation 7, indicated that the porosity factor was equal to $1/P^4$.

PARTICLE SHAPE

Most theoretical equations for the flow of a fluid through porous media assume the shape of the particles under consideration to be spheres. In practice this is hardly ever the case and correction

factors must be introduced to evaluate the increase in surface area associated with irregularly shaped particles, as well as the increase in the porosity of the bed.

A number of authors (19, 48, 64) have determined shape factors for irregularly shaped particles of approximately spherical outline. The usual form is developed from the volume to area ratio yielding an equivalent sphere diameter equal to some shape factor times the quotient volume/surface area. For irregular particles then $d = S \frac{V}{A}$, where S = shape factor, which is numerically greater than 6 which is the shape factor for a perfect sphere. Rose (68) developed a correction parameter for particle shapes which deviated greatly from spherical. Cubes, saddles, cylinders, both solid and hollow as well as beads and nails have been investigated and their correction parameters determined.

After hydraulic washing the grains of a porous media settle slowly into a bed, in a manner less than the most compact arrangement, usually having a porosity varying from forty one to forty five per cent (7). Beds of highly irregular grains will result in porosities of higher magnitude (65). Porosities in the order of forty eight to fifty five per cent for anthracite are quoted, whereas rounded sands show a porosity of about forty three per cent (69).

Departure from the spherical grain shape results in an increase in surface area which is an important change if the surface properties of the media are important in the filtration processes. A lessening of the resistance of flow through irregularly shaped grains, in spite of increased surface area, has been cited as being due to the increased porosity of the irregular grains (46).

RATIO OF CONTAINER TO PARTICLE DIAMETER

The study of the factors involved in rapid sand filtration in a laboratory results necessarily in the miniaturization of certain aspects of the filters.

The usual and most dramatic reduction is normally in the area of the filter. As the characteristic dimension of the filter decreases, there is an increase in the percentage of sand which is in contact with the walls of the container. Thus, as the D/d ratio (diameter of filter to diameter of filter particle) becomes smaller, the overall flow pattern may diverge from that of a filter of high D/d ratio, even though all other factors are kept constant, due solely to the increase in wall area per unit area of filter media. Photographs taken by Furnas (70) and by Graton and Fraser (79), show that the proportion of voids at the wall of a bed is greater than in the next layers away from the wall.

In a discussion by Carman (64) on the correction required due to wall effect, experimental results are presented which indicate that the compacted porosity of a bed of lead shot of a $\frac{D}{d}$ ratio of eight is approximately forty per cent and that the minimum porosity for spheres packed in a wide tube is thirty eight per cent. The latter figure is approached at a $\frac{D}{d}$ ratio of fifteen. Carman also stated that no elaborate wall correction was considered necessary for the effect of the wall provided that the porosity term represented the average porosity of the whole bed including the region at the wall, and that S_1, the corrected surface area per unit volume being equal to the surface area per unit volume plus 4 over the container diameter, be used for S (see Equation 4). He held that when the ratio

of the diameter of the container D, to that of the particle d, is greater than 10:1 the wall effect can be neglected, as it is less than experimental error. He applied the above correction to data of experiments concerning the laminar flow of a heavy oil through a two inch wide column containing steel balls 1/16" to 5/16" in diameter to adjust the experimentally determined values of f (Equation 4). In subsequent work he amended this correction to $S_1 = S + \frac{2}{D}$ and showed remarkable correlation between actual and corrected values of specific surfaces down to D/d ratios of 2.9 (51).

Research by Rose (68) resulted in a chart of relative resistance $F\left(\frac{D}{d}\right)$ (Equation 6) for $\frac{D}{d}$ ratios of from 1 to 60, for Reynold's numbers from 10 to 3000 for beds of spherical materials. At a $\frac{D}{d}$ of 20 the relative resistance varied approximately by plus and minus ten per cent for these extreme conditions. He stated that for beds with D/d ratio greater than fifty the wall effect can be entirely neglected. Rose contended that due to the wall of the container providing one restraint, the layer in contact with the wall of the vessel is randomly placed with two degrees of freedom only. This results in the paths through this layer being less tortuous than in the bed of the filter. He cited experiments in which pitot tube measurements revealed that the velocity across a bed of shot was constant except for a ring approximately ½ d from the wall, and here the velocity equalled one hundred and fifty per cent of the average.

The mathematical description of rapid sand filtration herein referred to as Fair-Hatch or Kozeny equation., set no lower limit upon the area in which filtration is taking place. Rose, however, gave a generalized equation for the laminar flow through a bed

of porous material. In a bed of $\frac{h}{d}$ = 60 and $\frac{D}{d}$ = 8 the relation between $\frac{H}{d}$ and R (Reynold's number) was determined, for flow in the laminar range (R less than 10). The relationship was found to be inversely proportional to R raised to the 0.98 power with a high probability that the exponent tends to 1.0 at R = 0.

The evaluation of the hydraulic resistance (H/d) to depth of bed $(\frac{h}{d})$ was determined for $(\frac{D}{d})$ = 12.2 and $(\frac{D}{d})$ = 21.7. For both conditions the resistance was found to be proportional to depth, indicating the same wall effect, if any, in this range.

Fancher and Lewis (62) studied the flow of air, oil, and water through beds of sand of four different sieve analyses. Friction factors were determined and plotted against the Reynold's number. The authors state that "it is apparent that an excellent correlation and alignment of the data for unconsolidated sands was secured by this method. While a line could be drawn for each sample, the average line as drawn is sufficiently accurate, not withstanding the differences in porosity, relative sizes and angularity of grains, composing the samples." By inspection, the slope of the average line was 1.0 between Reynold's numbers of .001 and 10. The experiments were carried out in tubes of 3/4" and 1"-I.D. (1.905 and 2.54 cm) which yielded $\frac{D}{d}$ ratios of 26.5, 34.5 and 69.

Brownell and Katz (61), in deriving a modified Reynold's number and friction factor, use, in part, data by Burke and Plummer (65), and state that as their correlation "is based on average porosity, including the portion of the bed adjacent to the wall, no correction was made for this effect." (i.e. wall effect).

Burke and Plummer (65) used commercial lead shot of three

sizes, 1.48, 3.08 and 6.34 mm, and four different columns of 1.794, 3.41, 5.25, and 7.81 cm diameter. These combinations gave D/d ratios of from 5.4 to 35.5. Air was the fluid used, and the range of flow was from laminar through transitional to turbulent. Wall effect was not considered, however, the average bed porosity was used in calculations.

Stanley (42), on the other hand, considered the wall effect from a theoretical and experimental viewpoint as it might affect the action of a laboratory scale filter. He pointed out that in addition to differences in the resistance to flow in the pores in the bed and the pores next to the wall, the coefficient of drag C_D (Equation 7) does not remain constant if the flow in a pore leaves, if only momentarily, the laminar range. Emphasis was placed on the fact that the effective diameter of the particles changes as the bed plugs with deposted material. For a -20+30 sieve fraction, he calculated a wall correction of 3.87% of the area of the bed and in view of the change brought about by deposition, this correction was considered excessive. Stanley used 1½" filters in his experimental work.

The consideration of "wall effect" in the majority of the above cases was in connection with the passage of a clean fluid through a bed of "clean" porous media in an effort to evaluate the increase in flow, if any, in close proximity to the wall. No data in the literature appears to be available concerning the differences in removal of particles which are semi-filterable between a sand bed of small, as compared to one of large, $\frac{D}{d}$ ratio, operated at rapid sand filtration rates.

The term semi-filterable in this text is used to describe

particles of which a reasonably high proportion are removed, in comparison to filterable particles such as algae and diatomatous earth or non-filterable particles such as hydrated metal oxides.

The possibility that slow sand filter efficiencies might be affected in a filter with a $\frac{D}{d}$ ratio of 18.5, for the effective size of sand, due to the large filter boundary surface, was tested statistically on effluent turbidity during a fifteen day period (71). The test involved the determination of whether any significant difference existed between the effluent turbidities compared with those from a filter with $\frac{D}{d}$ ratio of 65. It was determined that no disturbing influence on the effluent turbidity was due to the filter boundaries. No coagulants were used and turbidity was caused by clay particles suspended in a tap water.

MATHEMATICAL FORMULATION OF FILTRATION

One of the first attempts to arrive at mathematical expressions for the filtration of water through a bed of sand was made in 1937. The experimental work was carried out using white potter's clay, bacteria, and algae as filtering suspensions. The filtration of bacteria resulted in a set of complicated equations due to alleged growth of the micro-organisms within the filter. Based on a microscopic examination of the inorganic material which penetrated sand beds of varying sized particles operated at slow sand filtration rates (3.2-12.9 m.g.a.d.), Iwasaki (135) proposed the following mathematical relationships:

$$\frac{\partial C}{\partial l} = -\lambda C \qquad - \qquad 8$$

$$\lambda = \lambda_o + c\,\sigma \qquad - \qquad 9$$

$$\frac{\partial C}{\partial l} + \frac{\partial \sigma}{\partial t} = 0 \qquad - \qquad 10$$

where C = quantity of suspended matter in flow
l = depth of the sand layer
λ = impediment modulus or filter coefficient
c = coefficient of impediment modulus or rate constant
σ = quantity of suspended matter retained or specific deposit
t = duration of filtration

These equations indicate that:

1. The amount of suspended matter retained in any layer of sand is related to the quantity of suspended matter entering the layer.

2. The impediment modulus is not constant with time but varies directly in relation to the amount of material retained in the sand layer.

3. The decrease of suspended matter in the flow resulting from the passage through the layer of sand is equal to the quantity of suspended matter retained in the layer. This is a conservation

of mass statement or a statement of continuity.

The expressions are independent of rate of flow, and although developed from the action of slow sand filters have been used in the consideration of the mode of operation of rapid sand filters operating at 125 m.g.a.d. and above.

A similar equation was derived from theoretical considerations for rapid sand filters by Hall (74).

Ives (57) reviewed the work in which attempts had been made to evaluate the variables inherent in the filtration equations, specifically (i) the filter coefficient λ which is dependent upon the nature of the suspension, rate of filtration, water viscosity, and the pore shape (ii) specific deposit σ which is the quantity of material retained per unit volume of filter. and reflects the changes in the filter coefficient. His work demonstrated a fact that had been omitted in other filtration theories. Namely, that the pattern of effluent quality with regard to suspended matter varies with time. At the start of a run there is a minor initial breakthrough followed by a long period of improvement which blends into a terminal breakthrough which usually concludes the run due to an unacceptable effluent.

An equation for the change in the filter coefficient was developed (89) based on the following theoretical considerations:

1. A homogenous suspension was being applied under laminar flow conditions to an isotropic homogenous porous filter medium.

2. Particles of suspended matter were significantly affected by gravity.

3. Particles would adhere to media surfaces or previously deposited material due to van der Waal's forces if brought within range.

4. The removal of particles is proportional to their concentration.

The removal of material will initially increase the area for future deposition, therefore the value of λ, the filter coefficient, will increase in the form $\lambda = \lambda_o + C\sigma$ where C is a rate factor and σ is the specific deposit of material within a layer of the filter.

The result of increased deposit will be to plug the pores; in so doing:

a) the flow lines will shorten.
b) the interstitial velocities will increase.
c) the surface for continued deposit will be lessened.

These changes would have the effect of modifying the specific deposit equation to $$\lambda = \lambda_o + C\sigma - \frac{\phi\sigma^2}{P_o - \sigma} \qquad (11)$$

where Po = clean sand porosity
ϕ = rate factor

An experimental study was undertaken to test the theory (89) with the following ideal conditions:

1. Uniform suspension which remained constant.
2. Particle size uniform and geometrically definable.
3. Uniformly sized media.
4. Uniform flow rate and temperature.

The particles used were cells of the algae Chlorella and Scenedesmus.

The components of equation 11 were determined and subsequently filtration was simulated on a digital computer (136) with the conclusion that under the conditions stated, the computer described filtration and allowed extrapolation of filter runs to be made.

MECHANISMS OF REMOVAL

The mechanisms purported to be operating in the removal of particulate matter from a fluid which is passed through a porous media

have been outlined (42, 43, 54, 72) and will be discussed here in an attempt to bring some degree of resolution in the areas where conflict of opinion appears to exist, and also to elucidate those areas where general agreement appears to exist.

Surface and Interstitial Straining

Baylis (7) observed that coagulated matter either came to rest on a filter surface or passed into the filter and that immediately after a filter had been cleaned, nearly all the coagulated material passed into the bed and lodged in the crevices between the media particles. Under normal coagulation, the particles reaching a filter will generally be small and light. Large particles which reach the filter will be strained out at the surface providing they are strong enough to resist fracture (42).

From geometric considerations of the solid and suspended phases, it has been suggested by Hall (74) that removal in the media crevices is in direct proportion to the diameter of the suspended particle raised to the 3/2 power.

The hypothesis of straining being one of the predominant mechanisms of removal for calcium carbonate crystals from a softening plant has been put forward by Cleasby and Bauman (75). They found that the removal of hydrated ferric oxide floc could not be correlated with its size, and stated that if the removal mechanism within a filter is mechanical this should not be the case. Microscopic determinations showed that the floc particles were from 1 to 100 microns in diameter.

Eliassen (76), however, reported that he found, by microscopic determination, that the average size of floc particles de-

creased with depth from the surface of a filter and that there did not appear to be any change in particle size at the sampling locations with time.

Gravitational Sedimentation

Sedimentation has been described as the subsidence and deposition of suspended matter in a liquid by gravity (77). The processes of sedimentation are extremely complex and vary with particle diameter, shape and specific gravity, among other factors. McGauhey (78), has discussed sedimentation under conditions where viscous and inertial forces predominate and for the transition zone between these two extremes.

A mathematical study of sedimentation by Hazen (80) led to the proposal that very fine particles could be removed from water by passing it through a slow sand filter, the removal being caused by sedimentation in the pore spaces which act as sedimentation basins equipped with a large number of trays. A further analysis of this proposal (53) indicated that slow sand filters can be expected to remove particles with 1/60 the diameters of particles which may be removed in equivalently loaded settling basins, and that efficiency of filtration decreases with decreasing temperature. On the basis of these latter works, it has been suggested by Stanley (42) that the conclusion that sedimentation of particles within a sand bed as not being an important removal mechanism as made by Stein (81) is not valid.

Hall, (74) in a theoretical approach to a sedimentational theory of removal, considered particles falling under the influence of gravity in the liquid within the filter pores. The velocity re-

lative to the fluid is taken as being described by Stokes' Law, and the removal is therefore a function of the square of the diameter of the particle. Comparisons are given with the data presented from experimental procedures. Hall concluded that both interstitial sieving and gravitational sedimentation are operative in filtration. The former being predominant as flow rate increases or sand size decreases and the latter becoming more important as the flow rate decreases. or the sand size increases.

Boreli (82) pointed out the need for considering laminar flow in the filter when discussing sedimentation removal mechanisms. Both he and Hall appear to assume laminar conditions through the entire length of the flow line during the entire period of filtration and do not suggest what forces would act to move the particles out of the fluid stream lines.

Experimental information is advanced (75) to indicate sedimentation may be one of the important removal mechanisms for calcium carbonate crystals from softening plants. Ives (57) noted, however, that the removal of small light floc such as may be found in filtration following coagulation. is difficult to explain on the basis of gravitational hypothesis. This was subsequent to experiments he conducted on the filtration of suspensions of algae through uniformly sized sand media. This work was conducted to test a filtration theory based, in part, on the assumption that the principle force operating to remove suspended material from the flow stream was gravitational.

Cesium 137 labeled algae were used as the suspended particles and it was determined that more Chlorella were removed per unit of depth than Scenedesmus, and that the results were in accord-

ance with the gravitational hypothesis.

By the measurement of the specific surface area of suspended clay particles before and after slow sand filtration through large sized sand, it was contended by Jordan (71) that the explanation of removal being due to straining and sedimentation should be discredited, as he found that no size of particle was preferentially removed.

Inertial Impaction

The importance of impaction as a mode of removal of bacterial cells and spores in sterilization of air by porous media is well recognized.

Experimental work in this area of filtration (83) indicates that bacterial spore removal through fibrous filters approaches 100% at velocities of the carrier fluid in excess of ten feet per second. At velocities below 0.1 feet per second there exists a region of improved removal over the minimum associated with velocities of one to two feet per second. Evidence is offered to suggest that the increased removal in the low velocity range is due to electrostatic forces or gravitational sedimentation.

Ives (57) contended that inertial forces can be shown to be insignificant as a removal mechanism for particles of light material such as are found in water flowing at the velocities found in the interstitial channels in a rapid sand filter. Others (42, 72) dismiss the contribution of inertial forces to the removal of particles in rapid sand filtration as being negligible.

Stein (81), on the basis of microscopic examination of the deposits from a water containing flocculant material upon the surface

of parallel plastic rods, stated that inertial forces are not effective in bringing the suspended floc particles into direct contact with the solid phase.

Interception

As indicated previously (81), Stein conducted microscopic examination of the deposit of flocculant material upon parallel plastic rods. He found that the floc tended to deposit on the horizontal axis of the rods where the flow lines converged rather than forming mounds on the top of the rods. such as would be indicated by a purely sedimentation action as proposed by Ives (57).

Brownian Movement

Brownian movement, as a proposed method of deflecting particles from the flow lines of the fluid and bringing them into contact with the filtering media, has been discussed and dismissed as an unimportant removal mechanism by various authors (72, 42). Ives (57) stated that this action is insignificant for particles over two microns in size. Humphrey (83) stated that experimental work indicated that the diffusional mechanism is not important in the collection of particles greater than 0.5 microns. Wolff developed a theoretical mathematical consideration of the time required for half of the particles of a suspension to collide by Brownian motion (84). He indicated that for particles in the size range of one micron the time was in excess of six minutes which is far greater than the time of passage through an entire rapid sand filter.

Electrokinetic Forces and Surface Charge

Quartz is a crystalline form of silica and is a three dimensional completely cross-linked high polymer, and in the crystal

lattice each silicon atom with a charge of +4 is surrounded and attached to four oxygen atoms with an effective charge of -2 (90), thus microscopic neutrality is maintained within the crystal (91).

Kraemer (99) stated that electrostatic surface forces may arise in the following manner, "if a solid body is fractured the cohesional forces must be overcome; on the resulting surfaces these forces probably extend outward from the surface unsatisfied and capable of interaction with similar forces from molecules in the neighborhood of the surface." Unbalanced forces which then exist at the freshly formed faces may be responsible for adsorption of ions at the interface when the mineral is placed in water (92). Evidence has been presented by Gaudin (92) to indicate that OH^- and H^+ ions are adsorbed on charged solid surfaces of the aforementioned type, and that equilibrium is established between ions remaining in solution and those attached to such a surface. The presence of other ions in solution may alter the equilibrium depending on their nature and concentration. Such adsorption at liquid-solid interface implies the existence of ion double layers.

Handford (95) cited reports that the charge on a clean silica surface is due to adsorption of OH^- ions which occurs only at pH values in excess of 5.5, and that the maximum negative charge is due to 8 OH^- ions per 100 square Angstrom units. Iler (147) indicated there is considerable confusion as to the isoelectric point of silica and suggested the neutral point of colloidal silica lies between pH 4 and 5.

Douglas and Walker (96) also suggest that the preferential adsorption of H^+ or OH^- ions or other ions present in solution may give rise to surface charge and credit Freundlich with the statement that there exists a cationic and anionic adsorption site for

each 23.4 square Angstrom units on a quartz surface.

It has been suggested that the surface of quartz sand particles is covered with a layer of pure silicic acid 1 to 2 microns thick (92).

Greenland and Russell (93) indicated that the theory ascribing the charge on silica particles to the disassociation of H^+ ions from Si-OH groups on such surfaces is invalid in the low pH regions (3-5.5) where the charge remains constant. Here the Si-OH group would have to be strongly acidic. The probability exists that Si-OH groups could account for an apparent increase in negative charge as the pH increases from 5.5 to 11.0.

O'Connor and Buchanan (94) based a statement on work by other investigators that the surface of insoluble oxides reacts with water to yield hydroxyl groups and may ionize either as weak acids or bases. Their experiments indicated that surface ionization is the important process. They gain support from other investigators who described silica as a weakly acidic oxide with a negative Zeta potential and deduced that the electrical double layer was composed of ions dissolving from the solid.

Douglas and Walker (96) have theorized that ions might preferentially leave a crystal surface and pass into solution, the result being that the mineral surface acquires a charge of opposite sign which would tend to hold the dissolved ions in close proximity to the surface and thus set up an electrical double layer of ions. All investigators indicated above, and others (97, 57, 98) agree that silica and most other minerals exhibit a negative surface when in con-

tact with water (an exception being Corundum which has a positive charge). This charge is accounted for by the theory of a double layer of ions at the mineral-liquid interface.

The magnitude of the negative charge has been variously quoted (92, 94) as -170, -100, and -44 mv. The exact value being subject to change due to the treatment afforded the mineral particles. O'Connor (94) found that treatment with strong acids and bases did not appreciably change the negative charge. However, the charge on the particle increased with an increase in the concentration of the electrolyte in the liquid phase.

The treatment of fine silica sand grains with a cationic flotation collector reagent (Lauryl Trimethylammonium bromide) resulted in a reversal of the surface charge to positive from negative at very low concentrations of 2 millionths of an equivalent per liter due to physical adsorption of the cation. With n-dodecylamine acetate, the charge sign was not reversed, indicating less strong physical adsorption (94). However, the treating of silica with an anionic flotation collector reagent resulted in a maintenance of the negative charge sign and increasing charge density with concentration, this being apparently due to physical adsorption of the anion by the solid.

The adsorption of anionic detergents upon sands and clays has been demonstrated (100, 101, 102). Sandford and Gates (103) have suggested that the accumulation of a surfactant on sand would result in a hydrophobic coating replacing the normal hydrophilic one and could be simulated by coating the sand with a stearato chromic chloride. In the investigation of the effect of this coated sand on the removal of hydrated aluminium oxide floc and bacteria they con-

cluded as there was no evidence to indicate the presence of this coating had any effect on the removal efficiencies that therefore adsorptive forces were not of a major significance in the removal processes in a rapid sand filter.

The work of Cleasby and Bauman (75), in connection with the time for a filter to reach its peak efficiency and for uniform coating of sand grain to occur, led them to conclude that electrokinetic mechanisms seem primarily responsible for removal of ferric floc particles in a rapid sand filter. Stanley (42) has commented on the possible importance of electrokinetic forces during filtration, and his work has shown that pH and concentration of ions in the water affect the filterability of a hydrous ferric oxide floc. The increasing filtration efficiency of clay particles passing through a coarse slow sand filter correlated well with increasing electrophoretic mobility of the suspended medium, and it was concluded that the principle cause of clay removal under such conditions was due to adsorption or some allied process rather than straining or sedimentation (71).

Clarke and Chang (142) suggested that the inefficiency of rapid sand filtration in the removal of viruses from water may be attributed to "the inherently poor adsorption properties of sand."

Molecular Forces

The attractive forces between molecules, referred to as van der Waal's forces, which also cause the packing together of compounds to form soft molecular crystals (86) are, according to Moore (148), due to dipole-dipole and dipole-polarization interactions. Research and speculation as to their role in the filtration processes have been reported by Ives (57).

Considering particles and media in which the surface

potential is of the same sign, the attractive molecular forces will vary as the seventh power of the reciprocal of the distance, while the repulsive (double layer) force will vary as the square of the reciprocal of the distance. The two forces form a resultant with an energy barrier hump, or critical level as the two like-charged bodies approach one another with the attractive forces predominating at very close distances(87).

As the charge on the solid phase sand is negative,and as most small organic suspended phase particles found in water (bacteria, algae, color) are also negatively charged, a critical energy barrier may exist which must be overcome by the physical forces in the filter in order for removal of the particle to take place. These forces must move the particle to within extremely close proximity of the media (57) before molecular forces become operative. Markle and Markle (88), in their work on adhesion in filters, point out that the interactive force between a particle and an infinite surface holds good only for a distance of 100 Angstrom units (.01 microns) or less.

The formulation of a rational design of filters (89) is based on the assumption that particles brought within the range of van der Waal's forces of the granular filter medium or existing deposits will adhere to surfaces exhibiting such forces.

FLUID AND SUSPENDED PHASES

The characteristics of the fluid phase as well as materials it transports to the filter affect the mechanisms of removal of the impurities within a filter. These factors include:

Size of suspended particle.
Concentration of suspended particle.
Shape of suspended particle.

Density of suspended particle.
pH of fluid phase.
Chemical composition of fluid phase.
Temperature of fluid phase.
Coagulant floc characteristics.
Surface properties of suspended particles.

Operational procedures also play an important role in filtration. Factors of importance in this area are:

1. Rate of flow of fluid.
2. Uniformity of flow.

Size of Particles in Suspended Phase.

The size of suspended particles reaching a filter depends upon the materials in the raw water, the extent and completeness of pretreatment of the water, and at times on the intentional addition of material to the water after the pretreatment facilities.

Large particles may be intercepted at the sand surface (7) and the smaller particles will penetrate into the bed. On the basis of interstitial straining theory the particles should decrease in size with depth into the bed. This was noted by Eliassen (113) who found that the size of hydrated ferric oxide floc in the applied water had a wide range (from 20 to less than one micron) with an average of 11 microns. The particles did not completely penetrate the bed.

Gosh (39) conducted his experimental work with a synthetic turbidity composed of a Fuller's earth. The suspended particles were of a mean size of 20 microns. He concluded that the turbidity penetrated the entire depth of media regardless of the media composition (sand or glass) and size (0.46 to 0.77 mm).

O'Melia (41) used algae as a suspended medium and found that these penetrated sand beds of three sizes from .273 to .507 mm

and at all flow rates from .15 to 2.15 gpm/sq ft. . The size of the particles under study was from 15 to 60 microns. Best removals were obtained with large filamentous organisms and this was attributed to surface straining.

It may be concluded that the particle size, as such, the three cases above being within the same particle size range, has little effect on the removal of the particles. The important factor may apparently be whether the particles are flocculant or non-flocculant in nature.

Hall (74) has proposed that removal is proportional to particle diameter to the three halves power for straining and to the square for sedimentation. His theoretical work was checked using removal data for flocculant material. Eliassen (113) also suggested removal is proportional to the square of diameter of the suspended particle.

Concentration of Suspended Particles

Gosh (108) found that the percentage of material deposited in a filter bed does not depend upon the initial turbidity. His experiments were conducted using a synthetic turbid water composed of a suspension of Fuller's earth. No coagulating chemicals were added to the fluid phase in this work.

However, data in the work of O'Melia (41) on the filtration of algae through sand of .524 mm at approximately 2 gpm/sq.ft. would indicate that the removal efficiency increases as decreasing algae concentrations were applied to sand filters.

In comparison, it is instructive to note that high concentrations of flocculant material will tend to plug a rapid sand

filter at a rate proportionally higher than the rate for low concentrations. This must, of course, be qualified with a floc strength argument for high concentrations of floc may, under certain unfavorable conditions, mean low head loss and severe penetration (106, 109).

Stanley (42) reports depth of penetration of iron floc into sand filters varied directly as the total load of suspended matter applied per unit area, and that the penetration rate of the floc was directly proportional to the concentration when the comparison was on total amount of iron applied.

Shape of Suspended Particle

The shape of particles which might be encountered in filtration is as varied as the possible composition of the particles themselves. No references have been found dealing with the study of the filtering capacity characteristics of particles of varying shapes. However, O'Melia found that filamentous algae were removed to a greater extent than more compact species (41).

Ives (40), in filtration experiments without coagulants, required for close to ideal conditions that the particles be "unisize and of definable geometry." It is possible that the shape of the particles within reasonable limits is of minor consequence in comparison to particle type, that is, whether the particles are flocculant or non-flocculant.

Density of Suspended Particles

The density of the suspended particle is of major theoretical interest in the gravitational or sedimentation theory of removal as indicated by Ives (40) and discussed by Hazen (80), where the terminal velocity of sedimentation is proportional to the difference

between the density of the particle and that of the liquid medium.

This sedimentation theory might be more applicable for dense material such as Fuller's earch with a specific gravity of about 2 than for algae with a specific gravity of approximately unity, or chemical floc with a specific gravity of approximately 1.05 (40).

pH of Fluid Phase.

The relationship of pH of the fluid phase to the penetration of preformed hydrated ferric oxide floc has been suggested (42) to be analagous to the time of formation versus pH curve for coagulants, with least penetration of the floc occurring in the range of neutrality. pH values asspciated with water used for domestic purposes may result in the solution of aluminum salts at the high and low end of the scale. This solution of the flocculating material is limited in the case of iron salts.

The electrokinetic properties of colloidal or pseudo-colloidal particles are influenced by pH changes and they may exhibit a sign reversal as the pH passes through the isoelectrical point of the particle. This apparently is not true for algae which remained electronegative at all pH values that may be encountered in natural water (110). It has been suggested that the effect of pH on the double layer was masked by the ionized salts in the water, as a minimum charge was determined for algae placed in distilled water of differing pH values.

Chemical Composition of Fluid Phase.

The chemical composition of the fluid phase influences the character of the suspended phase, be it flocculant (42) or non-flocculant particulate matter (110). The chemical composition of the fluid

phase should have an effect on the surface properties of solid phase as well as the matter suspended in the fluid phase (99, 111), and also have an effect on the double layer of colloidal or pseudo-colloidal particles (112). Changes in filtration have been demonstrated (41, 120) to be associated with changes in chemical composition of the fluid feed to the filters.

Temperature of Fluid Phase.

A change in the temperature of the fluid phase in filtration results in changes in both the density and viscosity. Both increase with a decrease in temperature (104). The former exerts an effect on gravitational sedimentation, and the latter being directly involved in the flow equation.

Camp (105) pointed out that the optimum pH for coagulation is shifted by changes in temperature, but these changes have no measureable effect upon the time of floc formation if coagulation takes place at optimum pH value.

The temperature of the water is reflected in the character of the floc formed in the coagulation facilities and which carries over to the filters.

Hudson (81, 106) determined that periods of weak floc formation were found to occur during winter months and a water temperature of 40° F was taken as the dividing line between weak and strong floc formation. However, McCall (107) concluded from filtration experiments that the floc in properly coagulated water is sufficiently strong during cold weather to be trapped by sand filters, and will not pass through these facilities in great quantities.

Coagulant Floc Characteristics

On the basis of the recognition of varying floc strength, and on the strength of a floc particle being a function of the largest size pore it will block, a method of measuring the floc strength has been proposed (114). The inter-relationship of experimental data between the loss of head H, at which penetration of floc occurred in a bed depth of L, composed of particles of effective size d, was designated the floc strength index and was found to equal $\frac{H\ d^3}{L}$. High values of the index indicate strong floc and low values weak floc characteristics.

It has been suggested that the pattern of penetration of floc is tied to the head loss versus time relationship curve for a filter run according to the following:

1. A straight line curve indicates continued floc passage into the filter medium with eventual penetration and as such is indicative of a weak floc condition.

2. A run having a marked concave up curve is indicative of limited penetration and strong floc condition.

Application of critical values for floc strength index have been suggested as a basis of filter design in so far as maximum head loss, bed depth, or effective size are concerned. For laminar flow in a filter under weak floc conditions the floc penetration has been given as being equal to $K = v\frac{H\ d^3}{L}$ where v is filtration rate in gallons per minute per square foot. A limiting condition of $K = 0.4$ was suggested, but limiting values should be obtained by operation of filters for a number of years under conditions of breakthrough (115). This formulation of K was substantiated by experimental determinations (42).

For strong floc conditions floc penetration appears to be related to $K_1 = \frac{v\, d^2\, H}{L}$. The name eventually given to the function K was "breakthrough index." (116). The use of filter aids will markedly increase this breakthrough index (114).

Surface Properties of Suspended Particles

1. Coagulation Products. In recent years, the results of a number of studies relating the electrophoretic mobility of particles associated with coagulation have been reported. Black (118, 119), determined by electrophoretic techniques that the mobility of certain clay particles studied was approximately constant and had a magnitude of -1μ/sec./volt/cm. over a pH range of 3 to 10, being slightly more negatively charged at pH 3 probably due to increasing hydrogen ion concentration. The mobility was influenced by the concentration of added coagulant and the pH. The mobility of the floc particles produced by the alum coagulation of the clays studied could be reversed to positive by the addition of the appropriate amounts of coagulant. Best coagulation took place in the pH range of 7.5 to 8.5 where the floc particles exhibited a negative zeta potential.

In the alum coagulation of a water containing a negatively charged color colloid the best removal was obtained after a charge reversal from positive to negative in the pH range 5.5 to 6.5 The optimum removal associated with the ferric sulfate coagulation of a colored water was at a pH of about 3.5 occurring with a change in electrophoretic mobility from negative to positive as the pH decreased.

Reddick (38) stated that the zeta potential of colloidal turbidity in water is in the range of 15-25 miltivolts and as "con-

ventional alum or ferric floc is also electronegative in about the same range, a mutual repulsion exists between colloids and floc particles." To remove raw water colloids it was suggested that the zeta potential of both colloids and floc be reduced to about zero plus or minus 5 m.v. The electrophoretic mobility of ferric floc particles was determined to be of increasing negativity as the pH increased to 9.5 from 5.0. The dependence of the mobility of ferric floc on the anions in solution was illustrated (120).

It has been determined that the calcium carbonate sludge particles produced in the lime-soda ash softening process bear negative charges through the entire pH range of softening, and that magnesium hydroxide particles bear a positive charge (119).

The linear increase in mobility of clay particles in suspension from about -.8 mv to -1.7 mv with an increase in hexametaphosphate dosage from 0 to 500 ppm has been established and the resulting increase in removal of the clay particles through an aged slow sand filter noted (71).

The zeta potential is related to the mobility of the particle by a single factor incorporating the viscosity and dielectric constant both of which may be assumed to be constant for a given fluid at given temperature (38, 121). In an aqueous system the proportionality factor at 25° C is taken as being equal to 13 mv/u/sec/v/cm.(122).

2. Micro-organisms. The electromobility of a large number of micro-organisms as given by Bier (123) ranged from -0.76 μ/sec/v/cm to -6.4 μ/sec/v/cm. in the pH range of 6.9-7.3. Douglas and Shaw (124) determined the mobility versus pH relationships on a variety of model particles formed by coating hydrocarbon droplets (themselves negative-

ly charged (125) in all but the pH range below 3 and of a uniform charge above pH 9) with protein, lipid, polysaccharide, nucleic acid and products derived from bacteria. Relationships between mobility and chemical structure of the adsorbed surface layer were noted and the application of mobility versus pH curves for determining the nature of unknown bacterial surfaces were discussed. It was determined that the behavior was governed essentially by the number and ionization of the carboxyl groups on the surface. It has also been determined (126) that the principle if not exclusive charge group on Bacillus subtilus, Bacillus cereus and Bacillus magatherium was the carboxyl group.

3. Algae. In contrast to the numerous works in determining the zeta potential or electrophoretic mobility in the study of hormones, enzymes, micro-organisms, animal and human tissue, organic and inorganic material, and in the soil sciences, very little work has been undertaken in the determination of the surface characteristics of algae.

A bibliography of electrophoretic studies compiled in 1955 (127) lists some 3600 references in the fields mentioned above and others. This extensive bibliography lists no works dealing with algae. A study of the literature revealed only three direct references on the measurement of surface charge associated with algae.

The observations of Thornton (128) were made prior to all but the most elementary experimental work in the field of surface phenomena. This work would be of only academic interest if it were not for the fact that the results were diametrically opposite to later work, in that Thorton interpreted algae as bearing a posit-

charge.

Kolin, in an article published in 1955 (129), claimed success in separating a mixture of Chlorella and Ankistrodismus by an electrophoretic technique. Neither the absolute mobility nor the zeta potential were determined, rather, the relative charge on the cells was indicated, which pointed to the Chlorella having a greater charge than Ankistrodismus at the time of the experiment.

Ives (110) appears to have been the first to undertake an extensive study of mobility and hence the zeta potential associated with algae by means of electrophoresis. No corroborating work is known and certain of the techniques used and conclusions reached present fields for discussion.

The size of an organism did not appear to affect the zeta potential, and except for the Myxaphyceae, the values of the zeta potential for algae at natural water pH values were similar in magnitude for those of the cultured algae at the same pH.

In this study, the electromobility of eleven different algae of four classes was determined, and from this the zeta potential calculated. All organisms were electronegative and the absolute values were low, varying from 7.6 to 11.6 millivolts when the study was conducted on the organisms in their natural environment. This is in comparison to the usual range of zeta potential on colloidal particles being from 25 to 50 millivolts.

It was found that the value of mobility of a single cell of an algae (e.g. Asteronella) was the same as for the colonial organism. When the pH of the water was varied with sodium hydroxide or hydrochloric acid from the range of 3 to 11 to ascertain what in-

fluence this might have on the isoelectric point, it was determined that the algae remained electronegative throughout this whole range. However, a minimum zeta potential was determined in the neutral and slightly alkaline pH ranges when cultured algae were suspended in distilled water of varying pH.

Algae Cell Wall Constituents

The main constituents of the cell walls of algae are carbohydrate in nature. By utilizing X-ray defraction (130) techniques, Nicolai and Preston (131) were able to divide the green algae they studied into three groups, depending on the characteristics of the linear polymeric polysaccharides present in the cell wall.

1. Those which showed that the principle skeletal substance was well oriented highly crystalline native cellulose.

2. Those which showed a skeletal substance which was of the approximate crystallinity of reconstituted cellulose or a cellulose derivative.

3. Those which showed the major skeletal substance to be neither native nor reconstituted cellulose.

Northcote (141) reported that subsequent work indicated an incorrect interpretation of original X-ray defractions due to deposits of clay minerals. With the removal of these, a large number of the species examined were shown to contain native cellulose.

The crystalline material of cell walls usually is organized in a system of microfibrils which are embedded in an amorphous or continuous matrix. There is evidence that sugars which are non-glucosidic in origin may be present in the microfibrellar structure as well as in the matrix material.

Muscellaginous material containing large amounts of polysaccharides may cover the cell, lying outside the matrix and microfibrellar region and forming a separate portion of the cell wall.

The constituents of the 30-70% water soluble materials of an alga cell wall have been identified as polysaccharides and acids derived from them (132).

The probability that protein forms a general and important constituent of the cell walls of algae has been raised by Northcote (141).

4. Activated Carbon - The zeta potential has been determind on a slurry of 1 gram of powdered activated carbon in one liter of distilled water (51). The average potential was -36.5 millivolts with values ranging from less than -25 to greater than -50 millivolts. The high value of the zeta potential has been advanced as a reason for the slow settling characteristics of activated carbon in water. It has been suggested that the charge on activated carbon may be due to unsatisfied carbon bonds at the particle surface (90), and ionizable terminating groups containing oxygen and hydrogen (133).

5. Clays - Clay has been defined as that fraction of the erosion products of rocks derived from chemical decomposition which have a grain size of less than about .002 mm, and in common with all soil particles, carry a negative charge (134). The clay minerals are composed of layers of silicon oxides and aluminum oxides. The negative electrical charge borne by the clay particles has been explained as being due to (a) the broken bonds at the surface of the mineral (92) or (b) the negative positions in the lattice brought about by the substitution in the lattice of a cation of lesser

charge but of similar size i.e. AL^{+3} for Si^{+4} and Mg^{+2} for AL^{+3} (93). This charge, due to excess oxygen valences may be balanced with external and exchangeable cations (91).

Rate of Flow of Fluid

The rate of filtration as presently practiced, is tied to Fuller's report of the last century (2). The fact that the accepted filtration rate of 2 gpm/sq.ft. is at times arbitrary and does not reflect the ability of a plant to produce a suitable effluent, has led to the continuing interest in higher rates of filtration with modification of the floc characteristics.

The general equation of flow of a single fluid through a bed of porous material is a restatement of equation 4:

$$H = f \frac{L \mu v S^2 (1 - P)}{g \rho \quad d^2 \quad P^3}^{3-n} \qquad (12)$$

in which n is the stateofflow factor which varies from 1 for laminar flow to 2 for fully developed turbulent flow (66).

Various attempts have been made to numerically tie the rate at which a filter operates to penetration of coagulant and length of filter run. For a head loss of 8 feet the penetration of iron floc into a uniformly sized media has been shown to be proportional to one over the flow rate raised to the 1.56 power (42). Baylis, (7) on plant scale operation, found the length of filter runs up to 8 feet head loss, to be proportional to one over the flow rate raised to the 1.5 power. On pilot plant operation the length of filter runs up to 7 feet of head loss through beds of uniform sand were found to be proportional to one over the flow rate raised to the 1.48 power (43).

Hudson, (115) has suggested that there are reasons to believe that turbulent flow may take place in filters operated at high rates of flow, using coarse media or at time of high head loss.

It has also been stated that a filter operated at 4 gpm/sq. ft. will pass more than twice the turbidity than when operated at 2 gpm/sq.ft (137). This has not been substantiated and Baylis (11) reported less than 50% difference in material passage between rates of 4 and 2 gpm/sq.ft. provided adequate floc strength was maintained and the water well conditioned. The above figures were obtained from six years of records of the material which passed a filter and was retained on a cotton plug. Robeck (37) showed that the turbidity removal at 2, 4, and 6 gpm/sq.ft. were all adequate and of about the same order. Similar satisfactory removal of activated carbon was also achieved provided a coagulant aid was applied to supply a strong floc.

In filtration where the head loss versus time curve tends to get steeper as the run progresses, Hudson (137) contended there is not much advantage in operating the filter to a high loss of head. It was pointed out that constant pressure filtration might yield better quality water than constant rate filtration (115). Evaluation of filter performance when operated at rates which were gradually reduced from 4 gpm/sq.ft. as the head loss increased (16), revealed the inability of filters and apurtenances, which are designed for 2 gpm/sq.ft., to be operated at elevated rates. Although the quality of the water was not impaired at the high rates, the high head loss built up initially would result in less production of water than would be realized at reduced initial rates.

There is a period of passage of suspended matter through a filter at the start of each filter run. The operation of the filter to waste would eliminate this slug of highly turbid water from the system. It is now not general practice to operate a filter in this fashion, but rather to accept this turbid water as it usually only adds a small percentage of the amount of suspended material passing a filter during a complete run. The length of breakthrough is dependent, among other things, on the sand size and the duration of the breakthrough suggests that the coarse filtering material requires a length of time in excess of that required for finer material before it becomes fully effective in filtration (69). The magnitude and length of the breakthrough is proportional to the filtration rate (75). A slow start during which the filter is brought up to full flow rate over fifteen to sixty minutes is indicated by British studies (116) to be beneficial in eliminating, to some degree, the start up of breakthrough.

Hudson (81), records the results of comparison tests between two sand filters of .8 mm effective size, one operating at a constant rate of 2.4 gpm/sq.ft. and the other at a declining rate of 2.7 to 2.1 gpm/sq.ft. Evaluation of the effluent water was on the basis of suspended solids concentration. It was reported that a year's trial resulted in higher quality water being produced by the declining rate filter, together with longer filter runs, even without the addition of a coagulant aid. Similar studies conducted at Chicago, incorporating the use of activated silica, did not yield an improved effluent, but did, however, result in a fifty per cent increase in the length of filter runs (106). A 160 m.g.d. water

treatment plant was designed with filters composed of twenty inches of sand with an effective size of o.54 mm incorporating optional variable rate filtration on the basis of the criteria developed during the above tests (138).

Uniformity of Flow Rate

The passage by a filter of higher amounts of suspended matter for a period immediately following an increase in the rate of filtration, has been observed (17). Recently, a study of effluent quality as effected by varying flow rates was conducted (117) on uniform coarse sand. It was concluded that the amount of material flushed through a filter as a result of a flow variation is dependent upon (i) the magnitude of the variation, being zero for a 10% instantaneous increase and 22.5 times as much at 100% variation as at 25%, and (ii) rate at which the change is made, and is independent of the duration of the disturbance. The result of the study reflects unfavorably on the practice of filtration rates controlled by demand requirements.

III. EXPERIMENTAL APPARATUS AND PROCEDURES

General

The experimental apparatus employed in this research was the result of design which would allow a maximum degree of flexibility of operation yet result in a system in which the physical factors of filtration could be controlled with a high degree of precision.

In the design of filter equipment the following factors were deemed of primary importance:

1. that the head be maintained at a precise level.
2. that the rate of filtration be maintained at a precise quantity.
3. that the filters be designed so as to allow the introduction of various quantities of chemicals and particulate matter to each, or a combination of the filters.

In short, the equipment influent arrangements had to be flexible yet the control on the effluent was required to be accurate. A schematic diagram of the complete apparatus is shown in Figure 1.

The Filters

Four filters were constructed of extruded acrylic plastic of 3 3/8" inside diameter and having a wall thickness of 3/16". Each filter consisted of two lengths of flanged plastic tubing, the bottom section being four feet in length and the upper section four feet six inches. The flanged ends were clamped with 3" "C" clamps, a watertight seal being made with a gum rubber gasket. The bottom section was equipped with piezometer, sampling and discharge ports. Figure 2 depicts a model filter.

The filters were designed to operated with a twenty-four

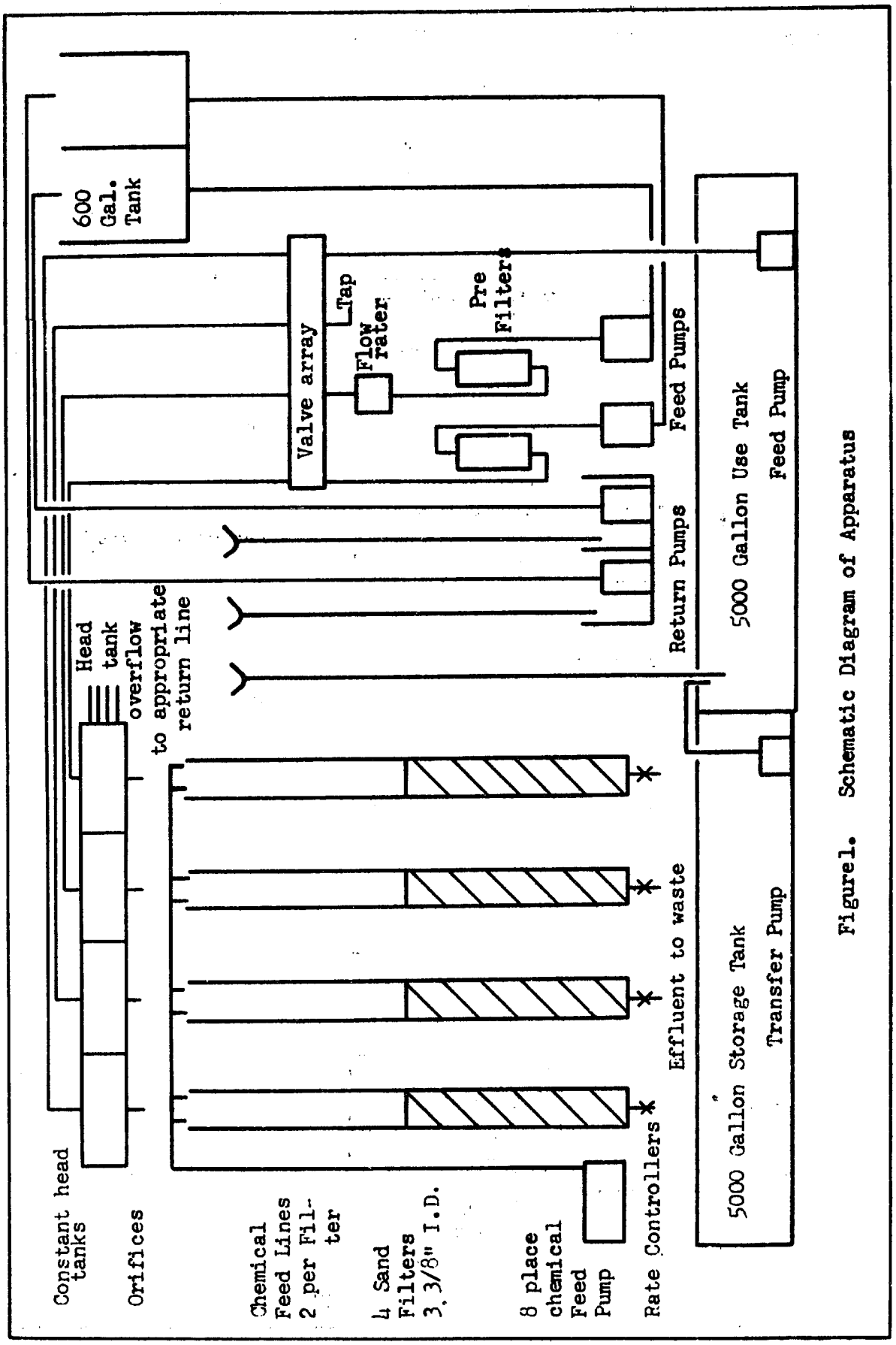


Figure 1. Schematic Diagram of Apparatus

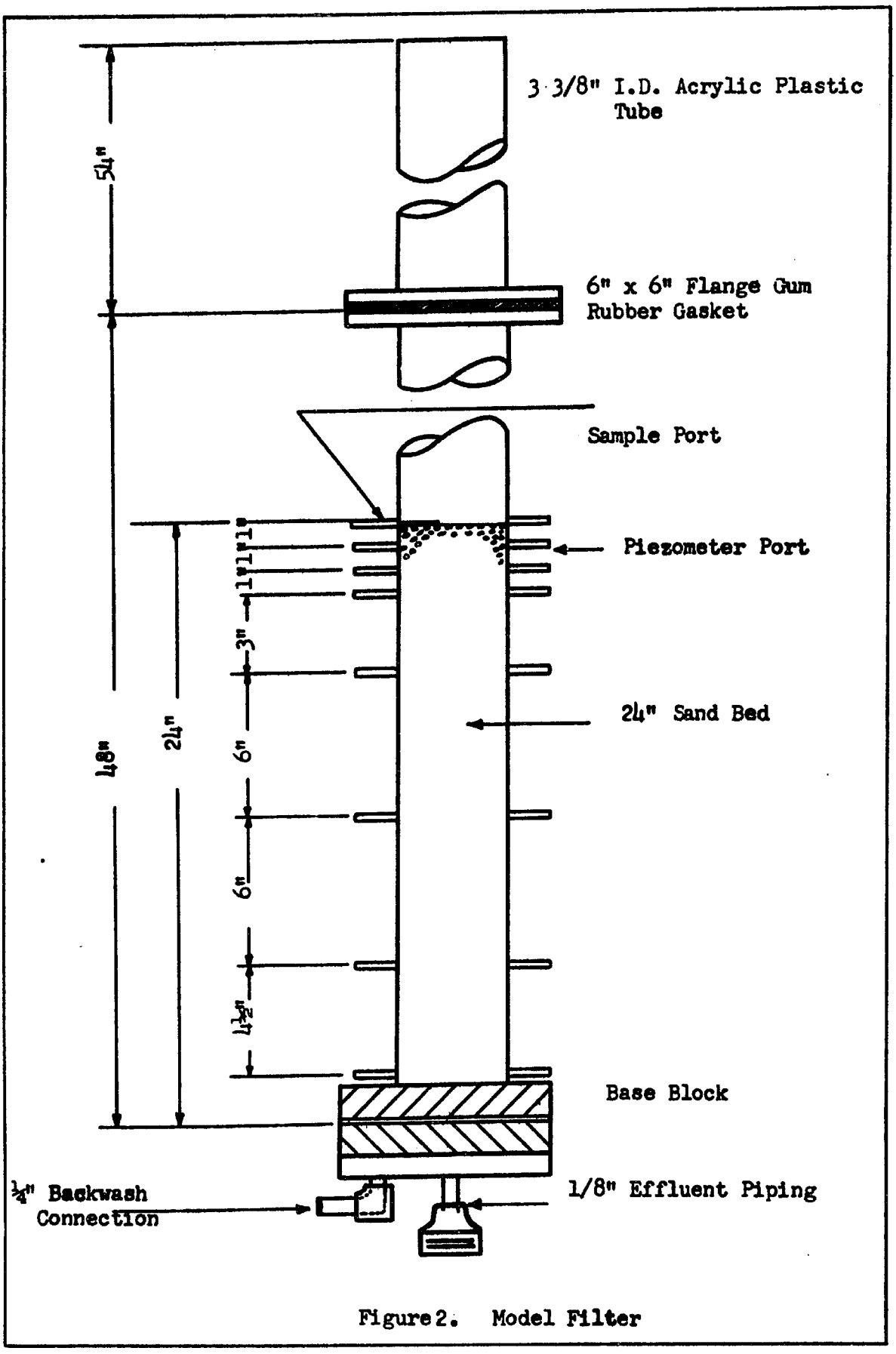


Figure 2. Model Filter

inch sand depth and had both a piezometer and a sample draw-off tap at the location of the sand surface (twenty four inches from underdrain) and 1, 2, 3, 6, 18 and 22½ inches below this point. Both piezometer and draw-off taps were constructed of ¼" I.D. acrylic tubing which was threaded to engage holes tapped in the filter tube. It was intended to have the tap tubes removable and a Teflon tape gasket was used to make a watertight seal. This material, however, was cut by the rough edges of the threads and could only be used once; in consequence, a thin layer of liquid plastic was finally placed around the tap and sealed it to the tube. When removal of the tap was required, due to breakage or plugging, the hardened liquid plastic was peeled off and the ¼" tubing unscrewed. Breakage of the tap tube in the hole was remedied by retapping the hole. The piezometer and sample taps were constructed as shown in Figure 3.

The piezometer tap was composed of a disc of stainless steel mesh between two sections of ¼" I.D. plastic tubing, the pieces being secured by a collar of 3/8" I.D. acrylic tubing cemented to the other pieces. The stainless steel discs did tend to clog with the iron used as coagulant. The procedure was established to wash these parts with 1:5 hydrochloric acid when the filter was dismantled between runs. Sulfuric acid was not used as it had a tendency to cloud the plastic and corrode the wire mesh. This arrangement of piezometer parts allowed rapid response of the piezometers to change in head yet was not subject to plugging by the sand particles.

The piezometer taps were connected to the piezometer tubes by means of a section of ½" I.D. machine-made rubber tubing of 1/16"

wall thickness. The piezometer tubes were made of 2-4 foot sections of 11 mm glass tubing mounted on a sheet of ½" plywood placed behind the filters. The piezometer board was covered with profile paper marked into feet, inches, and tenths of inches.

The sampling points were also constructed of ¼" I.D. plastic tube through which a ½ mm capillary tube was passed; the space between the two was filled with liquid plastic which was allowed to harden while kept in place in a vertical position by an adhesive dam. The capillary tube was longer than the plastic tube. It extended about ¼" beyond the plastic on the effluent end of the point, and a varying distance on the influent end. The varying lengths of the points allowed the sampling ports to be located in a vertical line on the front of the filter tube, but placed the influent tips in such a manner that no two fell directly under one another. To prevent the capillary tubes becoming clogged due to entrance of fine sand particles, a length of #24 phosphor bronze wire, slightly longer than the tube, was inserted. Bending the wire flush with the effluent face of the tube prevented it from slipping into the filter or out when the connecting rubber tube was manipulated.

The sampling points were connected by means of 4" of 1/8" gum rubber tubing to 1" long studs of 1/8" I.D. plastic tubing passing through a steady board constructed of a strip of 5/16" sheet plastic. On this flat plastic were mounted needle valves which were connected to the plastic studs by means of 1/8" rubber tubing. This arrangement allowed manipulation of the flow rate when required without the danger of disturbing the sand in the filter due to vibrations; this had been a point of difficulty in sampling emphasized by O'Melia (41).

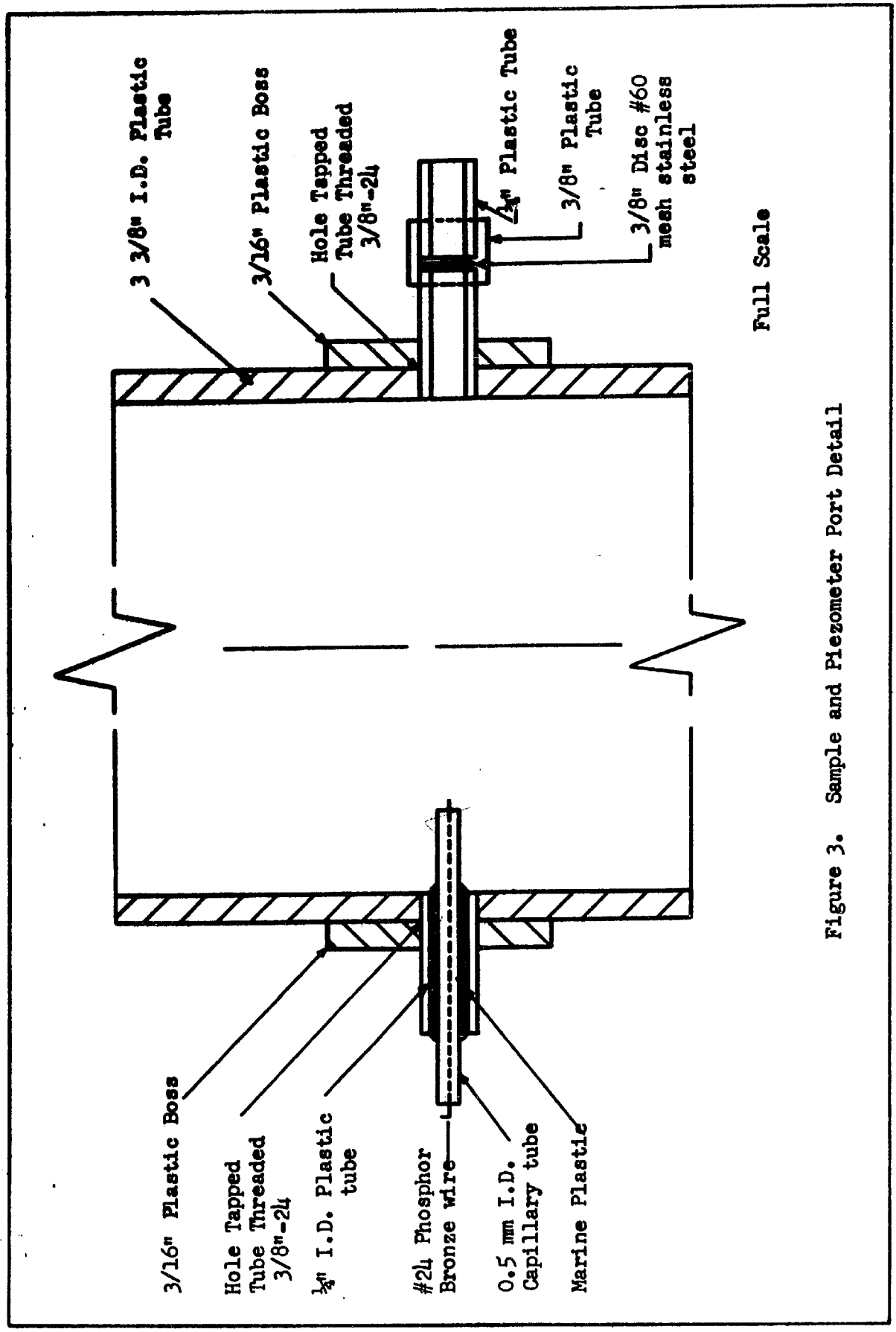
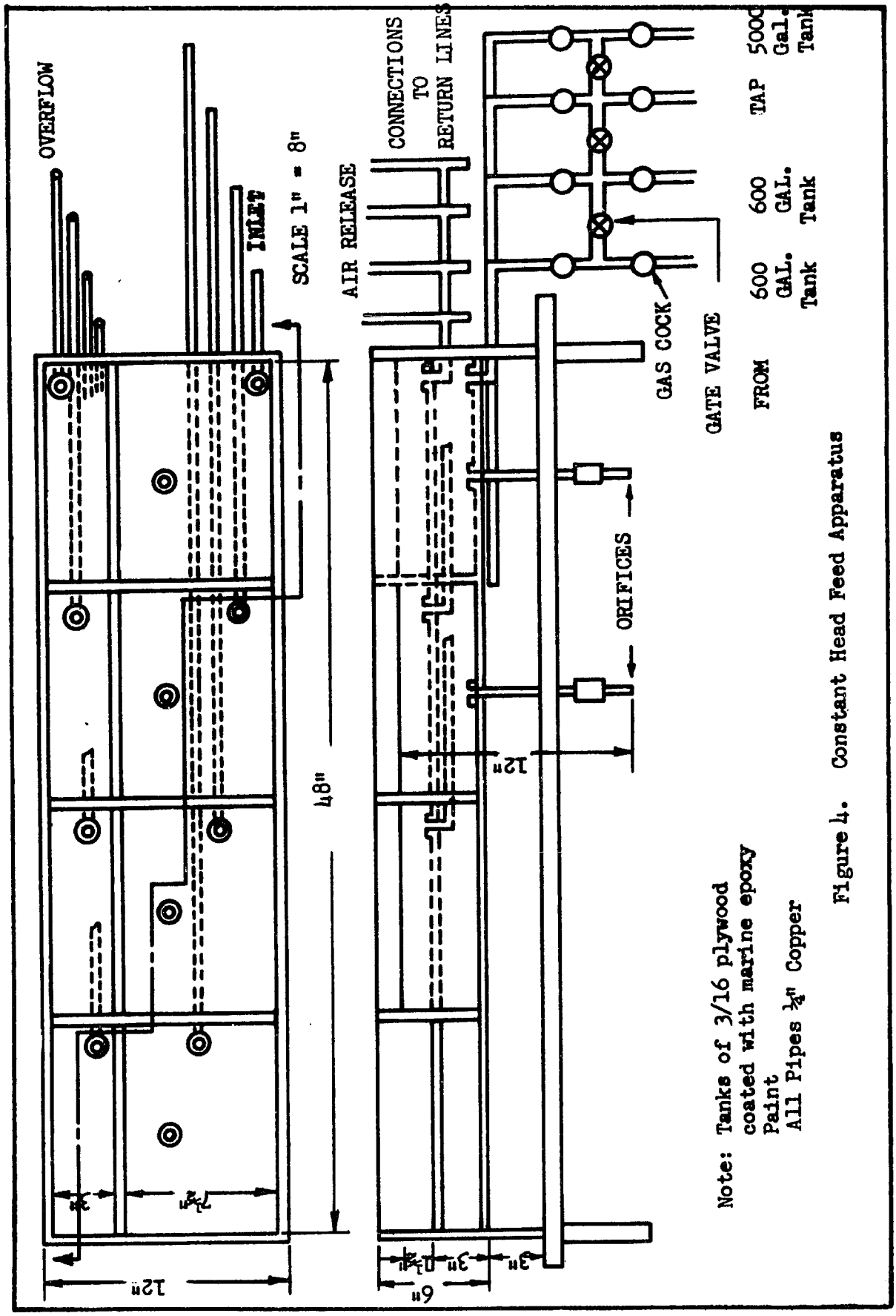


Figure 3. Sample and Piezometer Port Detail



Note: Tanks of 3/16 plywood
coated with marine epoxy
Paint
All Pipes ¾" Copper

Figure 4. Constant Head Feed Apparatus

It was found that a flow rate from the sampling points of less than 2 cc per minute could be maintained with the above apparatus.

It was also found that constant discharge through the sampling points yielded consistent results unobtainable when the points were closed between sampling periods. The liquid from the points between sampling periods was directed to the drain through a plastic tube riser attached to the plastic sample point steady board.

Liquid feed to the filters was through calibrated orifices operating under a constant head. Figure 4 shows the arrangement of the constant head tanks, inlets, orifices, overflow weir and outlet piping. The length of the overflow weirs is 11 inches, the head on the orifices is 12 inches, and the four orifices used in a series delivered either 110, 220 or 435 cc per minute. The orifices were calibrated to read within one cc per minute of one another. The inlet piping arrangement allowed individual liquid feed to individual filters, the same feed including tap water, to all filters or the same feed to two or more filters. A high degree of flexibility was obtained with the feed system as shown in Figure 4.

When it was desired that the feed contain other chemicals or organisms, these were delivered directly to the filter top by means of peristaltic pump units.

Water used in the experiments was obtained from the City of Ann Arbor distribution system which services the University. When drawn from the tap, the water was considerably cooler than the room housing the filtration equipment. To ensure that there would be no possibility of dissolved gases forming bubbles in the experimental apparatus, the water to be used for a series of runs was stored in

order that chemically similar water was available for the series, and heated to bring it to temperature equilibrium.

The water was discharged from the main into a 5000 gallon concrete tank. An electric heater controlled by a thermostat was incorporated in this tank to raise the temperature of the water to approximately room temperature. The temperature of the water used was found to vary between 21 and 25 degrees centigrade throughout the time that experimental work was in progress. A laboratory mixer was installed in parallel with the heating mechanism, and was allowed to operate continuously except prior to removal of water.

Considerable amounts of precipitates accumulated in this tank as the water reached temperature and chemical stability. pH adjustment was made using concentrated HCL to bring the water from its usual value of 9.6 to 10 to the range of 7.0 to 7.5. The high pH value of the tap water is the result of softening practiced at the water treatment plant.

After being aged as required, the water was transferred to a use tank of similar size and construction as the storage tank. From here some of the water was pumped to two six hundred gallon day use tanks. If required, water could be pumped from the 5000 gallon use tank directly to the filter apparatus constant head tanks through the feed line valving array. Water in excess of that required during the experiment was discharged over the weir of the constant head tanks and returned to the use tank by gravity.

The water containing algae which was kept in the 600 gallon day use tank was delivered to pumps which discharged through the inlet valving array to the constant head tanks. Two prefilters in the

discharge line from the pumps insured the removal of large foreign bodies which may have entered the open tanks and which might have interrupted the constant flow from the calibrated orifices to the filter. The prefilters were composed of sections of plexiglass tubing, stoppered at each end, and containing 1 inch of -16 to +20 sand supported on a porous plastic disc. Provision was incorporated for backwashing these units.

Rate of Flow and Liquid Level Control

The desire for an open-ended filter system led to the necessity of providing a constant head on the filter which had to be controlled within narrow limits. A rate of flow control system was required which would provide automatic operation, as it was determined that loss of head through the filters could increase by approximately eight feet in a few hours. The rate of flow and liquid level control system finally developed met the above requirements and functioned without major difficulties. In essence, the rate of flow control is a motorized valve, the action of which is governed by the level of water in the column above the filter. Figure 5 shows the construction of the rate of flow controller and associated equipment.

The needle of a standard 1/8" needle valve was machined down in such a manner that the number of turns of the shaft from full "on" to the full "off" position was increased to eight, and the discharge under a given head through the valve was almost linear except for some irregularities at very low flows i.e. in the range of 25 cc/min. and less. The stem of the valve was drilled and tapped to receive a 10 x 24 machine bolt. A slotted aluminum shaft, driven by a reversible 1 rpm synchronous reversible motor through a flex-

ible rubber connection provided the operational power for the valve. The valve was mounted in a horizontal position by means of two U bolts on a valve steady box constructed of 3/4" plywood. The inlet to the valve was provided with a short nipple and one half of a union which connected the valve to the bottom of the filter. The drive train for the valve extended to the right of the center line of the filter. The motor was mounted on the exterior of the valve steady box which was bolted to the filter support frame.

Electrical connections to the motor were made to jacks mounted in the steady box. All electrical wiring connections to the valve motor were made by means of plugs to these jacks, thus the motorized valve assembly could be easily disconnected physically, and removed for service and repair, if required. Electrical feed to the motor was introduced through the common lead.

Liquid level control was accomplished by means of a plastic ball float which operated either one of two micro switches depending on the level of the water. Electrical feed from the valve motor was applied across the micro switches. Whichever micro switch was operational due to the action of the float arm would complete the circuit to the appropriate terminal of the valve motor. Thus, as the head loss in the filter built up, the water level would rise, raising the float, and activating the upper micro switch. When the current was applied the circuit was completed to cause the valve motor to turn in the direction appropriate to open the valve.

If the level of the water for some reason fell below that required the "close" micro switch would complete the circuit to the motor closing the valve during the period of current flow. In-

corporated in the level float apparatus was a manual override and a direction of rotation switch. By means of these, the motor of the valve could be operated in either direction regardless of the location of the water level.

To reduce wandering of the water level a "normally closed" solenoid valve was placed in parallel across the "open" motor contacts. The operation of this valve was to withdraw a maximum of about 50 cc of liquid from above the filter. This immediate response reduction in control water level eliminated over opening of the rate of flow control valve. The total amount of liquid discharged from this valve was constantly less than 1% of the water applied to the filter. It was found that the 110 volt line to the solenoid had to be opened between successive operations to ensure proper functioning. This was accomplished by placing a relay in the line to the solenoid which was activated by an electric timer.

A further method of reducing the tendency of the water level to wander, due to over correction, was to feed the current to the rate controllers through a timer. This instrument was set in such a manner as to give a two second pulse once every minute. The length of pulse resulted in a rotation of the valve shaft of approximately 15°. The line to the solenoid valve was opened by the timer every other pulse. This resulted, when the "open" micro switch was activated, in the rate controller valve opening on two pulses, during one of which the solenoid discharged. Or if the "close" micro switch was activated the rate control valve closed on every pulse. When the liquid level was at the desired level neither of the micro switches were activated. Physical spacing of the micro switches governed the

null gap position.

The water level control mechanism was designed to maintain the level of the water within ½ inch of the desired level. The mechanism operated in a most satisfactory manner, requiring no attention during the course of the experiments, some of which lasted 50 hours and some of which developed 8 feet of head loss. Figure 6 shows a schematic diagram of the rate controller circuit.

Filter Bottom and Underdrains

Previous experience with acrylic plastic filters (41) indicated that leaking was likely to be a problem if the flanged section were subjected to pressure, this being especially so at the bottom of the filter where maximum head existed.

The bottom of the filter sections of plastic pipe were attached to wooden block 1½" thick and 6" square by means of marine plastic introduced in six lifts between the tube and the block. The outside of the tube and the inside of the block were scored to provide better grip. A block of wood of similar size held the porous polyethylene underdrain and provided a transition basin below the filter. The plastic underdrain was secured to the block to prevent passage of sand during filtering and so that there would be no shift when the filter was backwashed in place.

Four ½" bolts were counter sunk into the corners of the bottom block and sealed in place with marine plastic. These bolts passed through holes in the upper block and through a bearing plate of steel 3/16" thick. Pressure of the nuts was distributed around the blocks. It was essential that the faces of the blocks were flat and smooth.

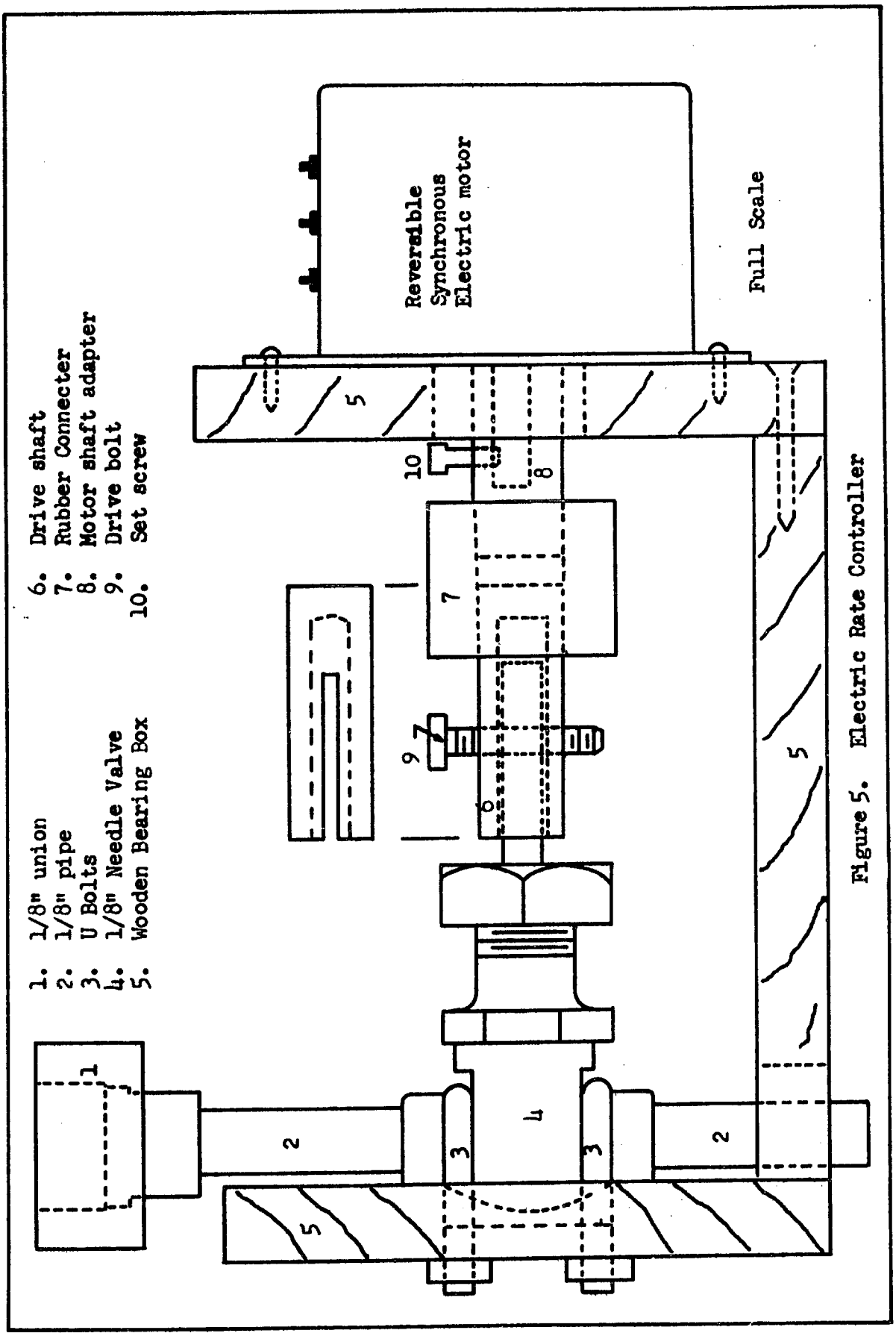


Figure 5. Electric Rate Controller

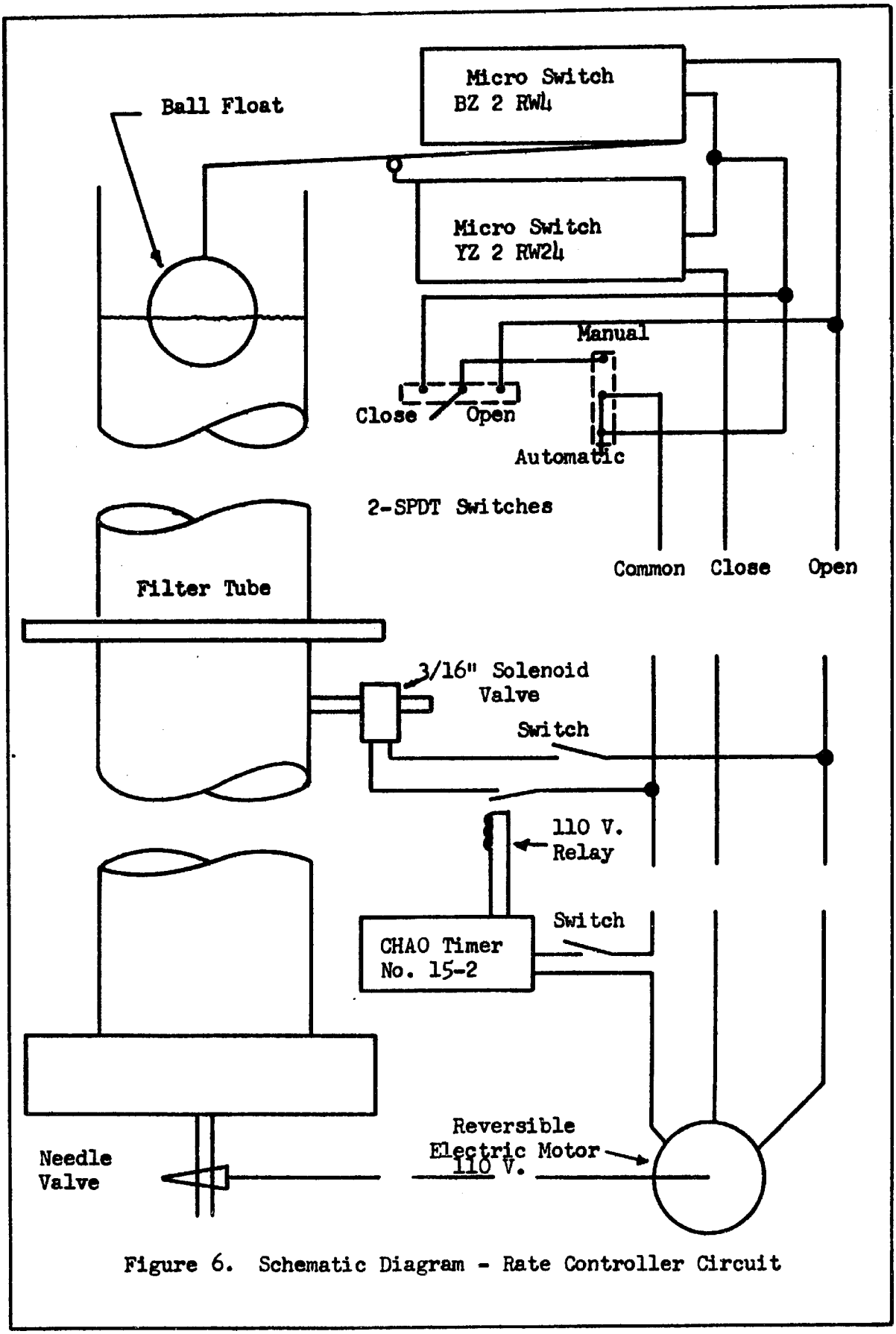


Figure 6. Schematic Diagram - Rate Controller Circuit

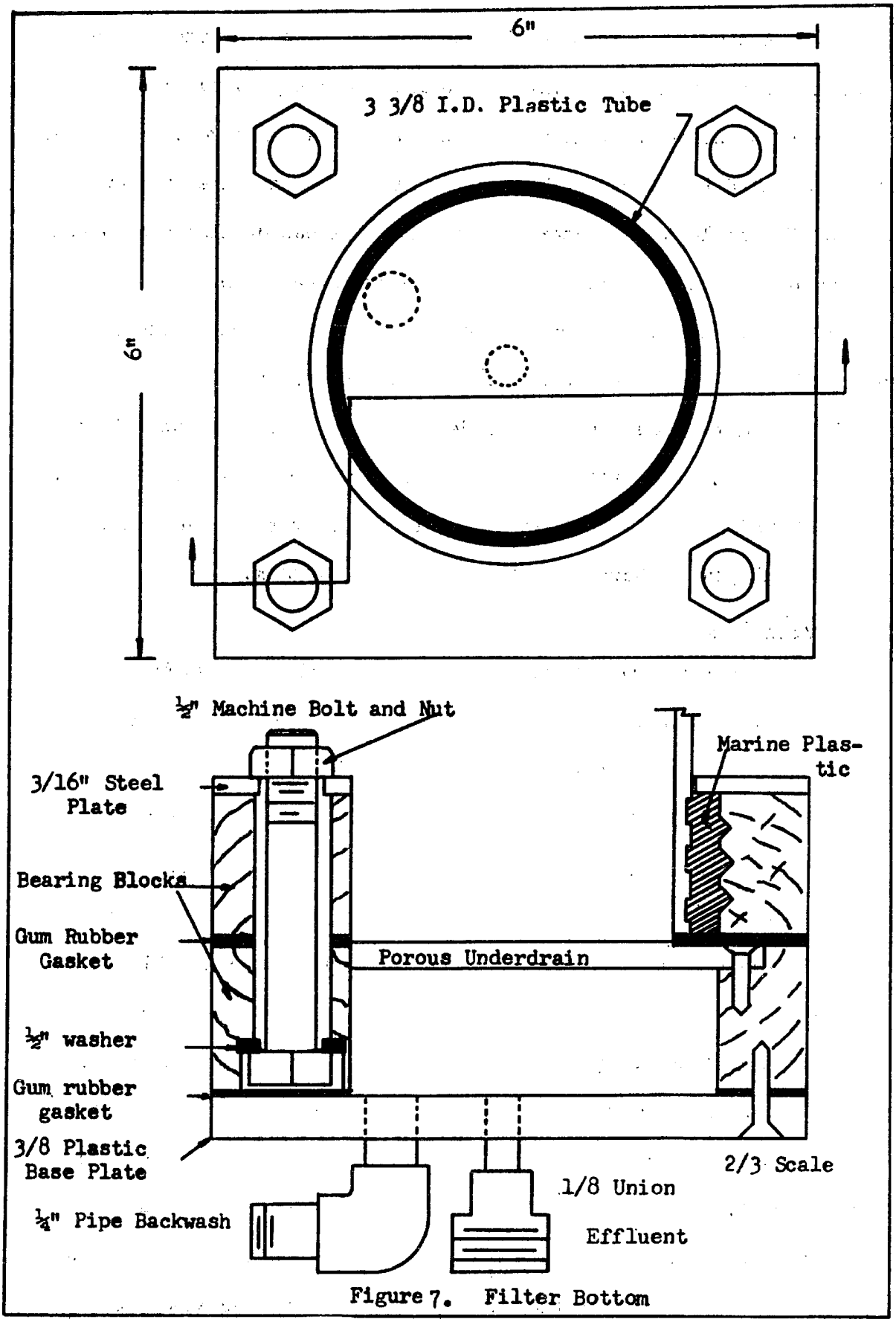


Figure 7. Filter Bottom

A sheet of 3/8" plastic was secured to the bottom of the block by means of screws. This was drilled and tapped to accept a 1/8" pipe in the center. A nipple and half of a union were installed. This connected to the other half of the union on the rate of flow valve. To the left of center the bottom sheet was drilled and tapped to accept a ¼" pipe which carried the backwash water into the filter. A permanent backwash line was placed below and in front of the filter bank. Four valves were installed and from the outlet of each a heavy flexible hose carried the water under pressure to the backwash inlet to the filters. The filter bottom blocks produced a wide stable base when fitted between two 1½" steel angles which supplied the filter support. Figure 7 shows in detail the filter bottom.

Algae Culturing

A green alga which had been grown under laboratory conditions for some years was the principal organism used in this experiment. This organism was particularly amenable to growth in inorganic nutrients under artifical illumination, and was of a type that had been proven to have high filter penetrating abilities (41). This organism was identified by Dr. A. M. Beeton of the Department of Civil Engineering Faculty as Selenastrum gracile Reinsch. This organism as grown was mainly in individual cells, rather than in colonies. It is of a crescent shape with dimensions of about 3 x 15 microns.

Another organism employed was a filamentous form, similar to that identified as Schizothrix calcicola and reported on by Echelberger (49). This organism at times overgrew the green algae in the cultures, especially those which were old or which had been grown at temperatures greater than 60° F. At the time that the experiments

were undertaken this organism was under active culture in the laboratory.

During the time of the experiments, algae was cultivated in batch cultures. Stock cultures were carried in five liter containers, and when a quantity of algae was needed a stock culture was transferred to a larger container, its volume increased to fifteen liters and was thus grown for one week. At this time the volume was increased to forty five liters and the culture again grown for seven days. The increases in volumes were made up with tap water and the appropriate concentrations of stock nutrient solutions were added to make up the strength of inorganic nutrients required.

Stock cultures and fifteen liter cultures of algae were carried in clear glass carboys. Illumination was by means of fourforty-watt fluorescent lamps. The cultures were kept cool by immersing the carboys part way in a water bath fed by a continuous stream of water from the city mains. The temperature of the uncontrolled bath varied in the range of fifty to sixty degrees F. The forty five liter cultures were grown in sixty-liter aquariums illuminated by six forty-watt fluorescent lamps and the temperature of the culture was kept at sixty degrees F. by immersing a cooling coil from a refrigerator unit directly in the culture.

Mixing of the organisms in the containers was accomplished by passing compressed air through diffusers suspended in the cultures. The air appeared to provide a sufficient supplementary carbon source and the container walls in time became covered with a carbonate deposit necessitating its removal with acid to permit light passage.

No attempt was made to keep a pure culture. However, it was

found that if the temperature of the culture was kept in the vicinity of sixty degrees F.,frequent transfers of the stock culture weremade and the carboys opening kept covered, the cultures as used would be in the neighborhood of 95% pure.

The most usual contaminating organisms were Schizothrix, Oscillatoria, Chlorella and Scenedesmus which were normally present in small numbers. Usually, the concentration of organisms in the large cultures reached 8×10^6 organisms per milliliter by the end of the seven day growing period and were of surprisingly uniform size, both within the culture and from one culture to the next. Size distribution curves were made on samples of feed fluid from the day use tanks prior to the first series of studies, and the settings employed on the counting apparatus were the same. Distribution curves for subsequent studies showed no evidence to warrant changes, therefore, for all runs the settings for the counting apparatus were the same.

The algae as cultured above were added to the 600-gallon day use tanks in sufficient quantity to give a suspension of the desired number of organisms. These were kept in suspension within the tank by means of mixers which were operated continuously during a run. Filter influent in excess of that required for filtration was discharged over the constant head tank weirs and collected in small sump tanks from where it was pumped automatically back to the appropriate 600-gallon tank.

The formula for the synthetic nutrients on which the algae were grown was originally obtained from the work of Katz and Myers (139) and that used is detailed in APPENDIX I.

Filter Sand

The sand used in the experiments was obtained by sieving a commercial grade Ottawa sand into the required fractions. The first size separation was accomplished by collecting the sand retained on a series of U.S. standard sieves through which 500 grams of sand per run was shaken for fifteen minutes in a Ro-Tap. At least fifty pounds of sand of each of the fractions listed in APPENDIX II were obtained. The sand thus collected was washed in concentrated hydrochloric acid and subjected to hydraulic separation to eliminate any materials of light specific gravity.

The fractions finer than -40+50 were not used in the major portion of the experiments as the head loss associated with the fine size particles was excessive at flow rates in excess of about 110 cc/min. and the build-up of head loss with the addition of a coagulant was too rapid to yield practical results.

After an initial period of use it was determined that the head loss versus depth curve of the sands was not liniar. This effect was similar to that observed by Gosh (39) and it indicated that there was some stratification within the filters of the sand obtained from one sieve fraction. Hand sieving of the entire stock of the sand was undertaken to ensure that the grains within any fraction were indeed described by the geometry of the sieves, and did not reflect the retention of finer particles due to physical behavior of the sieving process. In this resieving process it was determined that each fraction contained an appreciable quantity of fines. With the removal of these the curve of head loss versus depth became a straight line in accordance with the D'Arcy law of

flow through a porous media.

The size of sand particles used in the experimental work was determined by (i) the arithmetric mean of the adjacent sieve size openings, (ii) the count and weigh method first outlined by Hazen (45) to obtained the particle size by expressing the weight in terms of an equivalent sphere; the value of the diameter of the equivalent spherical particle is:

$$do = 0.9 \sqrt[3]{\frac{W}{N}}$$

where W = weight in grams
N = number of grains

This assumes a specific gravity of 2.65 which is consistent with the findings for the sand used in these experiments; and (iii) the microscopic measuring of the principal axes of a number of grains.

The results of the various determinations are presented in APPENDIX III. Throughout the body of this report sand sizes will be referred to by sieve fractions.

The specific gravity of a sample of the sand in each of the sand sizes was determined prior to the use of the sand and after the sand had been used for some months. There was a very slight but measurable decrease in the specific gravity of the sand with use. These determinations were conducted in accordance with ASTM Test D 854-58 and the results of the determinations are reported in APPENDIX II.

It is speculated that differences in specific gravity were due to the entrance of small pieces of acid resistant material such as dust, paint chips, and plastic chips into the filter media.

EXPERIMENTAL PROCEDURE

General

Between runs the lower section of the filter tubes were left filled with water to prevent the plastic drying out and leaking at the joints. Prior to a run, the filters were charged with a predetermined weight of the desired size of sand. The filters were backwashed to remove trapped air, and upon settling the filters were vibrated or tapped to consolidate the beds to a depth of twenty four inches after the manner suggested by Ives (57) and O'Melia (41). 12.2 pounds of sand were used per filter which upon consolidation yielded a bed with 40% porosity. The sand was acid washed after each run.

In order to determine the exact location of the deposits within the filter, removable cores of plastic tube were placed in the center of the filter for a number of runs. When plastic tube cores were placed in the filter, the weight of sand was reduced by an amount equivalent to the volume of the tube, thus maintaing the porosity and depth as before. The tubes were suspended in the filter section by removable brass tongs and the sand backwashed until such time as the level of the sand in the tube was the same as that in the filter. After partial consolidation, the tongs were removed and the beds consolidated to the required porosity. The placing of the cores was a delicate and time-consuming operation. The core sections were twenty inches of 3/4" inside diameter, 7/8" outside diameter extruded acrylic plastic. Lengths greater than twenty inches resulted in severe chimney effects and extreme difficulties in obtaining a uniform sand surface in the core and the filter.

After a run had been completed, the cores were removed from

the filter proper and the ends wrapped in plastic film. The cores could then be stored, or immediately analysed for deposit concentration. Visual comparison of the cores and the filters revealed no discernible differences in the deposits.

The cores were cut into the required lengths, usually one inch by means of a fine tooth hand-saw. The sand was washed from the core sections and the adhering deposit subjected to analytical determinations. If the cores were not analyzed immediately they could be stored almost indefinitely by sealing the ends to prevent moisture loss and freezing them.

Prior to a run, the battery of filters were brought to hydraulic equilibrium by introducing into the filters water of comparable chemical make-up to that to be used in the run. During this time a final check-up of all electrical and mechanical equipment was made.

Filter Run Criteria

The filter runs were designed in a manner to comply with the following criteria:

a) The run was to last a minimum of twelve hours.
b) The head loss was not to exceed seven feet.
c) Penetration of iron through the filter was not to be complete.

To comply with the above, the concentration of coagulant had to be varied with each sand size.

Head Loss Readings

Head loss readings through the clean sand were taken at the start of every run. During a run it was attempted to take head loss readings at least every two hours and more frequently at the end of a run as the maximum allowable head loss was approached.

Frequency of Sampling

Samples were taken at increasing time intervals after the start of the run, usually at 1, 3 and 6 hours from the start and every 4 hours thereafter. Analysis of the filter samples was, for the most part, conducted immediately after collection. As forty samples constituted a series for each sampling period, it was necessary to employ rapid methods for the determinations of algae and iron.

Iron Determination

Iron was determined colorimetrically, employing the Bipyridine method and utilizing a Coleman Model 14 Spectrophotometer. Throughout the experimental work, the coagulant chemical used was ferric chloride and the expression of quantity of coagulant used in this report is milligram per liter of iron.

pH Determination

Determination of pH as required was conducted with a Beckman Model H2 pH Meter and glass electrode. Dilute sodium hydroxide solution was pumped to the filters to maintain a constant pH.

Algae Determination

Before the start of a run a microscopic count of the algae in the culture to be used was made, employing a haemocytometer cell. On the basis of this count a suitable quantity of the culture was transferred to the water in the 600 gallon day use tanks to make a dilution of the desired concentration. A distribution curve was run on this feed water to check that the concentration of organisms as calculated had been obtained.

The instrument used to count algae was a Model B Coulter Counter. A description of this instrument and the operational procedures of its use are detailed elsewhere (140).

The instrument was used as a particle counter on samples taken from the filter and to size particles prior to the runs. A distribution curve was made prior to a run by plotting the counts obtained against control setting used. The counts corrected for background and coincidence, if necessary, produced a plateau on the plot which usually extended over a range of three control settings. The magnitude of the counts in the plateau area was that associated with the calculated algae concentration as determined from microscopic count.

When counting low numbers of organisms it was essential that background counts be kept as low as possible and to this end all chemicals, electrolytes and dilution waters were passed through a millipore filter Type RA before use.

It was also imperative that all iron floc be dissolved prior to an algae determination as the floc would break up with agitation and give varying and false high counts. Details of counting techniques are given in APPENDIX IV.

IV. EXPERIMENTAL OBSERVATIONS AND DISCUSSION

The experimental investigations undertaken within this filtration study were separated into three main categories. The first group of studies, dealing with the plain filtration of algae, were conducted to obtain background information. The second series of investigations , the simultaneous addition of flocculant and non-flocculant material, had as its objective the determination of an appropriate method of utilizing coagulant with the filtration process in order to accomplish optimum removal of filter penetrating particulate matter. Studies in the third section, relating to the pattern of penetration, were conducted to determine the location of deposited material within a filter, both flocculant and non-flocculant, in order to (i) explain certain observations made in the preceding sections and (ii) gain further insight into the filtration processes.

Experimental observations are, for the main part, presented in graphical and tabular form with accompanying description.

An attempt was made to interrelate the observations from various runs, and a reasonable degree of success was achieved considering that it was not intended, nor was it possible, to control precisely all variables in the filtration process, and that the differences between varied systems within a particular run were considered to be of greater interest than those distinguished between similar systems from different experimental runs.

ALGAE FILTRATION STUDIES

Filtration of algal suspensions, which had not received any form of pretreatment, were conducted to verify and expand work previous-

ly conducted by O'Melia (41) and to ascertain if the experimental organisms were responding to the filtration process in the same manner when applied as a suspension as they did when they were applied as a dilution from a batch culture after the manner employed by O'Melia. It was also necessary to determine, for the method under which suspensions of algae were planned to be introduced to the filters, whether a significant removal could be associated with plain sand filtration of algae at conventional rapid sand filtration rates.

Suspensions of relatively pure cultures of different algae were utilized as well as a mixture of organisms. The rates of application studied were 120, 220, and 435 ml/min. Equivalent hydraulic loadings were 0.49, 0.98 and 1.87 gal/min/sq.ft.

Figure 8 for run A-1 shows removal efficiencies associated with filtration of a suspension made from a culture of the organism Schizothrix. From this figure it is apparent that removal efficiencies for all four sand sizes decreased with time and the rate of decrease itself decreased as the run progressed. While terminal removals were of a low order for all sand sizes employed, finer sand sizes exhibited greater removal efficiencies than did the coarser sands.

Analysis of samples taken from the sample ports tapping the filter showed the majority of removal of organisms took place in the upper portion of the filters. This is graphically represented in Figure 9 where the percentage of the number of organisms applied to the filter found remaining in the samples taken at various times is plotted as a function of depth at which the samples were obtained. A progressively smaller percentage of the organisms applied was removed as the time of filtration progressed and this removal was con-

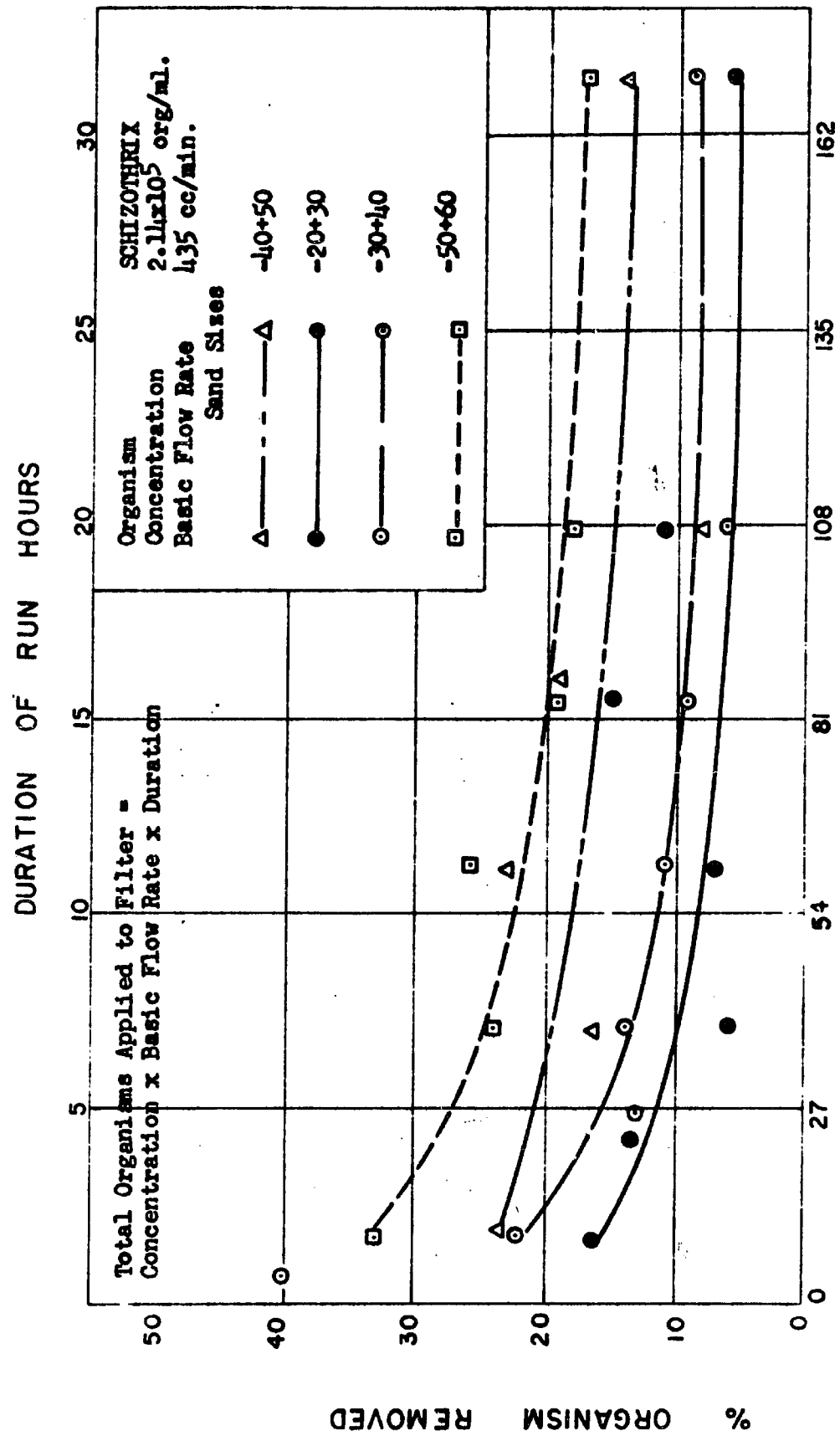


FIGURE 8. Algal Removal Efficiencies of 24 inch Beds of Various Sized Sands Filtering a Suspension of a Filamentous Organism - Run A-1

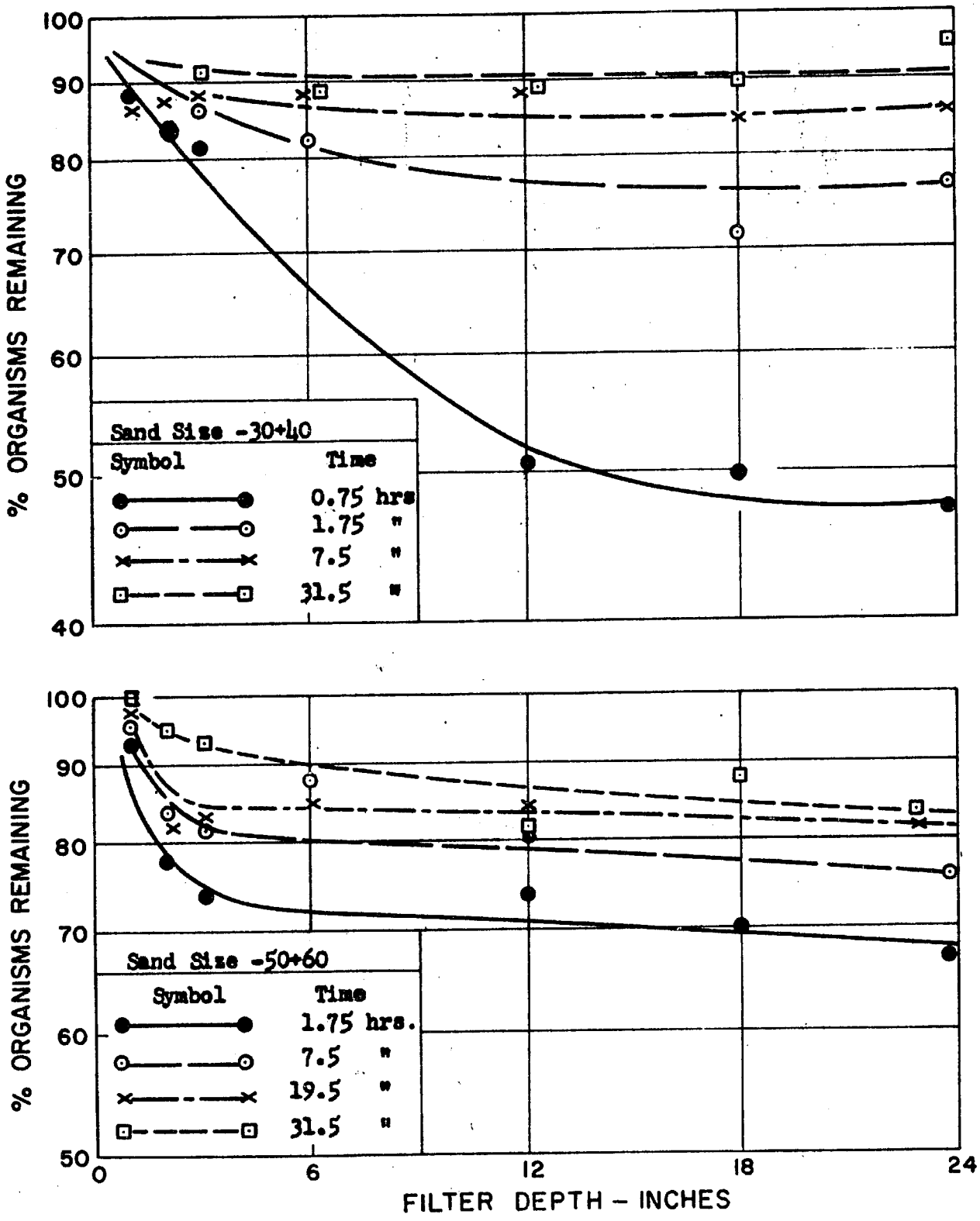


FIGURE 9. Organisms Remaining in Suspension at Various Filters Depths - Run A-1

Organism - Schizothrix
Concentration - 2.14×10^5/org./ml
Basic Flow Rate - 435 ml/min.

fined to the uppermost layers of the filters; this pattern was common to all runs conducted.

Figures 10, 11 and 12 illustrate the removal efficiencies associated with filter runs A-2, A-3 and A-4 of suspensions of seven day cultures of Selenastrum. The basic rates at which these filtration studies were conducted were 120, 220 and 435 ml/min., respectively.

The pattern of removal was consistent in each of these runs and is similar to that determined for run A-1 in that the removal by fine grained media is greater than that by coarse media, and that the removal efficiencies decrease with time with a decrease in rate of removal. Removals associated with the coarsest sand fell to zero in all three runs, and the tendency appeared to be for all removal efficiencies to approach zero with time. The major location for removal of algae was in the uppermost layers of the sand in a manner similar to that evidenced in Figure 9 for run A-1.

Based on total number of organisms applied, removals associated with higher hydraulic loadings are progressively smaller than those associated with lower flow rates. The effect of shear forces due to increased velocity of fluid flow in plain filtration of non-flocculant particulate matter is illustrated.

Resistance to shear forces would appear to differ with different organisms. The filtration rate at which run A-1 was conducted was equal to that of A-4 and was considerably higher than the rates of A-2 and A-3. Removals in run A-1 were higher than in all other runs. The algae used in run A-1 was a filamentous form in comparison to one of discrete shape utilized in subsequent runs.

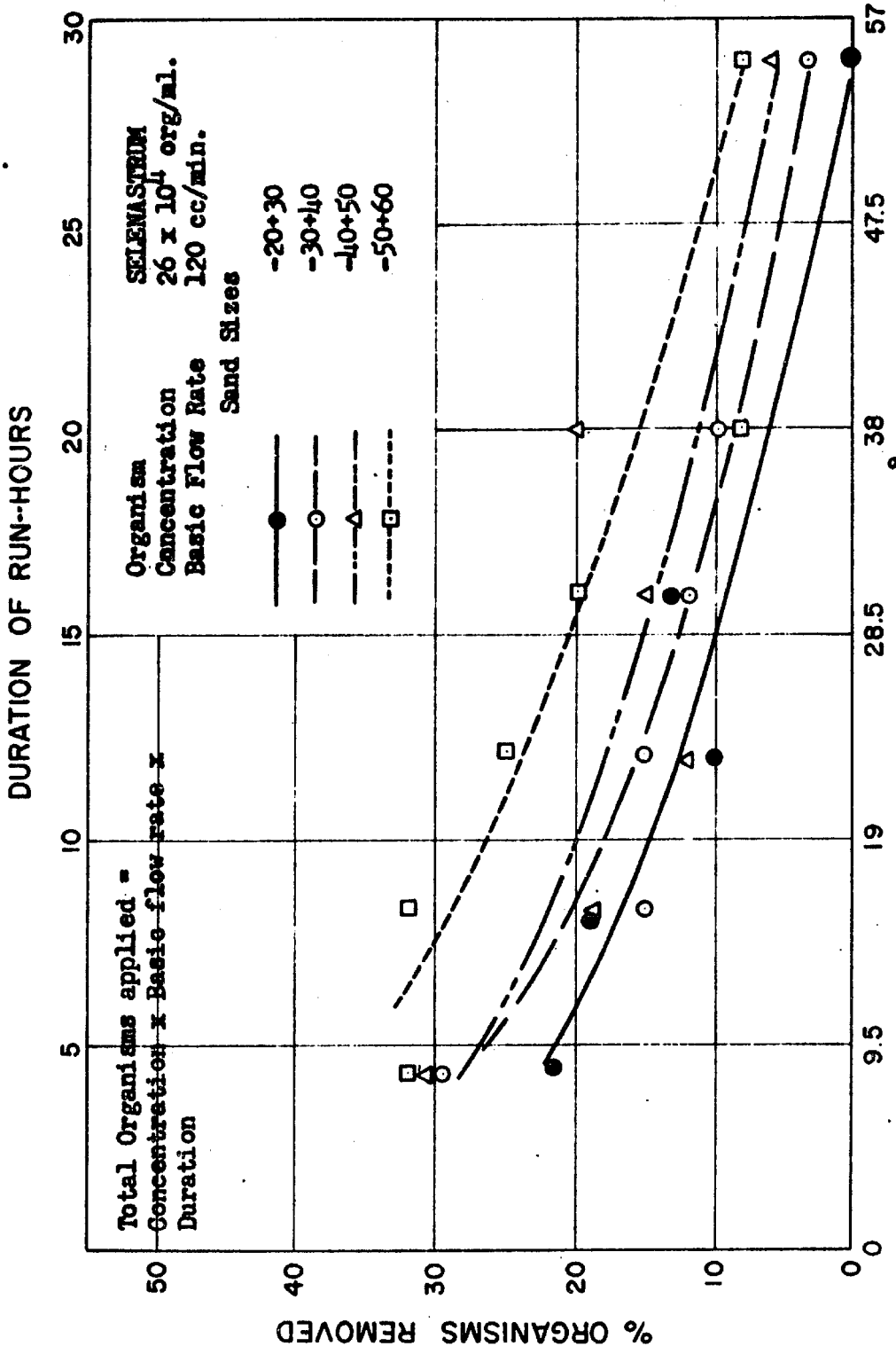


FIGURE 10. Organism Removal Efficiencies for 24 Inch Beds of Various Sized Sands Filtering a Suspension of Selenastrum Run A-2

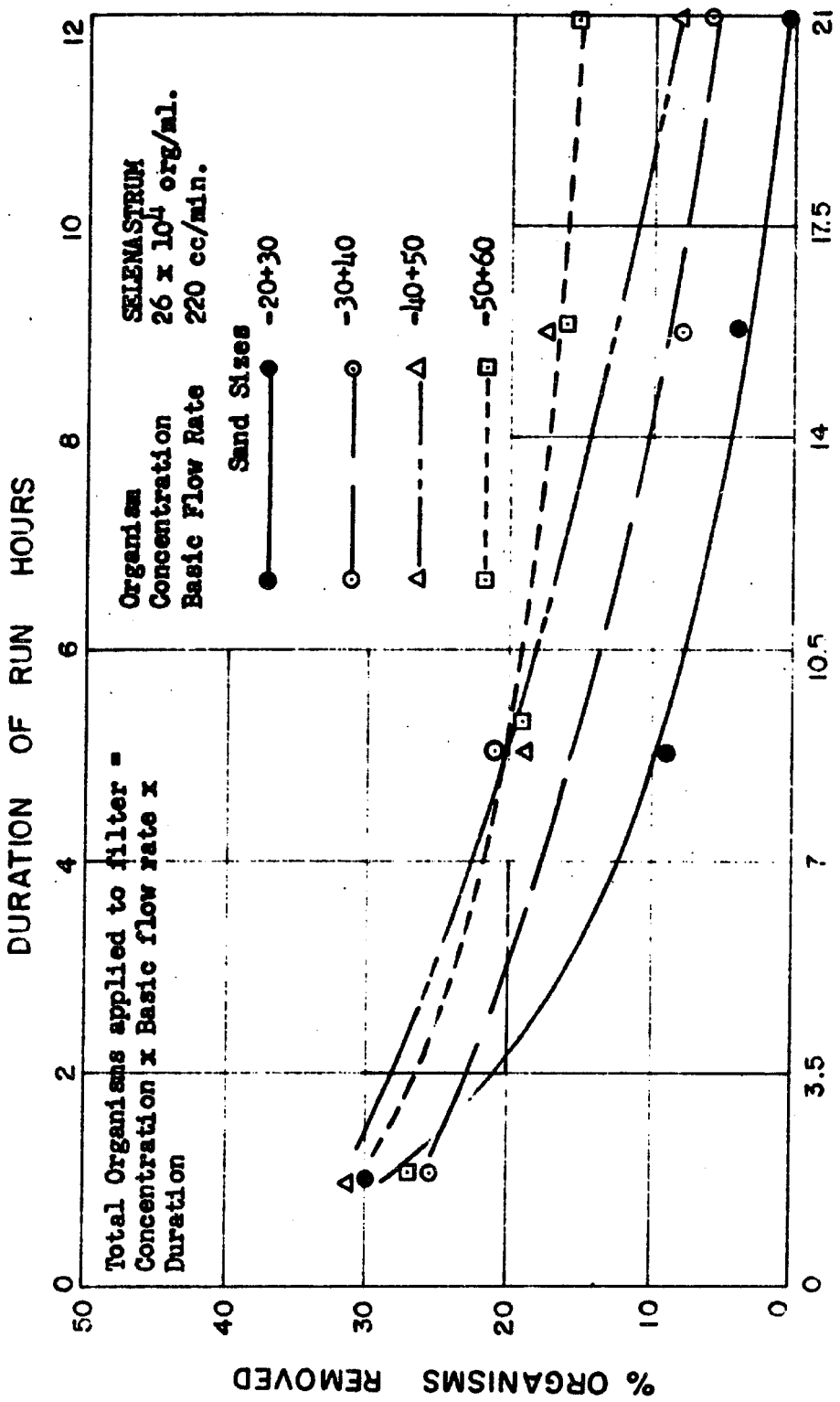


FIGURE 11. Organism Removal Efficiencies for 24 Inch Beds of Various Sized Sands Filtering a Suspension of Selenastrum Run A-3

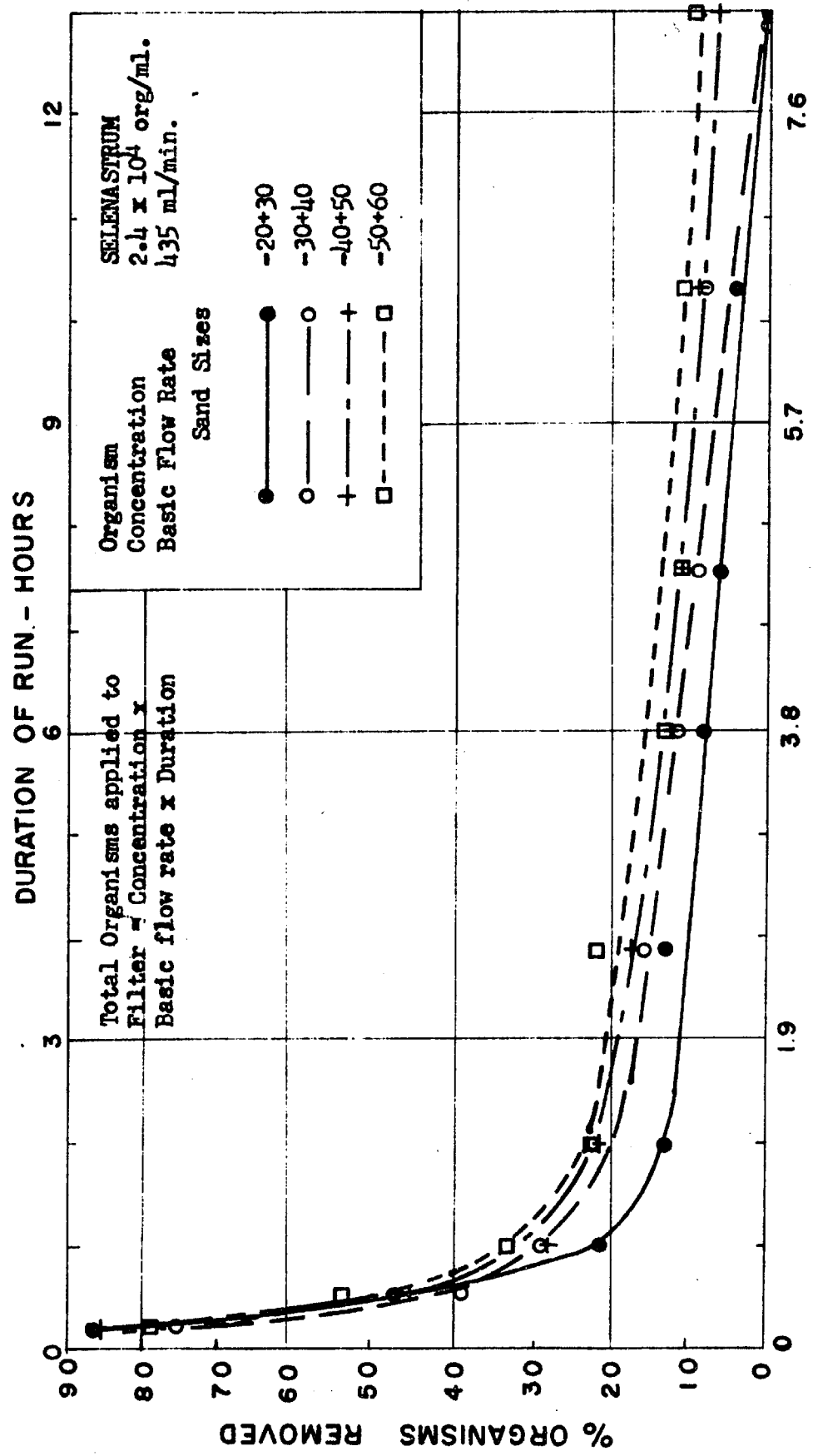


FIGURE 12. Organism Removal Efficiencies for 24 inch Beds of Various Sized Sands Filtering a Suspension of Selenastrum Run A-4

Figure 12 shows in detail the pattern of removal associated with the initial part of the filtration process for run A-4. A very rapid increase in the number of organisms passing the filter is seen to occur. This is followed by a period of steadily declining retention of organisms on and in the filters. Considerable surface straining took place and a thin mat of organisms built up on the surface of the filters. From the results of this run, carried out at a basic flow rate of 435 ml/min, it is apparent that the contribution to the removal of organisms made by plain filtration was small after a short period of operation of the filters.

Figure 13 illustrates results obtained in removals associated with the plain filtration of an old mixture of a number of organisms including Selenastrum, Schizothrix, Oscillatoria and some forms of diatoms. Patterns of removal are similar to those in run A-1 to A-4. Efficiencies of removal during the first part of the run are much higher than when Selenastrum alone was utilized at a similar flow rate.

Removals and ratios of the removals accomplished by the filters of finest media to those of the other sizes for runs A-2, A-3 and A-4 are shown in Table I for the three filtration rates investigated after a total of 7×10^9 organisms had been directed to each bed. The diminishing value of coarse sand sizes for plain filtration of Selenastrum at increasing rates of filtration may be observed from the increase in the value of ratio numbers in the columns.

Decreasing removal efficiency associated with increasing size of the media particles at any one flow rate, is indicated by the increasing values of the ratios in each row. The numerical reductions in percent removal of organisms at the increasing fil-

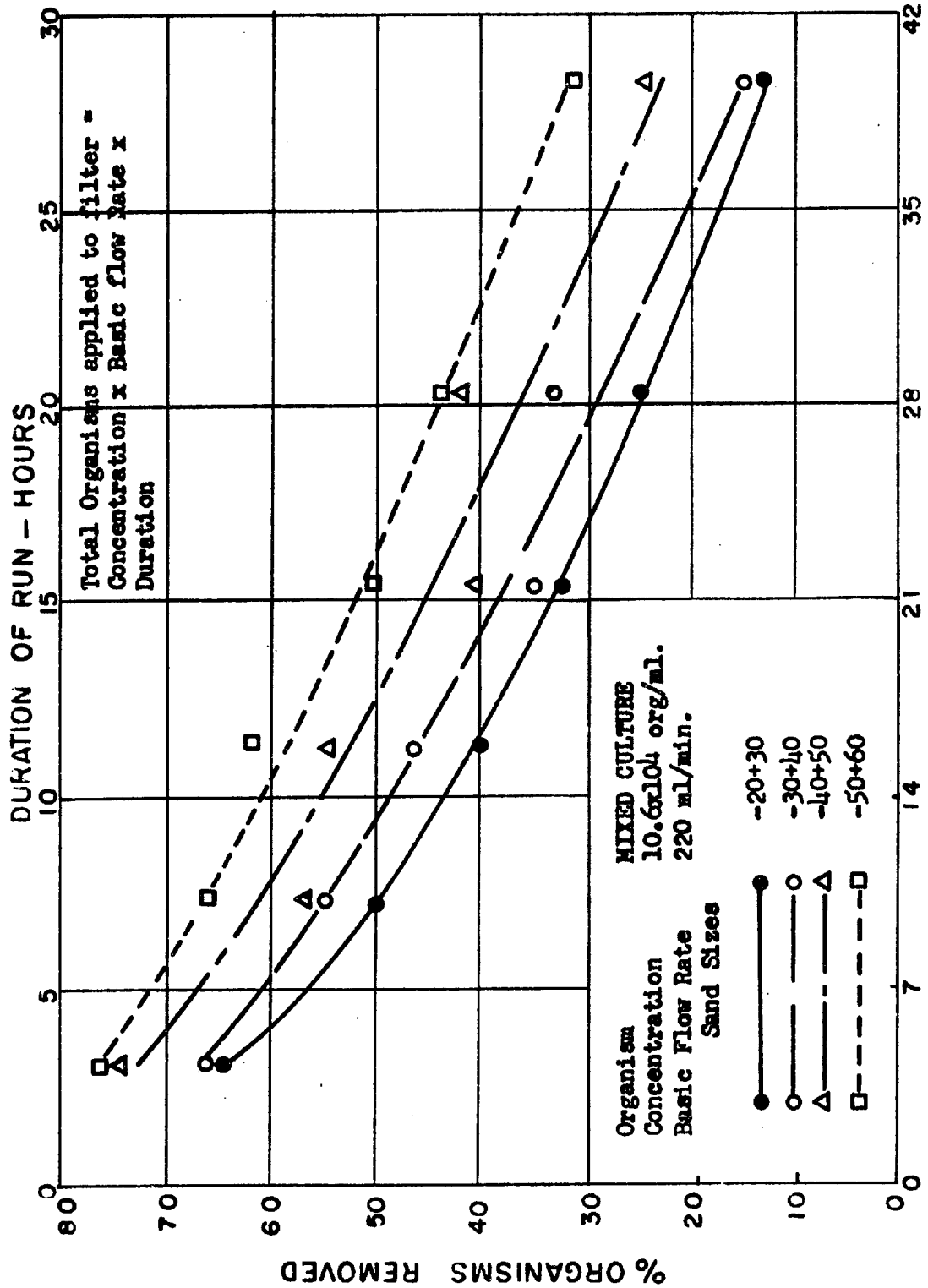


FIGURE 13. Algal Removal Efficiencies of a Mixed Culture of Organisms Filtered Through 24 inch Beds of Various Sized Sands

TABLE I

Percentage Removal of Organisms Accomplished by Filters at Different Hydraulic Rates After Application of 7×10^9 Organisms Per Filter

Filtration Rate	Percentage Removal								
	Filters		Ratio	Filters		Ratio	Filters		Ratio
	4	3	4:3	4	2	4:2	4	1	4:1
0.485 gpm/sq.ft.	34	31	1.1	34	28	1.2	34	22	1.6
0.97 gpm/sq.ft.	23	24	0.96	23	17	1.4	23	13	1.8
1.87 gpm/sq.ft.	10	7	1.4	10	3	3.3	10	2	5

Sand Sizes

Filter 4 -50+60
Filter 3 -40+50
Filter 2 -30+40
Filter 1 -20+30

tration rates may also be seen.

This latter observation is not substantiated by the conclusion of a previous investigator (41) who reported no discernible effect of flow rate on removal of algae when based on the total number of organisms applied to a filter. The shape of the "percent removal versus number of organisms applied" curves herein shown would indicate a removal process applicable for each flow rate in which the capacity of the filter to remove organisms was limited and the ease of removal was influenced by the organisms already removed.

None of the suggested mechanisms of removal outlined in Section II would appear to be unaffected by an increase in the velocity of the fluid and still yield removal patterns such as those determined.

Gosh (34) who investigated removal of Fuller's Earth turbidity from a water by plain filtration, concluded that the effluent turbidity depended much more on the velocity of flow than on the size of the media and the effluent turbidity was high for high velocities. Baylis (11) and Hudson (137) reporting on comparisons of rapid sand filters operated at normal and elevated filtration rates mention the passage through the filter of increased amounts of turbidity associated with higher velocities.

From experimental studies in which algal cells were the only form of particulate matter applied to uniformly sized sand filters, the following observations may be made:

(a) Removal of algal cells within various runs was in inverse proportion to the size of sand employed.

(b) A considerable amount of removal occurred at the sur-

face layers of the sand and the location of maximum removal progressed toward the surface as the run proceded.

(c) Maximum removal efficiencies occurred during the early stages of a run and decreased with time with a decrease in the rate of removal.

(d) Removals for all filters tended toward zero with time.

(e) There were differences in the filterability of different types of organisms.

(f) Organisms in great numbers penetrated the filters of even the smallest sized media studied.

It was assumed, therefore, that the cultured organisms applied to the filters as a suspension in the influent water were performing in a manner similar to that associated with organisms which had been fed directly to the filters as a dilution of a culture, and that the organisms responded to plain filtration in a way similar to that which other non-flocculant particulate matter had been determined to react, and further that the removal due to plain filtration at normal rates is of minor consequence after a short period of operation.

SIMULTANEOUS FILTRATION OF FLOCCULANT AND NON-FLOCCULANT PARTICLES

The application of a preformed floc to a filter has been studied (42), and has been suggested as a possible method for increasing removal of algae which may be present in a filter influent (41).

The first part of the present study involved the evaluation of various methods for preparing and feeding coagulant which might have practical possibilities for plant use.

To evaluate the possibility that coagulant flocs prepared under different conditions may exhibit different removal capacities,

four feed suspensions of hydrated ferric oxide floc were prepared using the same quantity of chemicals. These four concentrated feed suspensions of coagulant were prepared in the following manners:

1. To a solution containing 36.7 gm/l of ferric chloride, an appropriate quantity of a sodium hydroxide solution was added to produce a floc suspension with a pH of 4.8.

2. To a solution of ferric chloride, the same as employed in 1, an appropriate quantity of a sodium hydroxide solution was added to produce a floc suspension with a pH of 10.0.

3. The order of addition of the chemicals used for the solution described in number 1 above was reversed while the quantities were maintained identical to produce a floc suspension of pH 4.8.

4. The order of addition of the same quantities of chemicals used for the solution described in number 2 above was reversed to produce a solution with a pH of 10.0.

The suspensions were slowly stirred to prevent settling of the floc and allowed to age sixteen hours prior to use. The suspensions were pumped to the top of the filters and discharged through 0.5 mm capillary tubes in sufficient quantities to produce calculated concentrations of 5 mg/l in filters 1 and 4 and 2.9 mg/l in filters 2 and 3. The actual quantities of coagulant determined in the influent to the filters was slighly greater than the theoretical values and are shown on Figure 14.

The four filters were charged with -30+40 sieve-fraction sand and were operated at a basic flow rate of 220 mg/l from a single source of influent feed which contained 5.1×10^4 Selenastrum organisms per milliliter.

Figure 14 illustrates the percentages of organisms removed and the head-loss increases associated with the filters during a run of thirty four hours duration and designated run C-1.

Removal efficiencies associated with all four differently prepared iron flocs increased with time rapidly at first, then at a gradually declining rate as the run progressed. A maximum removal appeared to be reached, after which no further improvement with time took place.

Removal of organisms was nearly identical in the filters receiving similar concentrations of coagulant with lower removals being associated with lower feeds. The maximum removal obtained for filters 1 and 4 was 80% and that for 2 and 3 was about 70%.

Anticipation of the formation of positively charged hydrous ferric oxide precipitates in an acid environment, which would cause more complete removal of presumably negatively charged organisms, was not fulfilled. Speculation as to the reason for the uniformity of removal for flocculant material prepared and stored under different conditions may be based upon (i) short preparation time and (ii) long aging time. The elapsed time from dissolving the ferric chloride in water and its reaction with sodium hydroxide was approximately one hour. The possibility exists that this short time was less than the critical time of floc nuclei formation at the 36.7 gm/l concentration of the ferric chloride, and that the nuclei did not form in the solution before the addition of hydroxide took place.

It is quite possible that charge differences, which may have existed when the different flocs were first produced, may have become insignificant with aging and stirring, and by the time the material

was utilized discernible differences no longer existed.

The determination of the charge characteristics of floc produced and aged under different pH conditions awaits investigation, and may offer a promising area for future study. However, from operational considerations it would appear that equal removals of organisms can be obtained from the application of equal quantities of preformed coagulant floc regardless of the order of addition of chemicals in its preparation or the pH under which it was stored. Removal of algae appeared to be directly, but not linearly, related to the quantity of coagulant added.

The increase in head-loss versus time curves for all four filters showed slight concave upward tendencies with equal feed concentrations of coagulant yielding similar curves. At the highest feed rates the allowable head loss increase was not exceeded until after thirty hours of operation.

Figure 15 shows organism removals accomplished by the passage of a feed solution containing a filamentous form of algae through beds of various sizes of sand particles with the simultaneous application of approximately equal quantities of coagulant. For a comparatively light application of coagulant, calculated to be 0.6 mg/l and determined as noted in the body of Figure 15, a high removal efficiency was experienced. This efficiency increased with decreasing sand size. The pattern of removal was similar to that shown in Figure 14 for a different type of organism in that there was an increase in removal with time and that the removal tended toward a steady value.

The increasesin head loss associated with this run were com-

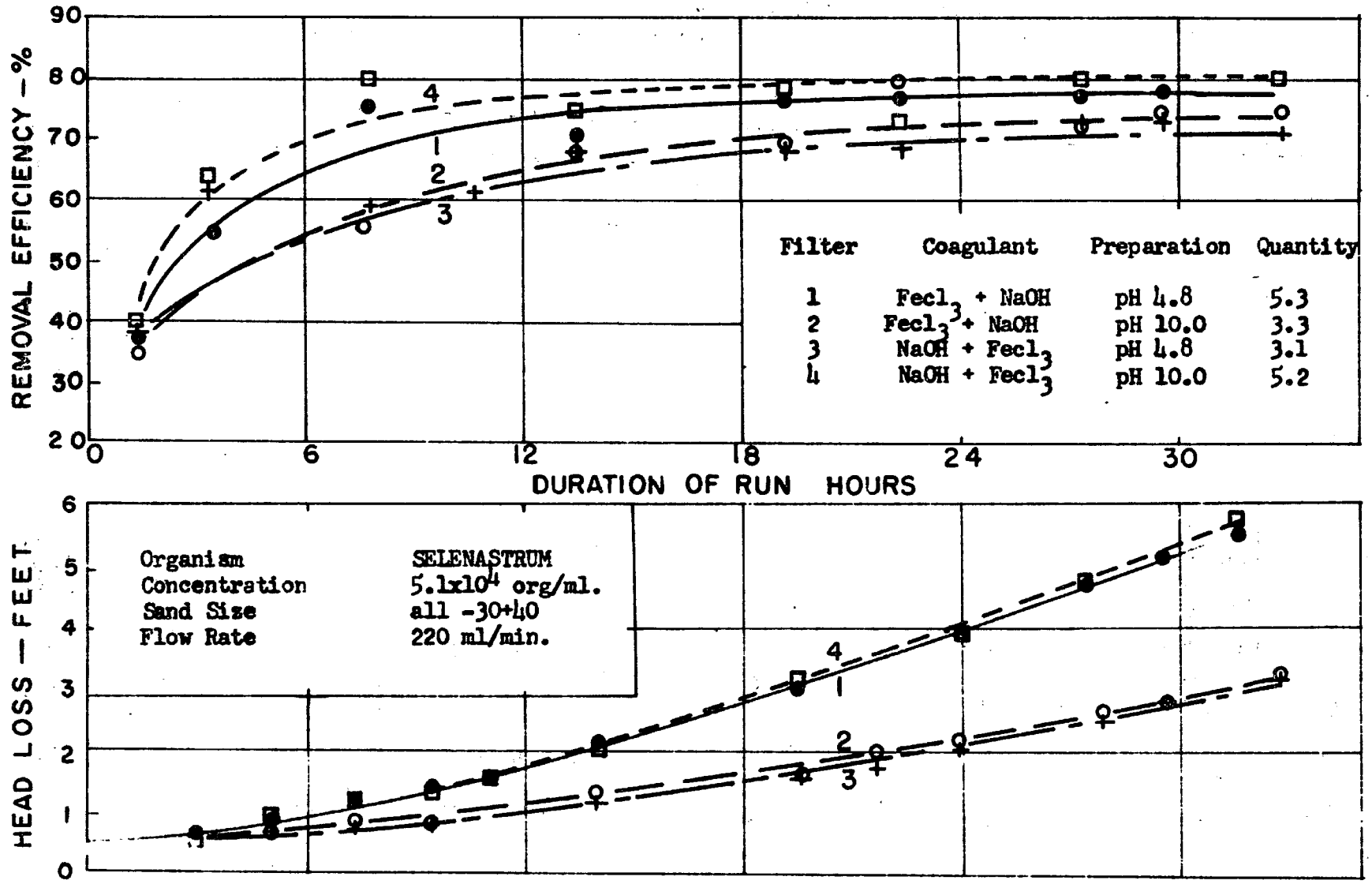


FIGURE 14. Organism Removal Efficiencies on Head Loss Increases Developed During Run C-1

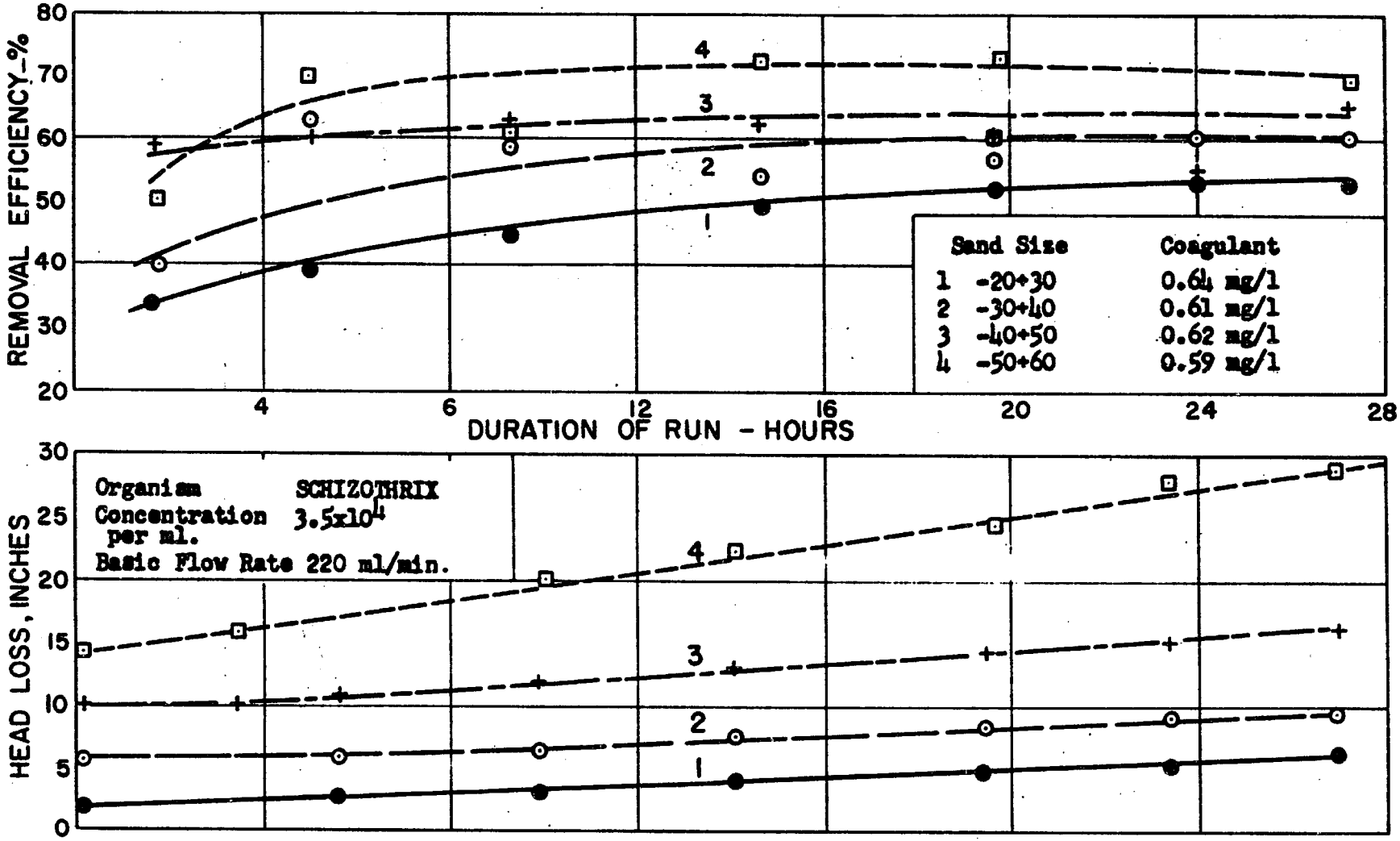


FIGURE 15. Organism Removal Efficiencies and Head Losses Developed During the Filtration of a Suspension of Filamentous Organisms Through Various Sized Sand Run C-2

paratively small for all sand sizes with the increase experienced being greatest for the smaller sand sizes. The head loss curves were nearly linear with time with no noticeable concave upward tendency except in the early stages of the run.

Figure 16 represents the results of an experiment in which solutions of chemicals were introduced to the top of the filters. This solution feed of the coagulant yielded similar algae removal patterns as those determined in runs C-1, and C-2, where a feed of preformed coagulant floc was utilized.

Table 2 is a compilation of removals and accompanying head loss at specific times for a number of coagulant dosages and illustrates the increased removal of algae and increase in head loss accompanying the solution feed of coagulant, and also the attendant high removals of filamentous organisms by a low application rate of coagulant.

The higher removals associated with solution feed of coagulant and the similarity of this type of addition in the laboratory to the application of chemical on an operational basis led to further investigation and finally to the adoption of this method throughout the rest of the study as the standard for the addition of coagulant.

Figure 17 is a plot of the change in head loss with respect to time for different coagulant dosages fed in run C-1 and C-2. Values for dH/dt were obtained from linear sections of the curves. From the solid curve for the solution feed of coagulant it would appear that nearly a straight line relationship exists at the higher concentrations. Only two points could be plotted for run C-1 for coagulant fed as a floc. The line joining these two points appears to be parallel to

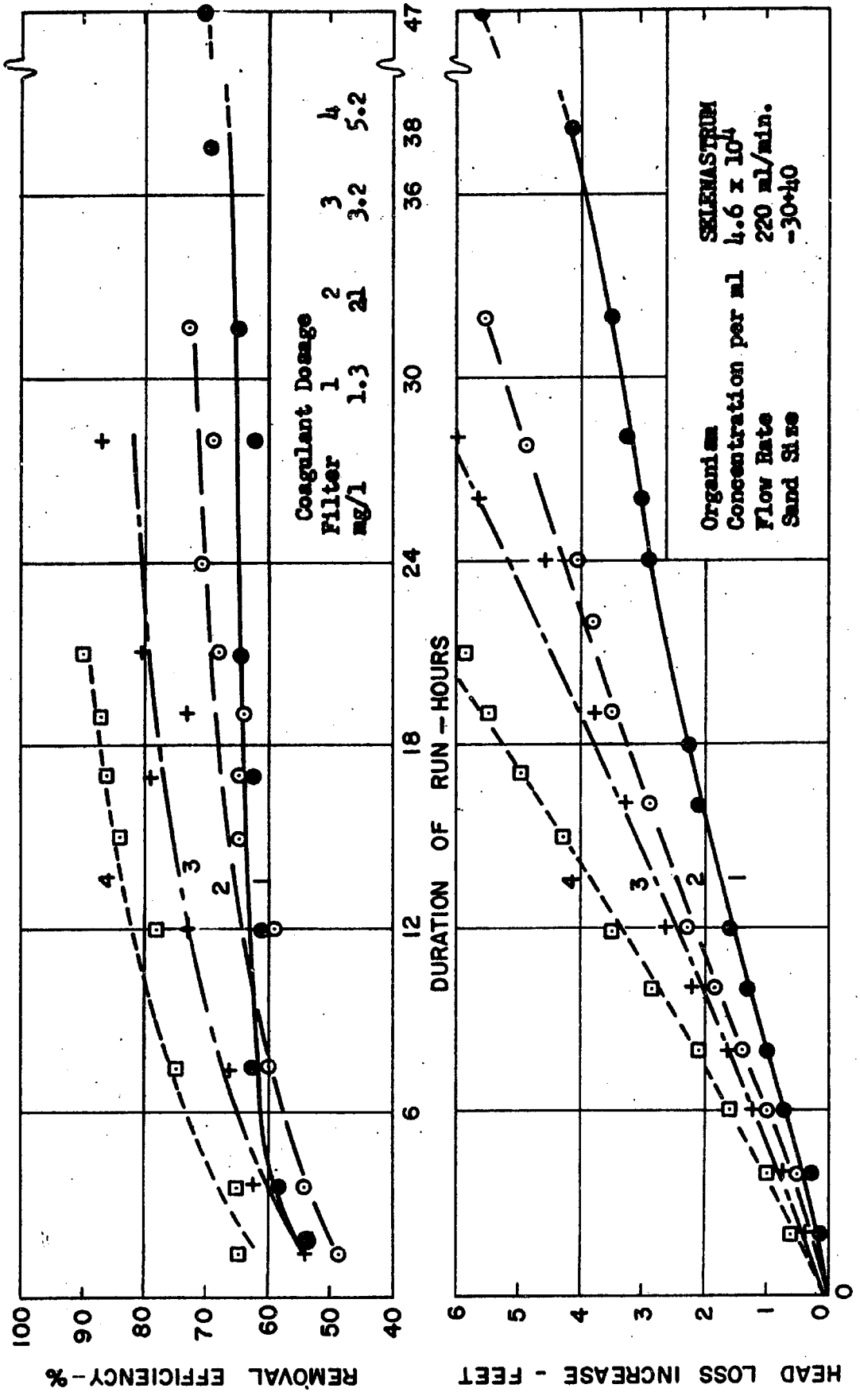


FIGURE 16. Organism Removal Efficiencies and Head Losses Developed During Run C-3

TABLE II

Organism Removal and Head Loss for 24" Beds of -30+40 Sand

Organism		Coagulant		% Removal			Head Loss Increase Feet		
Name	$\frac{x10^4}{mL}$	mg/l	Type	12 hours	24 hours		12 hours	24 hours	36 hours
SELEN-ASTRUM	5.1	5.3	Floc	79	81	83 (33)	1.25	3.5	6
	5.1	5.2	Floc	76	78	79 (33)	1.25	3.4	6
	5.1	3.4	Floc	63	71	74 (33)	0.8	1.8	2.8
	5.1	3.3	Floc	63	71	74 (33)	0.8	1.7	2.7
SELEN-ASTRUM	4.6	5.2	Sol'n	83	90(22)		3.4	6 (22)	
	4.6	3.2	Sol'n	73	80	83 (28)	2.5	5.2	6 (28)
	4.6	2.1	Sol'n	64	70	73 (32)	2.2	4.3	5.5 (32)
	4.6	1.3	Sol'n	62	64	66 (36)	1.6	2.8	3.9
SCHIZ-OTHRIX	3.5	0.6	Floc	57	61	63 (27)	0.25	0.5	

Basic Flow Rate of 220 ml/min. Numbers in parenthesis indicate hours.

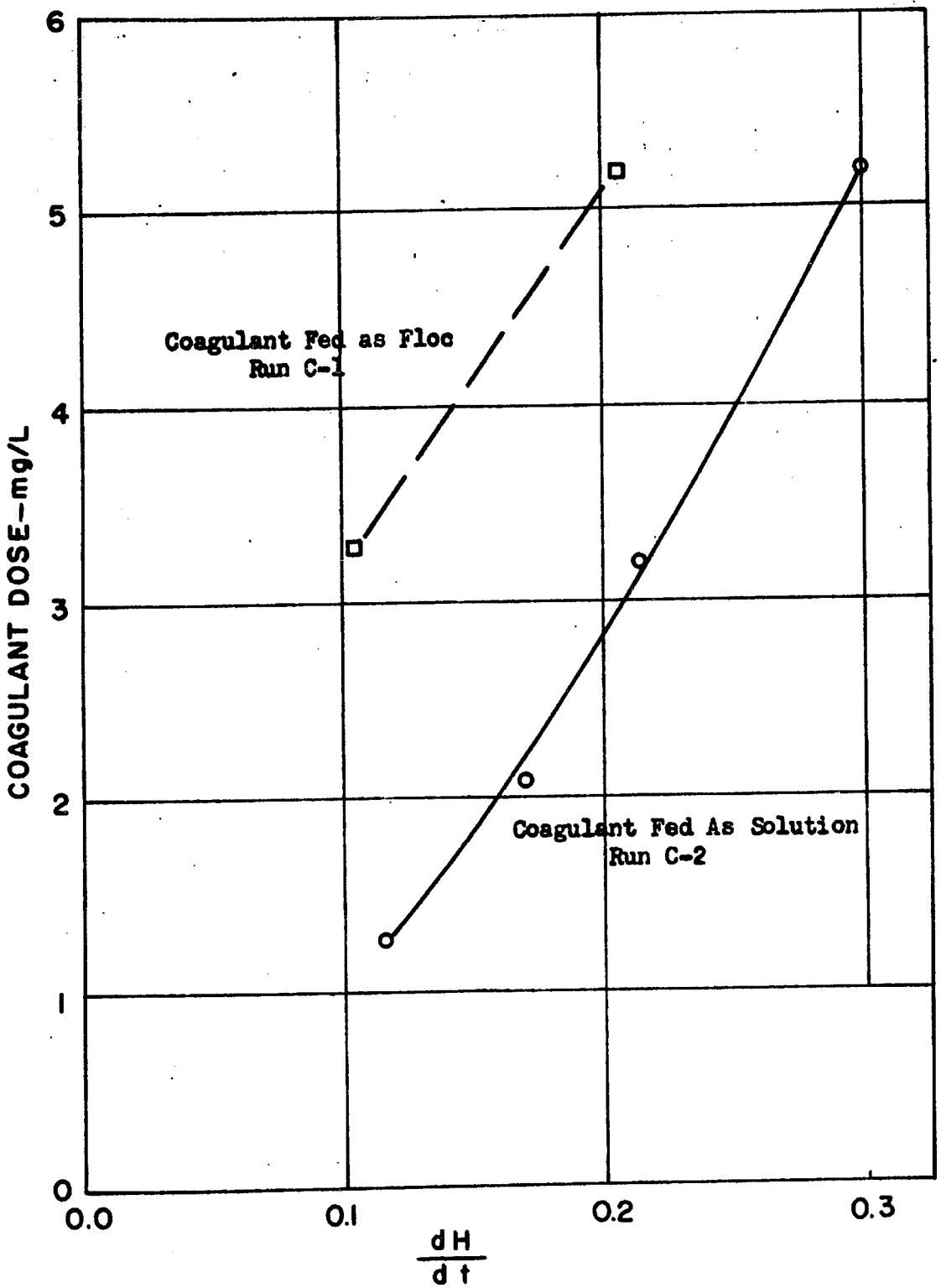


FIGURE 17. Rate of Head Loss Increase Produced by Different Coagulant Dosages for Floc and Solution Feed of Coagulant

the curve for the solution feed coagulant for run C-2 in this high range of coagulant feed. Further data would be required to confirm this, however, it might not be unreasonable to anticipate such an occurrence as size of floc and age with its related changes may be the major differences in the two coagulants. From the projection of the curves it would appear that they must approach the origin from different directions reflecting a somewhat different initial head loss pattern at low concentrations.

Organism Removal and Penetration of Old and New Coagulants at 435 ml/min.

Figures 18 and 19 are plots of the results of runs C-4 and C-5 conducted at a basic flow rate of 435 ml/min. The influent to all filters in each run was from the same source and therefore the concentration of organisms applied to each of the four filters was identical. Different sand sizes were utilized in three filters and two different coagulant dosages were applied. Preformed floc was pumped to the filters in Run 4, and a coagulant fed as a solution was used in Run 5.

At the rate of hydraulic loading at which these runs were conducted, removal of algae by the preformed floc was relatively low, especially for filters of coarse sand size. A removal of approximately 10% was achieved with coagulant fed as a preformed floc at a rate of 0.9 mg/l. At 2.8 mg/l, maximum removal of organisms amounted to approximately 25%. Both removals were based on filters of -20+30 sieve size sand. Removal of organisms increased for a decrease in the size of the media employed and 0.9 mg/l of coagulant applied as floc to the filter of -40+50 size sand resulted in approximately 33% removal of organisms. Comparatively low head losses developed even

at the higher coagulant feed rates.

When coagulant was added in solution form, removal of algae in all filters appeared to be improved, with due consideration being given to differences in coagulant feeds and numbers of algae in the influent. At the high rate of application, complete penetration of coagulant through the filter composed of the -20+30 size sand was experienced in less than twenty-four hours. Flattening of the loss-of-head versus time curve indicates significant breakthrough of the coagulant. The filter was left in operation after breakthrough and was found to be passing approximately 90% of the algae and 50% of the coagulant applied. It would appear that an upper limit of coagulant application for a certain sand size and concentration of particulate matter in the influent is indicated after which penetration of the bed is likely to take place after a short period of operation.

Coagulant penetration into the filters occurring during run C-4 and C-5 is shown in Figures 20 and 21. These figures were obtained by plotting the maximum depth to which deposited iron had penetrated at various sampling times, as determined from samples obtained from various sampling ports. A line drawn below all points of maximum penetration relative to time may be taken as indicative of the rate at which penetration occurred. This rate appeared to be a maximum at the start of the filtration process, after which time it gradually decreased until a uniform penetration rate was reached.

It is apparent from curves 1 and 2 of Figure 20 that for similar concentrations of algae in the influent and the same size of sand, penetration and rate of penetration were directly related to

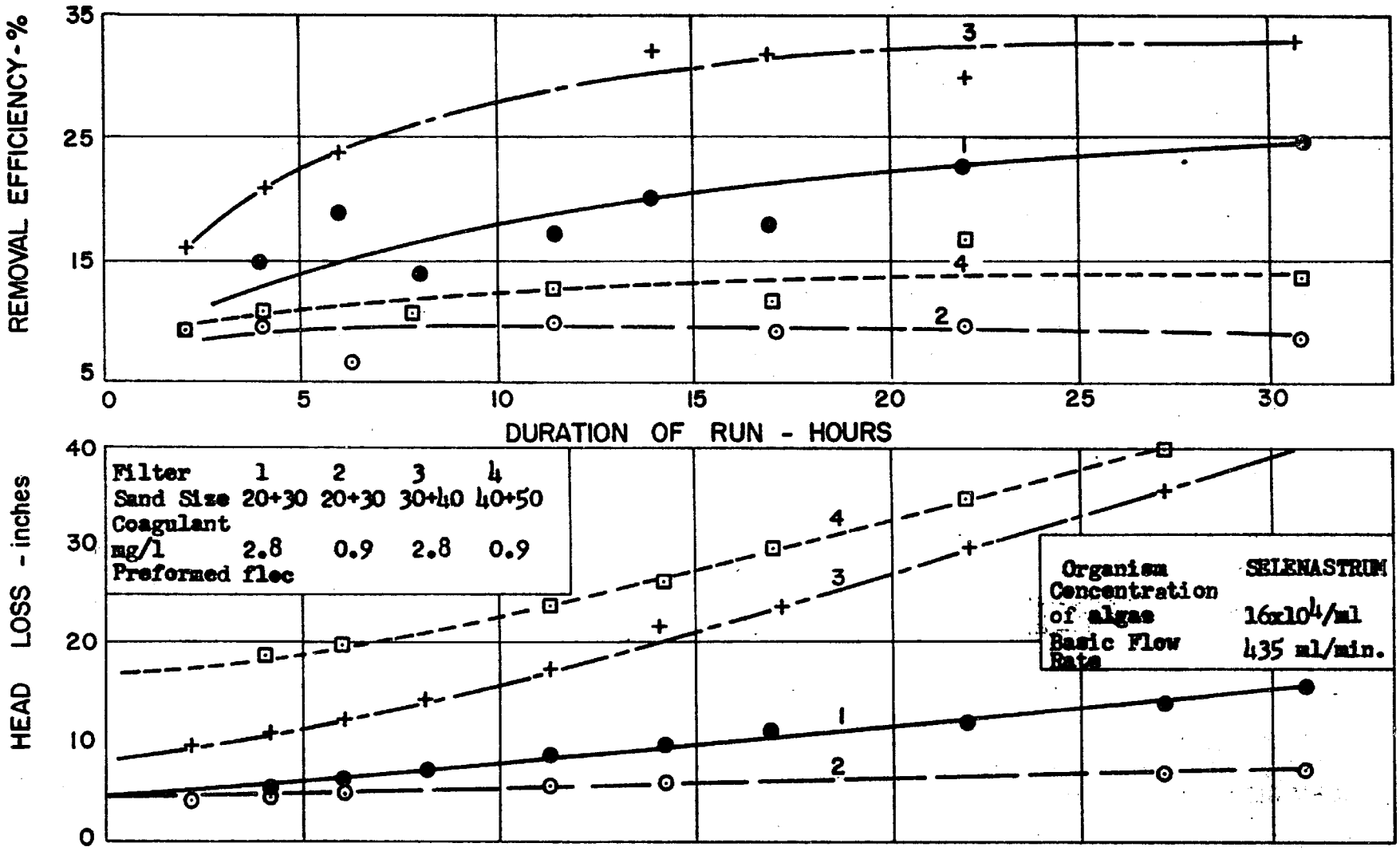


FIGURE18. Organism Removal Efficiencies and Head Losses Developed During Run C-4 Employing Preformed Floc

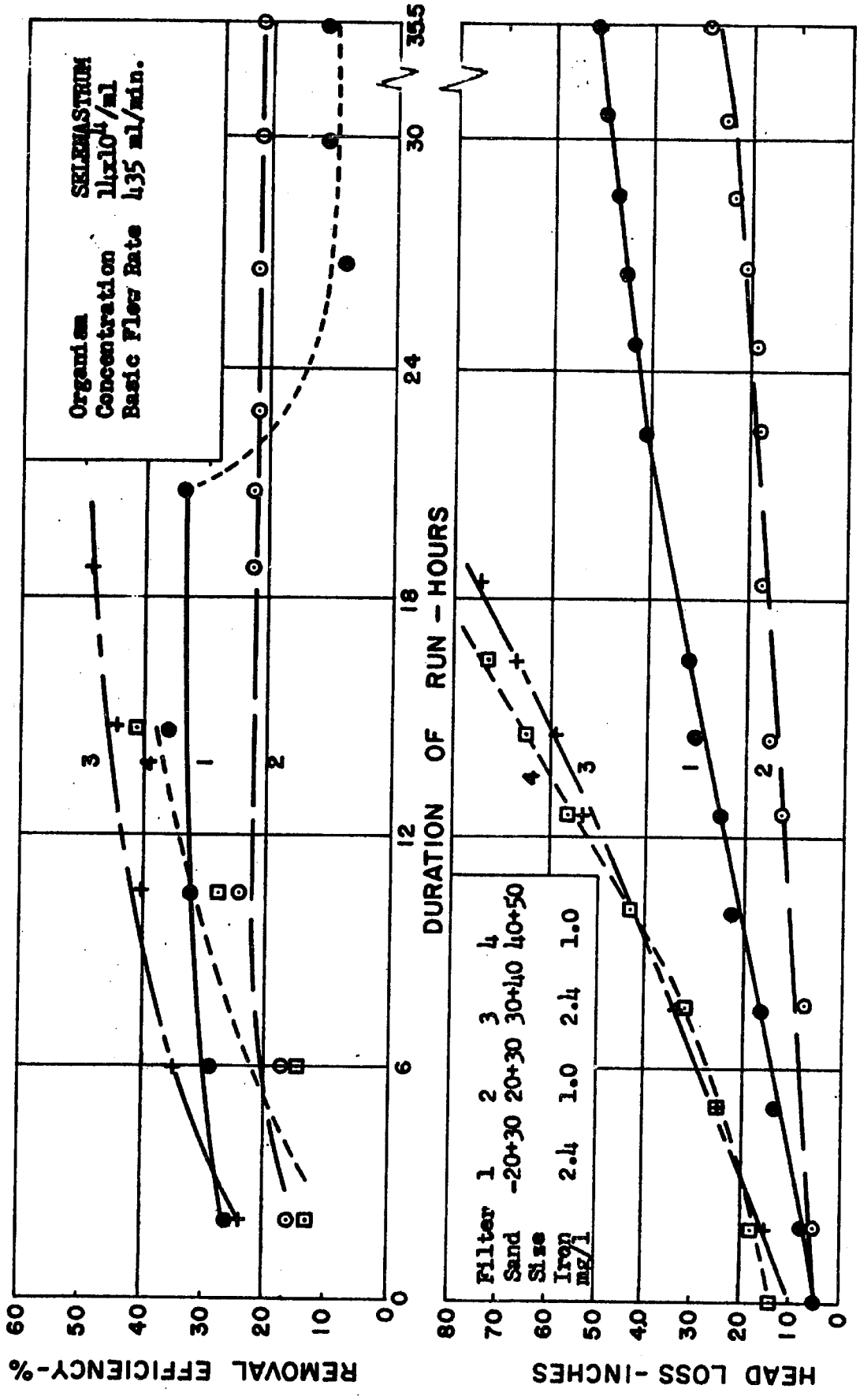


FIGURE 19. Organism Removal Efficiencies and Head Losses : Developed During Run C-5

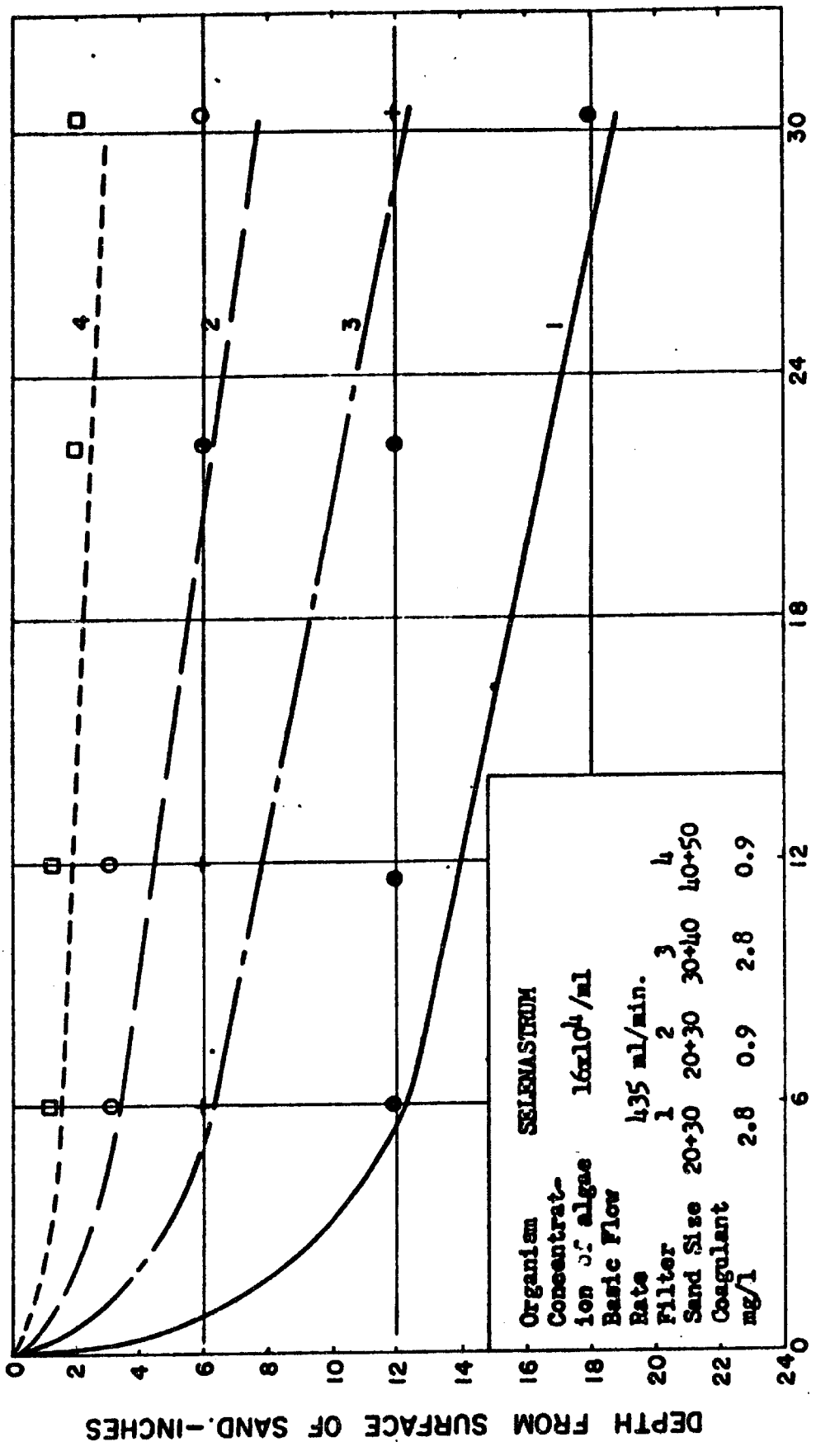


FIGURE 20. Penetration of Preformed Floc During Run C-4

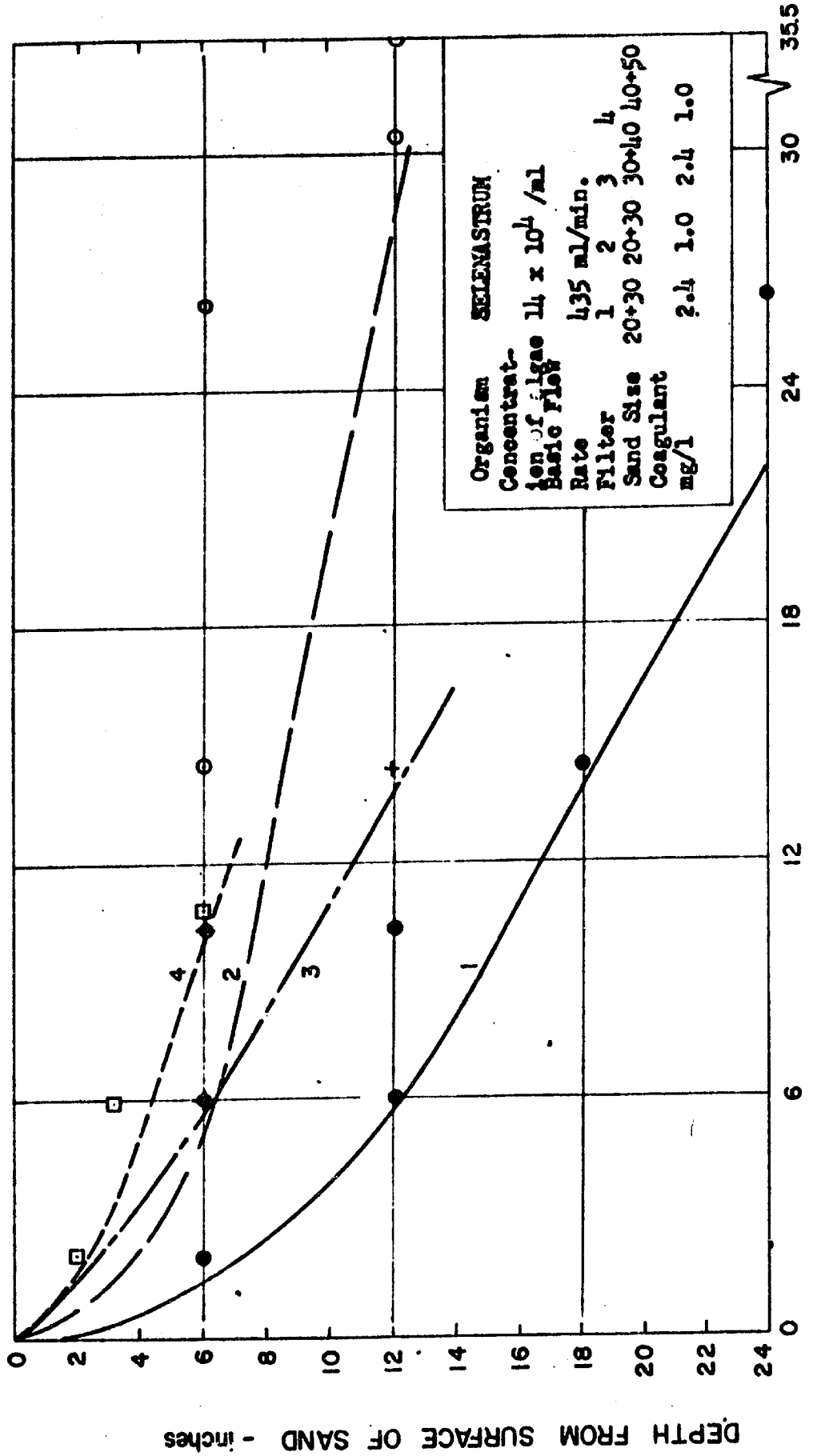


FIGURE 21. Penetration of Solution Fed Coagulant During Run C-5

quantity of coagulant added. From curves 2 and 4, Figure 20, it can be seen that for a given concentration of organisms in the filter feed and for the same coagulant application rate, penetration was greater for larger sand sizes.

Figure 21 illustrates that penetration and rate of penetration of coagulant, when added as a solution, were much greater than when a preformed floc was fed, if direct comparison to Figure 20 can be made. Patterns of penetration established for coagulant fed as a floc may be seen to be similar to those in filters where coagulant was fed as a solution.

Extrapolation of the line of penetration for filter number 1 would indicate complete penetration of this filter at about 22 hours after initiation of the run. This time corresponds to the change in slope of the head loss curve in Figure 19.

Final penetration of coagulant fed as solution into the filters was greater than for preformed floc at a similar rate of application even though three of the filter runs were terminated after a considerably shorter duration of operation. Penetration of coagulant into filter number 2, run C-5, was greater than that into filter number 2 in run C-4 at any comparable time after the rapid initial penetration. Maximum penetration into filters 3 and 4 was of secondary consideration to head loss in terminating the runs of these filters.

Removal of Organisms for Three Different Methods For Applying Coagulant.

Run C-6 was undertaken to establish, under a given set of conditions, removal efficiencies associated with coagulant fed as a solution and as a preformed floc and removal of organisms associated

with a filter which was charged with coagulant prior to its operation with a feed-fluid containing algae.

Clark (150, 151) reported that the operation of a slow sand filter in which aluminum hydroxide was precipitated before the filter was placed in use, resulted in production of a low colored water from an influent which was highly colored. To determine if there would be merit in charging a rapid sand filter with coagulant prior to introducing it into service for the purpose of removing particulate matter, the following test procedures were adopted.

Filter 4 was operated with an influent fluid of pH 8.6 which contained no particulate matter. Sufficient ferric chloride was applied as a solution to produce an iron concentration of 2 mg/l in the filter influent. The filter was charged with coagulant for fifteen hours, after which time the application was terminated. The head loss increase developed was nearly linear during this time, as shown in Figure 22.

During the time coagulant was being applied to filter number 4, floc was precipitated from a separate ferric chloride solution by the addition of sodium hydroxide. This preformed floc was stirred gently to prevent settling until used. At the end of the period of charge of filter number 4, water containing 11.6×10^4 organisms per ml was applied to filters 2, 3 and 4. During application of this feed solution to the three filters, a sufficient quantity of the preformed floc was introduced to produce 2 mg/l of iron in the influent of filter 3, and filter 2 received a feed of dissolved coagulant equivalent to an influent concentration of 2 mg/l. No additional coagulant was added to filter number 4. The filters were operated for fifteen hours. During operation of the filters the head loss increase was recorded

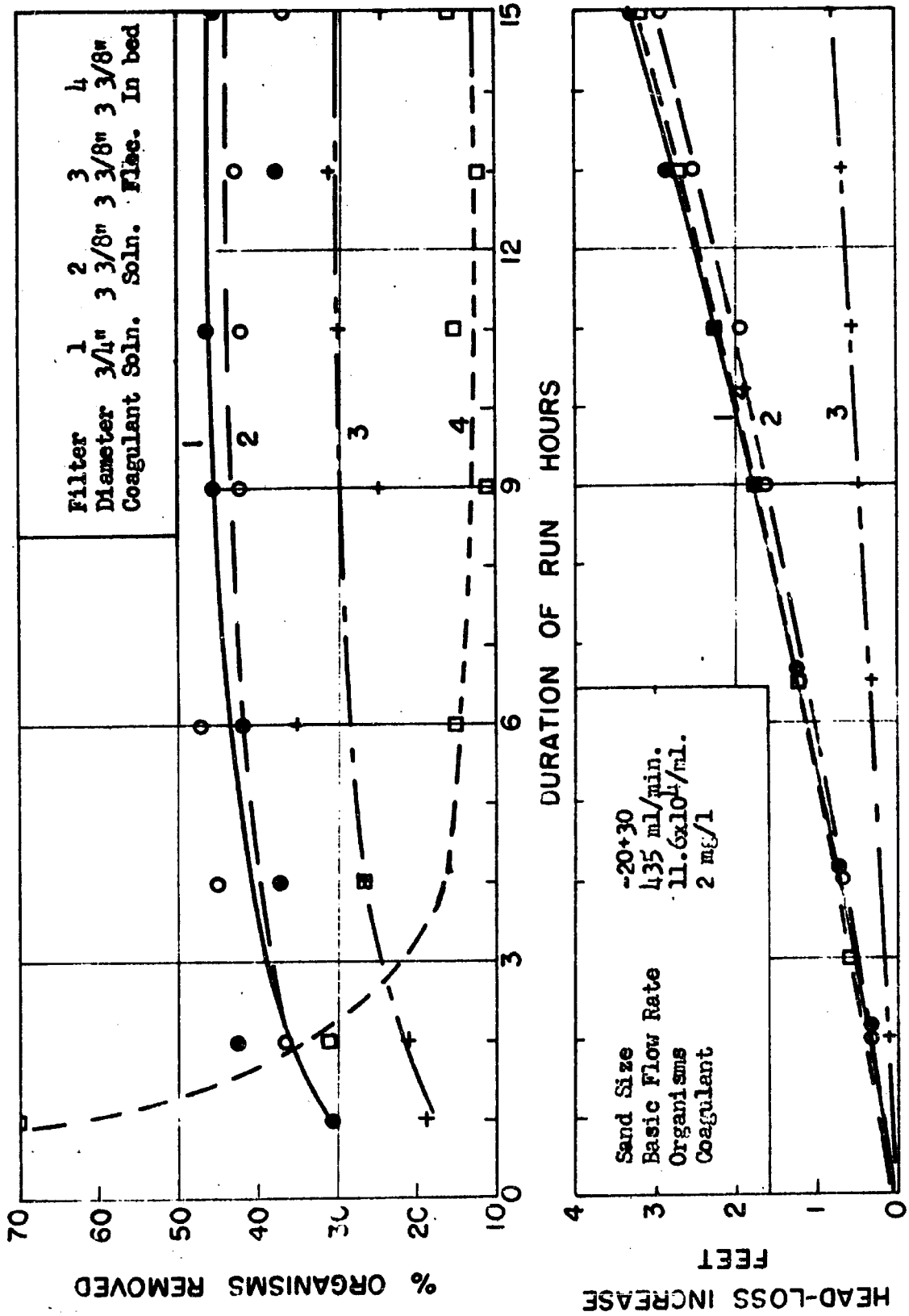


FIGURE 22. Organism Removal Efficiencies and Head Losses Associated With Different Methods of Coagulant Application to filters of Different Diameter

and determinations of the removal of organisms were conducted.

Figure 22 shows the head loss pattern developed in the filters as a function of time and removals of organisms associated with the three methods for applying coagulant. Nearly identical head-loss curves developed during the charging of filter 4 and the operation of filter 2. There was an increase of three inches in the head-loss of filter 4 during the filtration process. The head-loss increase for filter number 3, which received preformed floc, was much more gradual than that for filters 2 and 4 which received a solution of coagulant.

The patterns of organism removal for filters 2 and 3 were consistent with results of other experiments discussed previously in that removals increased to an apparent maximum and remained more or less constant for the remainder of the run. For the cases of coagulant fed as a solution the removals of organisms were considerably higher than for the case where coagulant was fed as a floc.

Removals associated with filter number 4 showed a reversal of this pattern in that removals were greatest at the first of the filtration period and decreased rapidly with time to a low, nearly constant value. This was also the pattern associated with plain filtration of algae.

Microscopic measurements made of the size of particles of preformed floc as they existed in the liquid in the filter tubes, showed that particles were of irregular shape. Those measured exhibited a maximum dimension which varied between 4 and 24 microns with a mean maximum dimension of 10.6 microns.

Coagulant which was fed as solution imparted an apparent color to the water but no floc particles could be observed under micro-

scopic examination. However, a sample of the fluid drawn from directly above the filters did exhibit a strong Tyndall effect.

The differences in organism-removal efficiencies accomplished by coagulant applied as a solution, as a preformed floc and as a precipitated floc in place on the filter media suggest that floc surface and attendant charge presented to the organisms may be a significant factor in removal of algae.

Floc particles formed when the coagulant was added as a solution were in intimate contact with the algae during formation, and would have tended to present almost continually during this period, a fresh, large area for interaction.

Preformed floc particles, although discharged into the filter through ½ mm capillary tubing, would have tended to agglomerate before contact with the algae, and thus would present a somewhat smaller area for reaction. The floc in place in the filter would present an even more limited surface for reaction.

Removals accomplished were qualitatively consistent with the predicted relative areas of floc presented to the algae. The pattern of removal, increasing to a maximum in the cases of coagulant addition and decreasing rapidly in the "coagulant in-place" filter seem also to reflect whether the floc surface was presented in a continuous or in a batch manner.

It is apparent that pre-charging a filter with coagulant floc for removal of algae from a subsequent influent is an inefficient removal procedure. The most effective method studied for removal of organisms of a filterable nature was by the continuous addition to the filter influent of a solution of coagulant.

Comparison of Operation of Filters of Different Diameter.

As an integral part of Run C-6, a comparison was made between the operation as represented by head-loss increase and per cent organism removal of the experimental standard 3 3/8"-I.D. filter and one of 3/4"-I.D. This comparison was undertaken to determine whether corrections would be required when reporting data obtained in a subsequent section of study from utilizing 3/4" filter cores within the 3 3/8"-I.D. filter. The proportionally greater surface of filter container might have been of significance in disturbing filtration processes in small diameter tubes. In effect, this portion of the run was a study in which the $\frac{D}{d}$ ratio was a variable. A-20+30 sand gave a $\frac{D}{d}$ ratio for the 3 3/8" filter of 116 and for the 3/4" filter the $\frac{D}{d}$ ratio was 27.

The 3 3/8" filter was removed from position number 1 and a 3/4"-I.D. filter equipped with all appurtenances of the other filters was substituted.

Solution of coagulant, filter influent and a suspension of algae to compensate for the volume of coagulant solution were pumped to the filter in quantities sufficient to produce a filtration rate equivalent to that at which the other filters operated and at a coagulant dosage of 2 mg/l.

During runs employing the small diameter filter the rate of flow controller was operated under manual direction whenever head loss built up sufficiently to warrant an increase in controller settings. The head loss increase curve and percent removal efficiencies associated with the 3/4" filter are shown in Figure 22. Very slight differences existed between build-up of head loss in filter number 1 and number 2, which were in operation at the same time.

Comparison of the head loss curve for the 3/4" filter with that for filter number 4 shows good agreement, indicating equivalent hydraulic and coagulant control throughout run C-6.

The percentage of organisms removed by 1 and 2 show considerable scatter but curves of best fit appear to be in close agreement. An average of six determinations revealed that filter number 1 was receiving an influent containing 11.5×10^4 organisms per ml. and number 2 an influent with 11.6×10^4 organisms per ml. This slight difference did not appear great enough to yield an apparent three per cent difference in removal after fifteen hours operation between filters 1 and 2. The results were tested statistically to determine if this difference in removal was significant.

From the per cent removal of organisms versus time graph from Figure 22 it would appear, for filters number 1 and 2, that until about the fourth hour of operation removal efficiencies may have been increasing. Based on the assumption that removal remained constant after the fourth hour, the Student's "t" test was applied to the data for percent removal as determined by count of organisms in the effluent of the small and large diameter filters.

It was wished to ascertain if there was any significant difference between the removal efficiencies of the experimental standard 3 3/8" diamter filter and the 3/4" filter when they were operated at equivalent hydraulic, suspended matter and coagulant loadings. If any differences in removals did in fact exist these might be ascribed to the wall effect being greater in the smaller filter tube.

The null hypothesis, that there was no difference in the means of the removals of the two filters was postulated, and the solution

carried out according to the small-sample distribution method of testing differences of two means (44). As the computed value of t fell within the non-critical interval for twelve determinations at the 5% critical value the null hypothesis was accepted. Therefore, it was assumed for all practical purposes there was no difference in the means of removal efficiencies. It was also assumed that the difference in diameters of the filters was not significant in causing any erratic effects on the removal of organisms within the filter. The pattern of head loss added extra weight to the validity of the assumption.

In view of the above, it was assumed that no significant difference existed in the cores within the filters and the filters themselves with regard to removal of suspended matter. No visual difference could be discerned between the location of deposits in the cores and the filters. Any differences could only be positively proven to exist by destructive testing for deposition within 3/4"-I.D. filters as compared to 3/4"-I.D. cores. For obvious reasons this procedure was not undertaken.

Organism Removal and Penetration Patterns for High and Low Applications of Coagulant and Suspended Matter.

Figures 23, 24 and 25 show organism removals and head-loss increases occurring during runs C-7, C-8 and C-9. Four filters were charged with the same size of sand in each run. Different size sand was used in each run. Within each run two different concentrations of coagulant were applied to influents containing two different concentrations of algae.

In each of the three runs, filters 1 and 3 received a high dosage of coagulant whereas filters 2 and 4 received a low dosage.

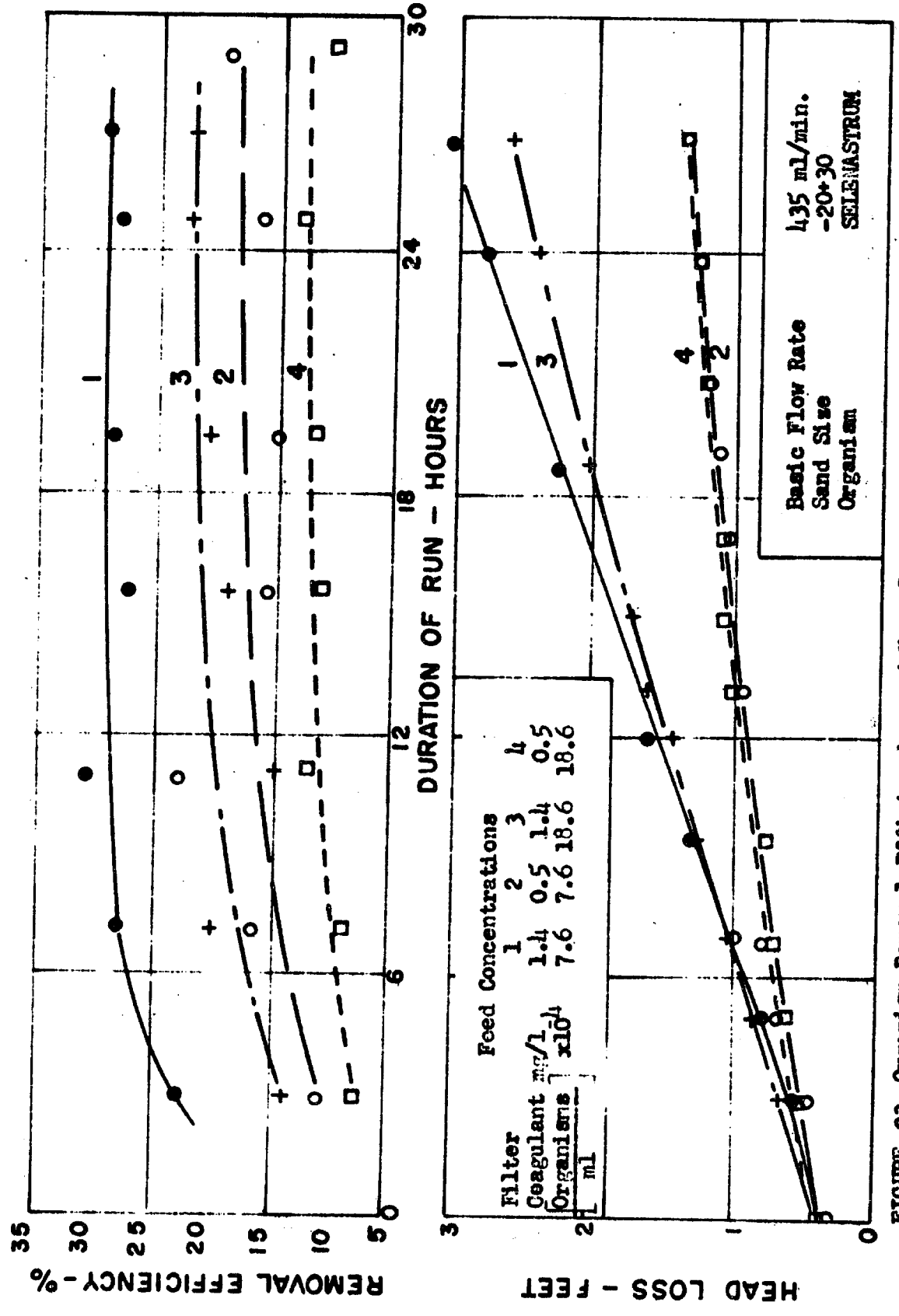


FIGURE 23. Organism Removal Efficiencies and Head Losses Developed During Run C-7

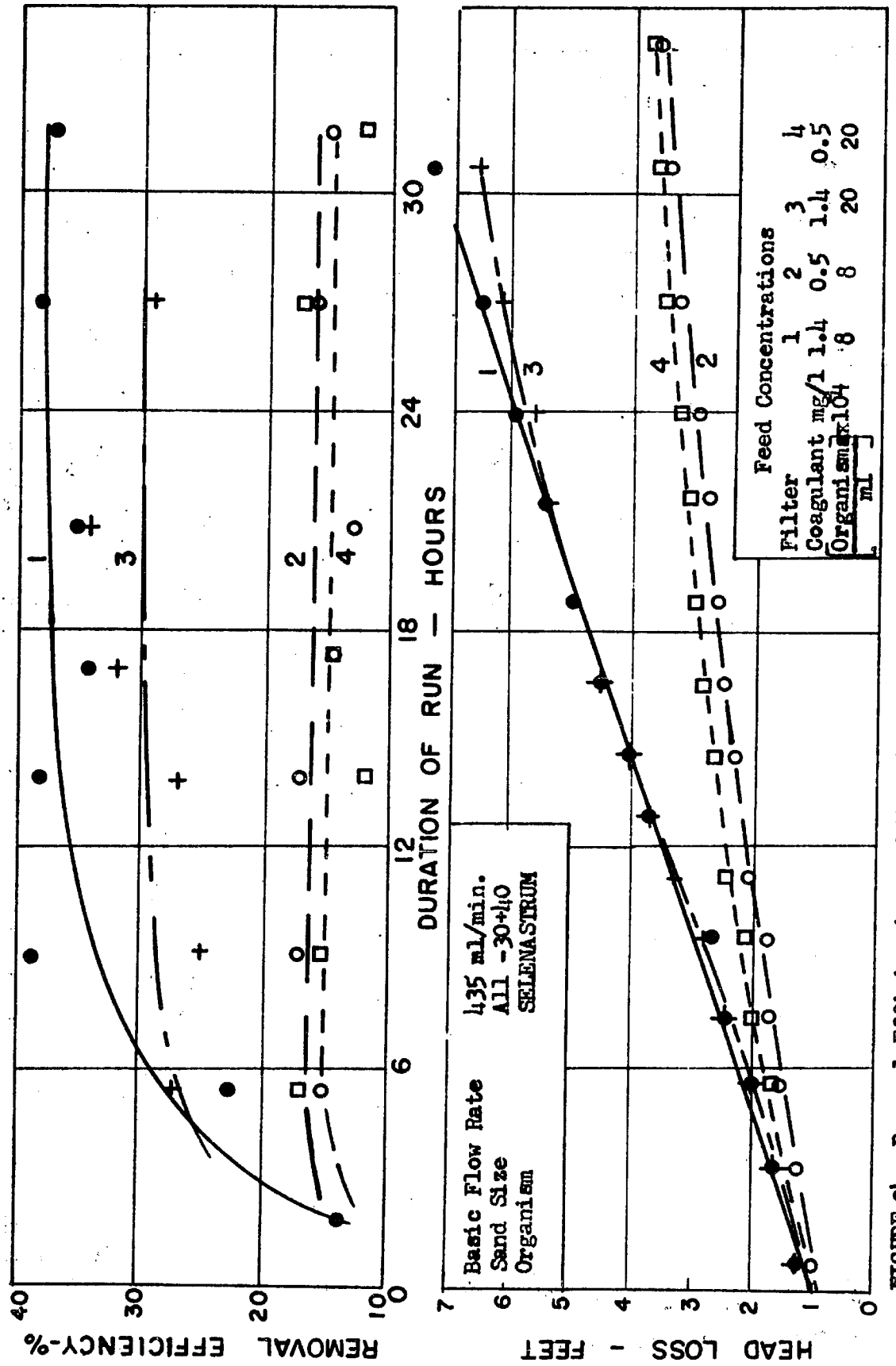


FIGURE 24. Removal Efficiencies and Head Losses Developed During Run C-8

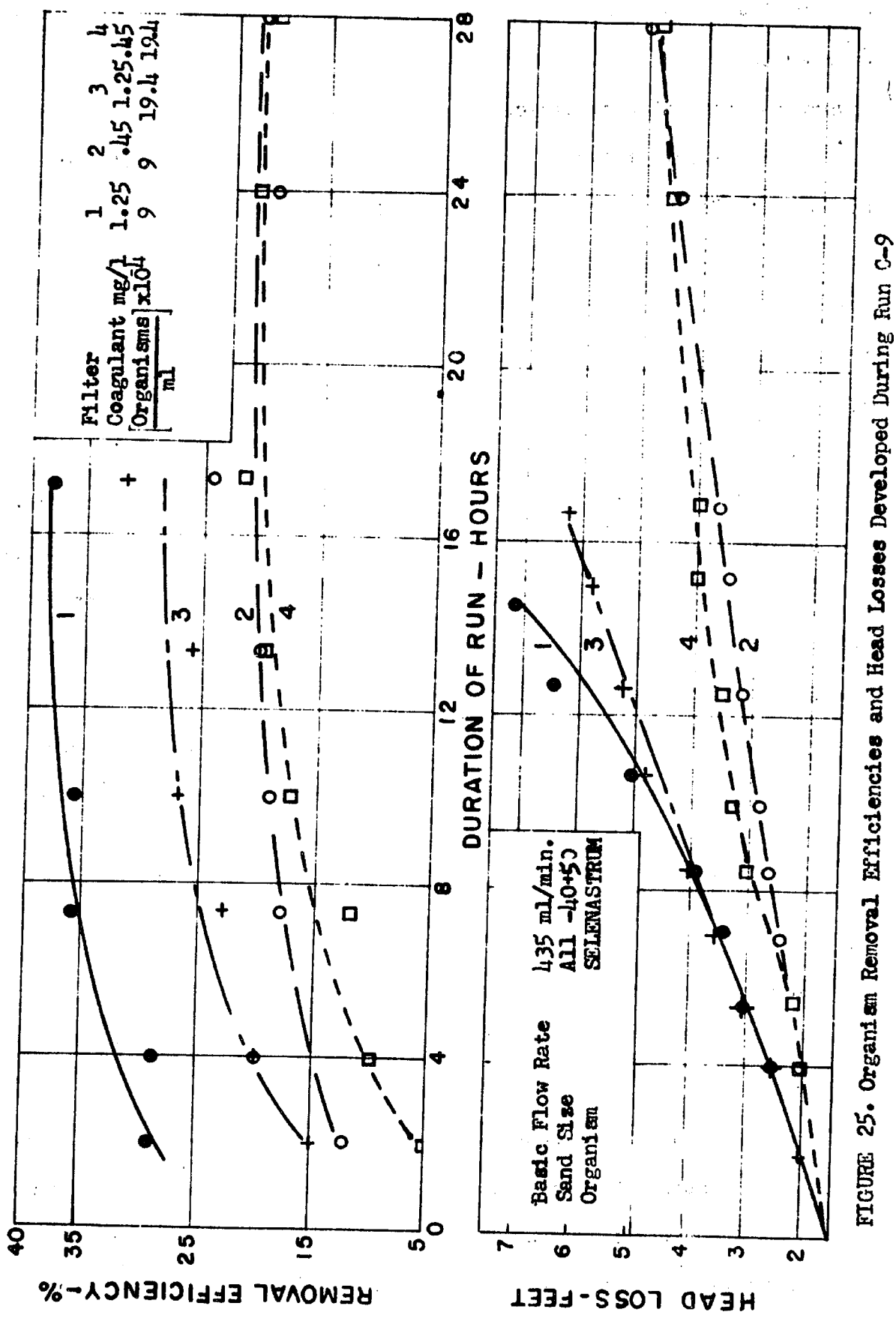


FIGURE 25. Organism Removal Efficiencies and Head Losses Developed During Run C-9

Filters 1 and 2 had an influent containing a low concentration of algae applied to them. Filters 3 and 4 received a feed water containing a higher concentration of algae.

A study of figures 23 to 25 reveals that removal efficiencies are similar in form for the three sand sizes investigated.

Removal of algae may be seen to be a function of the sand size employed, and within a single run percentage removal of organisms is directly dependent upon concentration of coagulant and is inversely proportional to the organism concentration present in the influent.

Head loss versus time curves for the low coagulant concentration were practically identical for high and low concentrations of algae in the feed water for run C-7 employing -20+30 sand. For the other two sands investigated the curves diverged somewhat, but were nearly identical at the conclusion of the run.

Head loss curves for the greater coagulant dosage diverged in all runs. Curves for the filters receiving high concentrations of algae in the influent exhibited concave downward patterns.

Table 3 summarizes removals of algae occurring in runs C-7 to C-9 after twenty four hours of operation. From this table it may be observed that for the same quantity of coagulant applied, although the percentage removal of organisms was lower for a high concentration of organisms in the influent than for a low concentration, the number of organisms removed increased with an increase in the number of algae in the feed water. This condition existed for all sand sizes utilized.

There was a general increase of the removal unit (organisms per milliliter) x 10^{-4} per unit of coagulant with a reduction in sand

TABLE 3

Summary of 24 Hour Removals Runs C-7 to C-9

Run	Sand Size	Filter No.	Feed		Removal		
			Coagulant mg/l	[algae/ml]x10⁻⁴	Percent	[algae/ml]x10⁻⁴	[algae/ml]x10⁻⁴ / unit of coag.
C-6	-20+30	1	1.4	7.6	30	2.3	1.6
		2	0.5	7.6	17	1.3	2.6
		3	1.4	18.6	22	4.1	2.9
		4	0.5	18.6	12	2.2	4.5
C-7	-30+40	1	1.4	8.0	38	3.0	2.2
		2	0.5	8.0	16	1.3	2.6
		3	1.4	20.0	30	6.0	4.3
		4	0.5	20.0	14	2.8	5.6
C-8	-40+50	1	1.25	9.0	38	3.4	2.7
		2	0.45	9.0	20	1.8	4.1
		3	1.25	19.4	28	5.5	4.4
		4	0.45	19.4	16	3.1	6.9

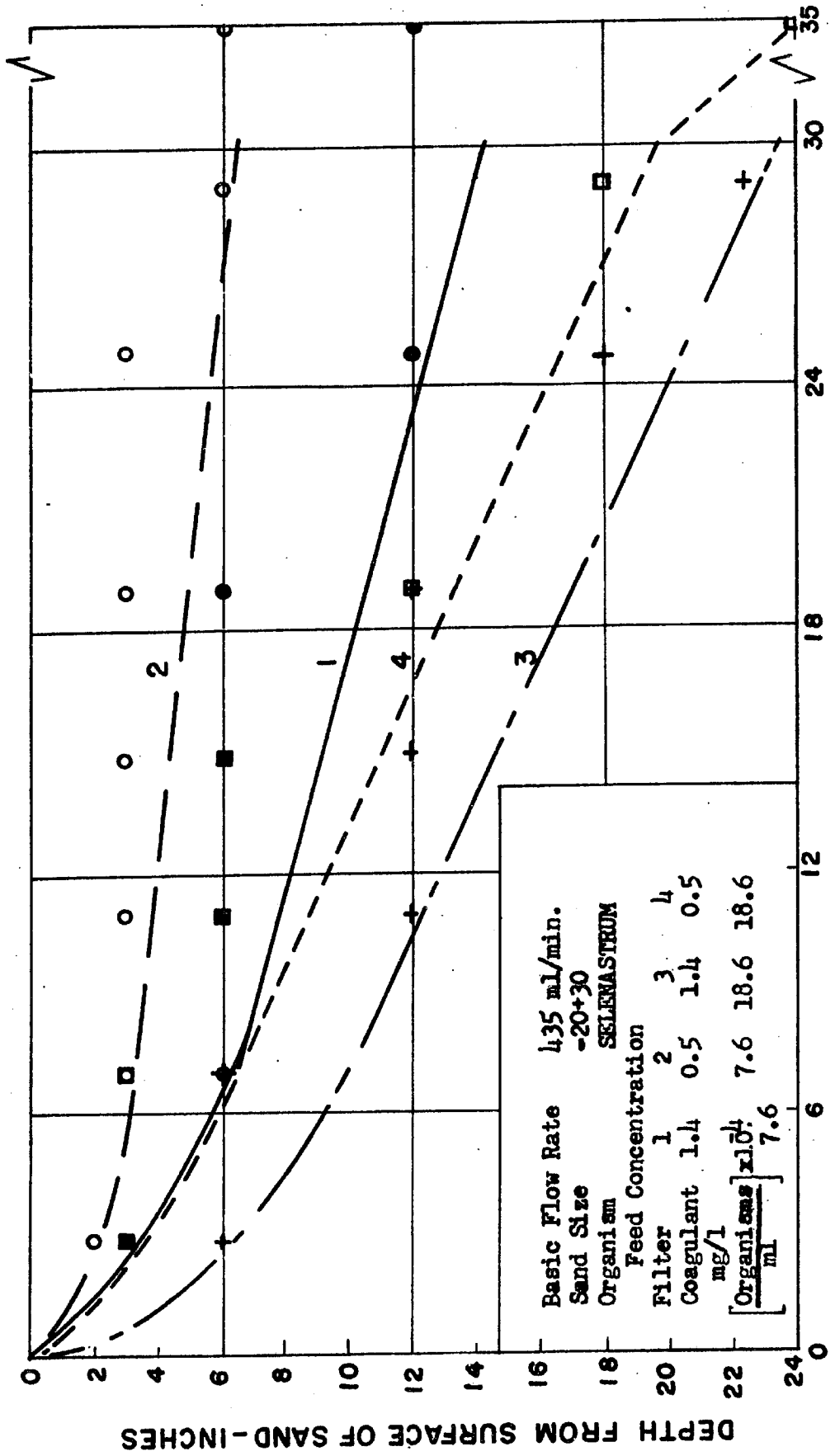


FIGURE 26. Coagulant Penetration Occurring During Run C-7

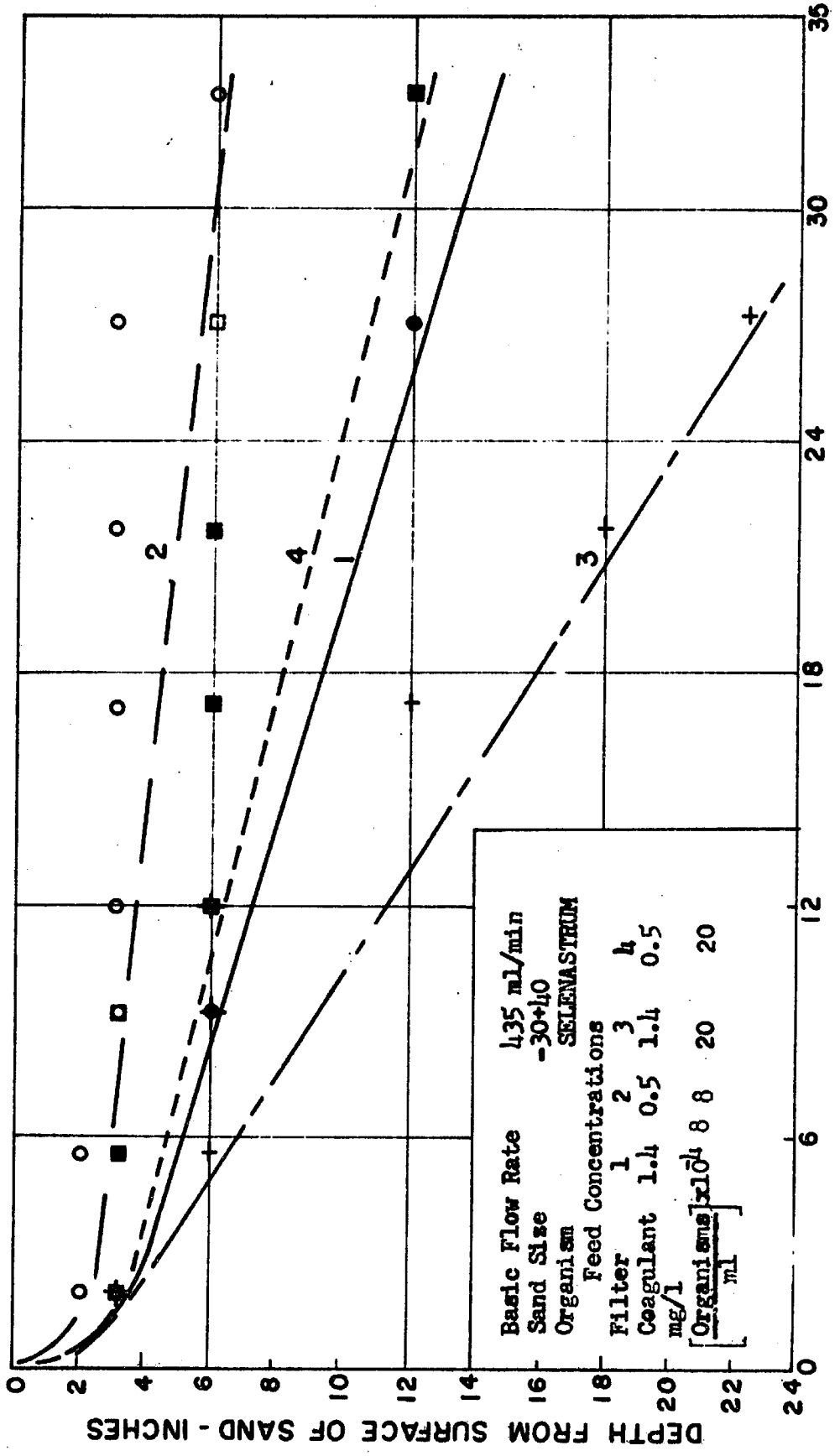


FIGURE 27. Coagulant Penetration Occurring During Run C-8

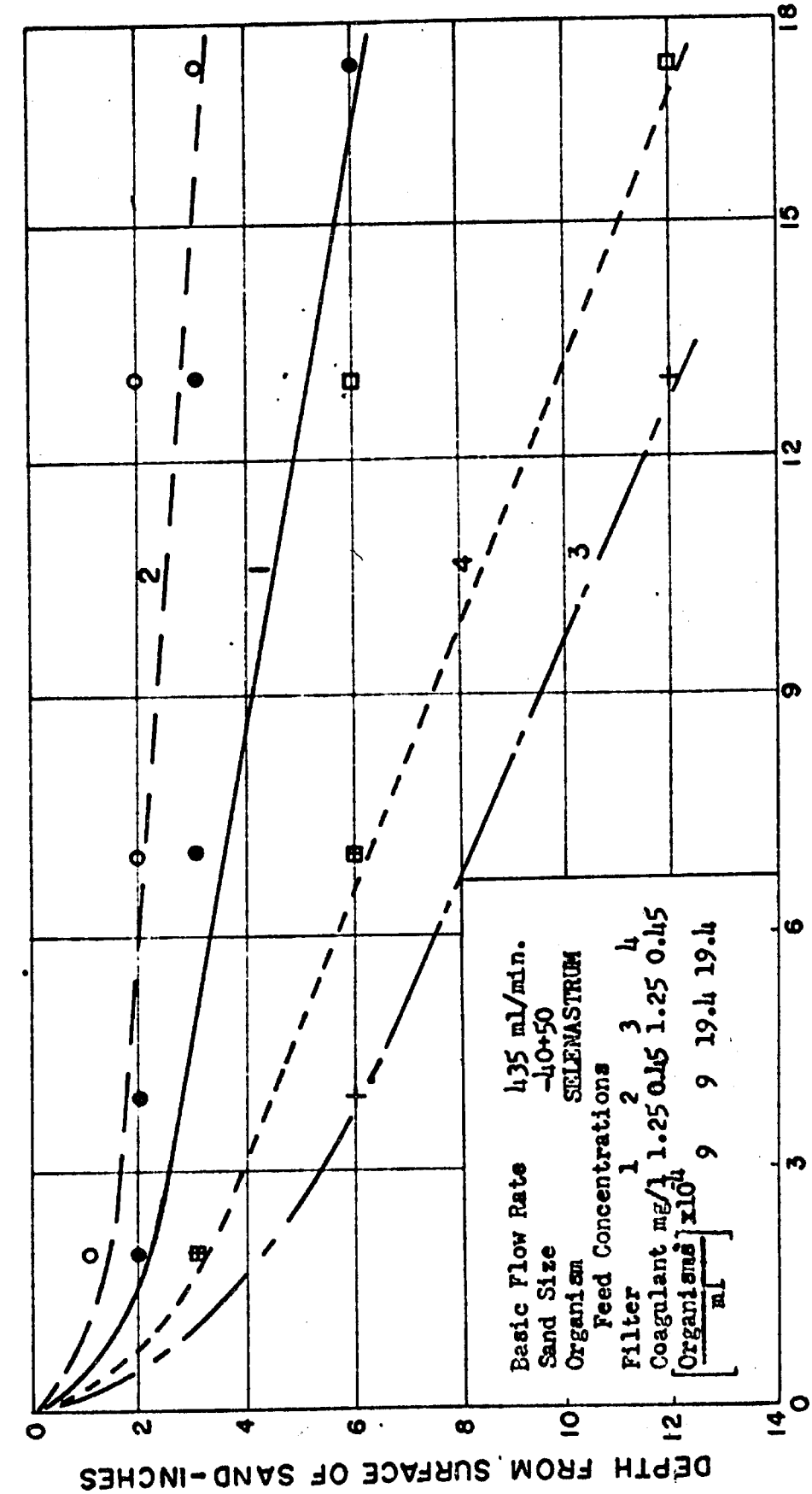


FIGURE 28. Coagulant Penetration Occurring During Run C-9

size. Within any one run, for a given coagulant dosage, this unit increased with an increase in the algae content of the influent.

Figures 26, 27 and 28 show the penetration of coagulant into the filters with time for runs C-7 to C-9. Each of these figures reinforces the observations made previously, for Runs C-4 and C-5, that rate of penetration becomes linear with time and that for a given organism concentration the penetration of deposited coagulant increased with an increased coagulant dose. It is important to note from the figures that for a given concentration of coagulant the penetration increased with an increase in the number of organisms in the influent.

When studied in conjunction with the head loss curves it is apparent for the filters receiving the high concentration of coagulant, 1 and 3, within each run, that the lowering of head loss in the filters receiving a high load of suspended material is accompanied by considerably greater penetration of the coagulant into the filter. The same pattern of penetration is apparent for the filters receiving the lower coagulant concentration. However, as the head-loss pattern for filters 2 and 4 was approximately the same it is possible that a ratio of organism to coagulant may be reached after which no further increase in the head-loss takes place as a result of increased penetration.

Organism Removal Patterns for Different Levels of Coagulant

Figures 29, 30 and 31 are plots of the removals of organisms and the head loss increases observed during filter runs C-10 to C-12. An influent containing approximately 5.5×10^4 Selenastrum organisms per milliliter was employed with a different sand size per run. Four different levels of coagulant dosage were used in each run.

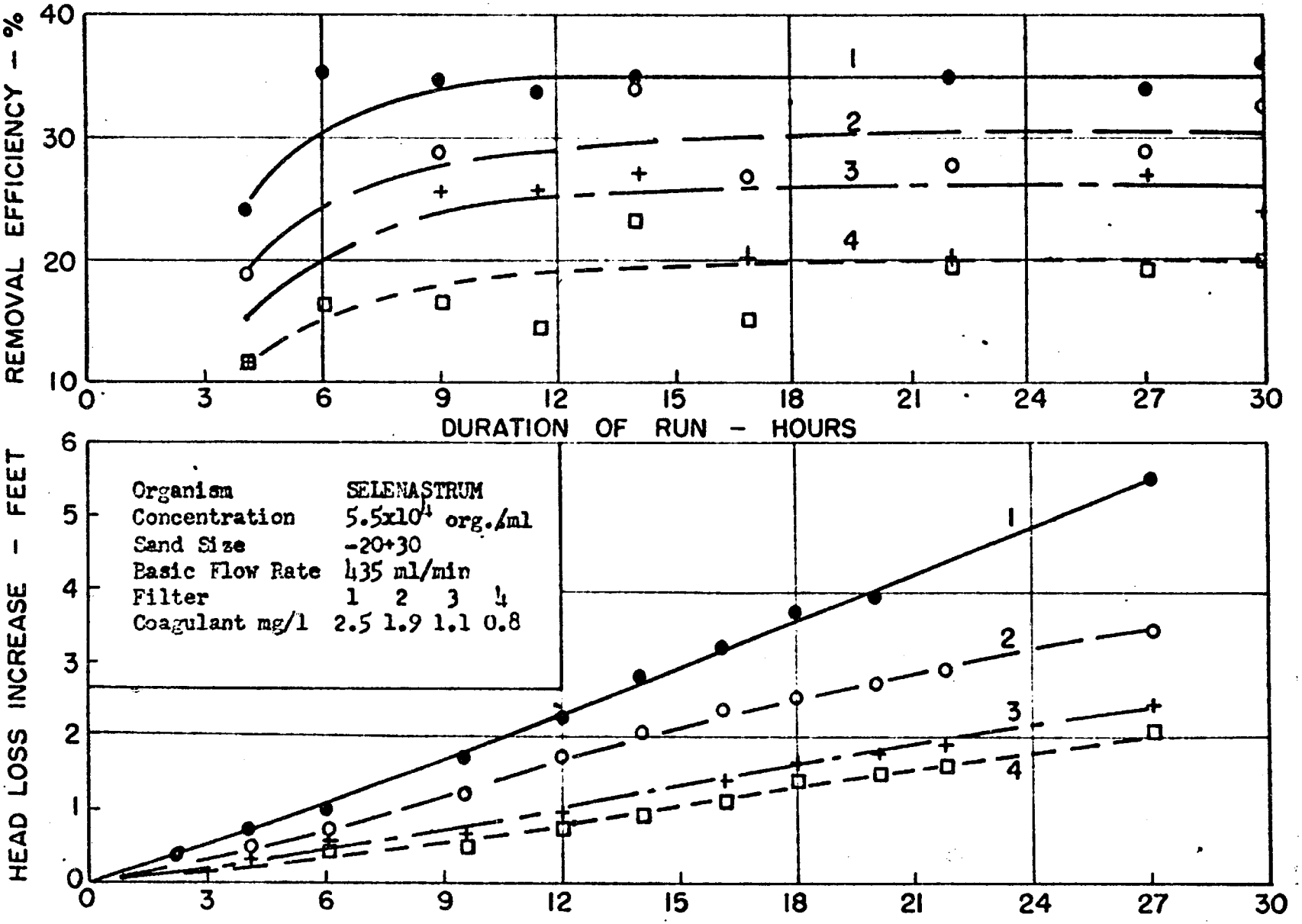


FIGURE 29. Removal Efficiencies and Head Loss Increases Developed During Run C-10

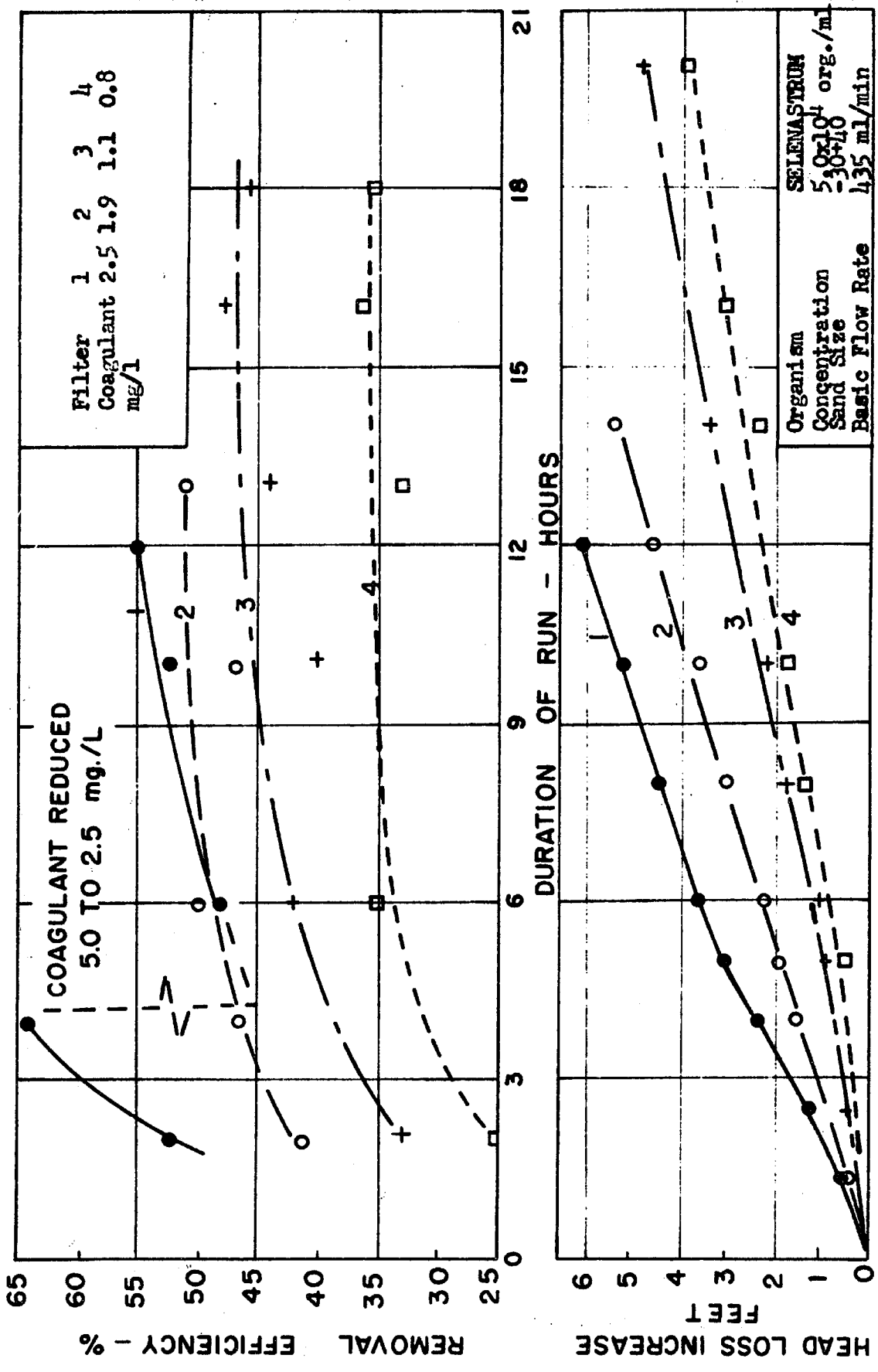


FIGURE 30. Removal Efficiencies and Head Loss Increases Developed During Run C-11

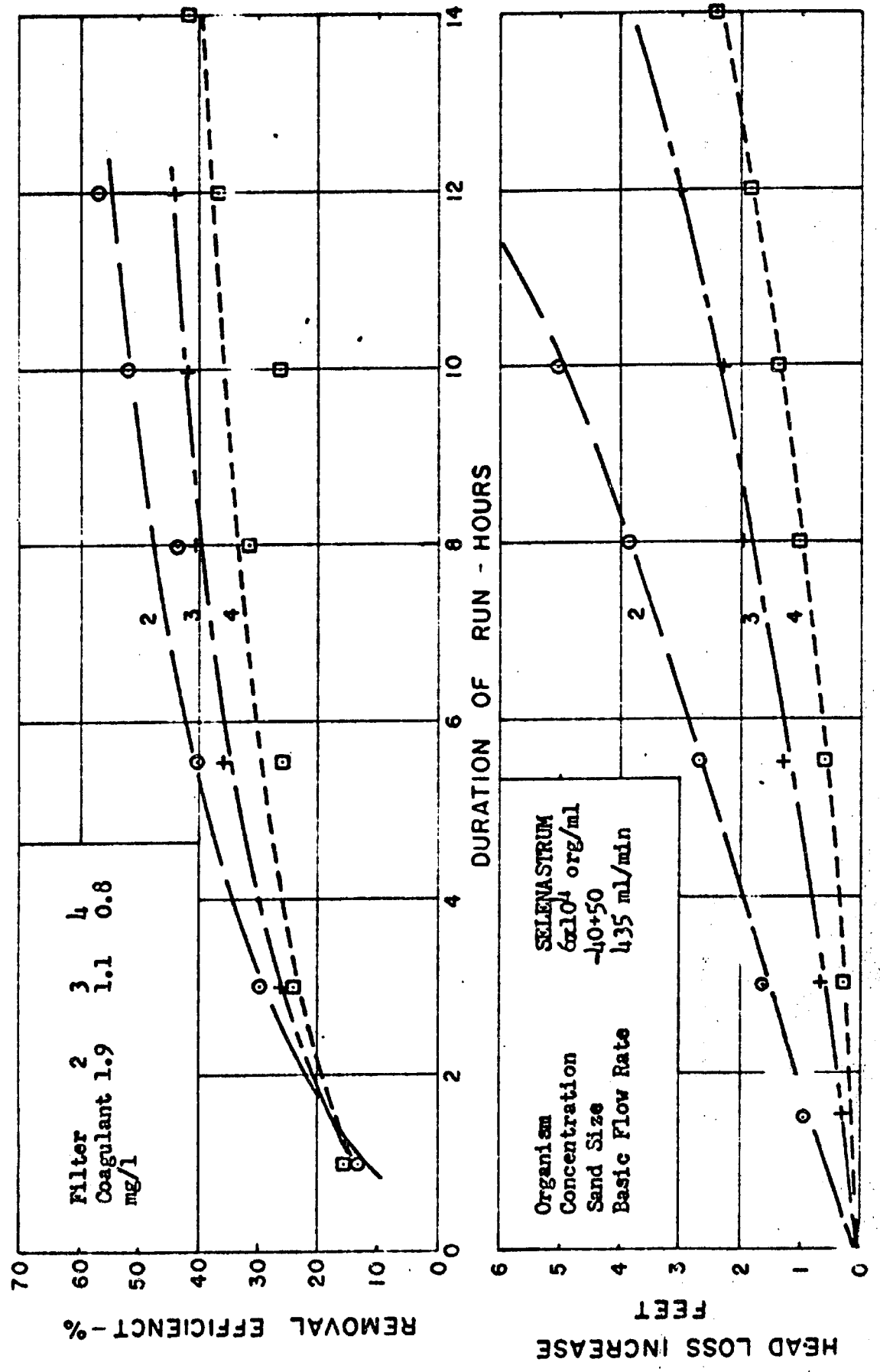


FIGURE 31. Removal Efficiencies and Head Loss Increases Developed During Run C-12

It may be noted from Figure 29 that a maximum feed rate of 2.5 mg/l was utilized with -20+30 size sand without breakthrough of the coagulant taking place as happened in run C-5, shown in Figure 21. It would appear that a critical organism-coagulant-sand size factor was not reached in run C-10. Figure 29 also shows that head loss increase developed for run C-10 in all four filters was nearly linear with time during the first few hours of the run but developed a concave downward pattern in those filters which received the lower coagulant dosages. The associated removals of organisms was low, ranging from about 20 to 35 per cent for the coagulant range of 0.8 to 2.5 mg/l.

During filter run C-11 the results of which are illustrated by Figure 30, a feed of 5 mg/l of coagulant was employed in filter number 1 and after four hours of operation the coagulant feed rate was halved. This was accompanied by reductions in head-loss increase rate and removal of algae. A tendency toward a concave downward pattern of head loss developed in the filters receiving the smaller amounts of coagulant. A concave upward pattern in the head-loss-increase curves was evident in all filters in Run C-12 as shown in Figure 31. The effect of reduced coagulant dosages was to decrease the upward curvature. Removals at the end of twelve hours of operation varied from 35 to 55 per cent for coagulant application rates of 0.8 to 1.9 mg/l. The duration of the run was limited for the high dosage rate due to head loss considerations.

Figures 32 and 33 represent the results of runs C-13 and C-X in which somewhat lower dosages of coagulant were employed and filter influents with lower concentration of organisms were utilized.

From Figure 32 it may be seen that removal efficiencies

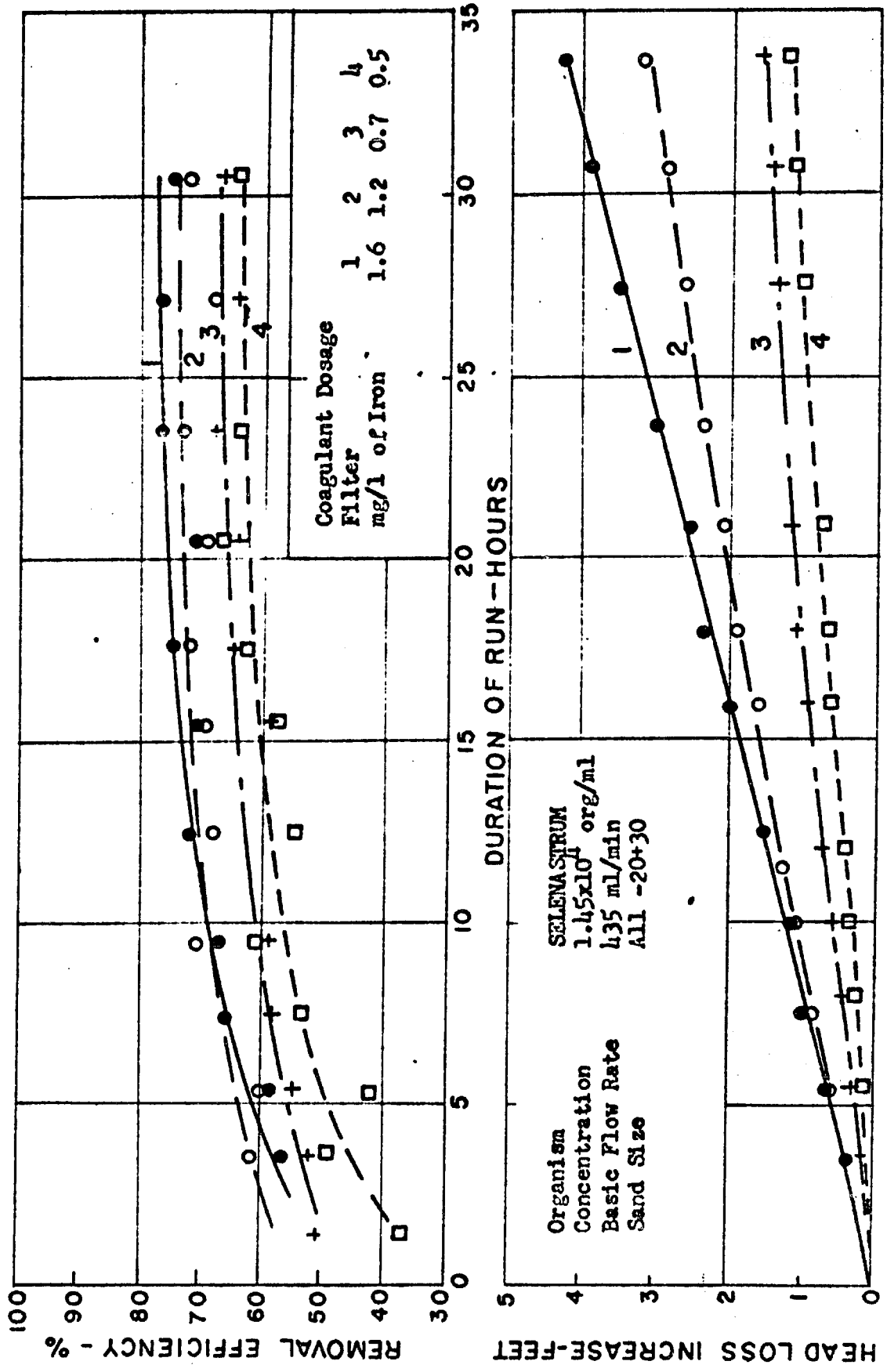


FIGURE 32. Removal Efficiencies and Head Loss Increases Developed During Run C-13

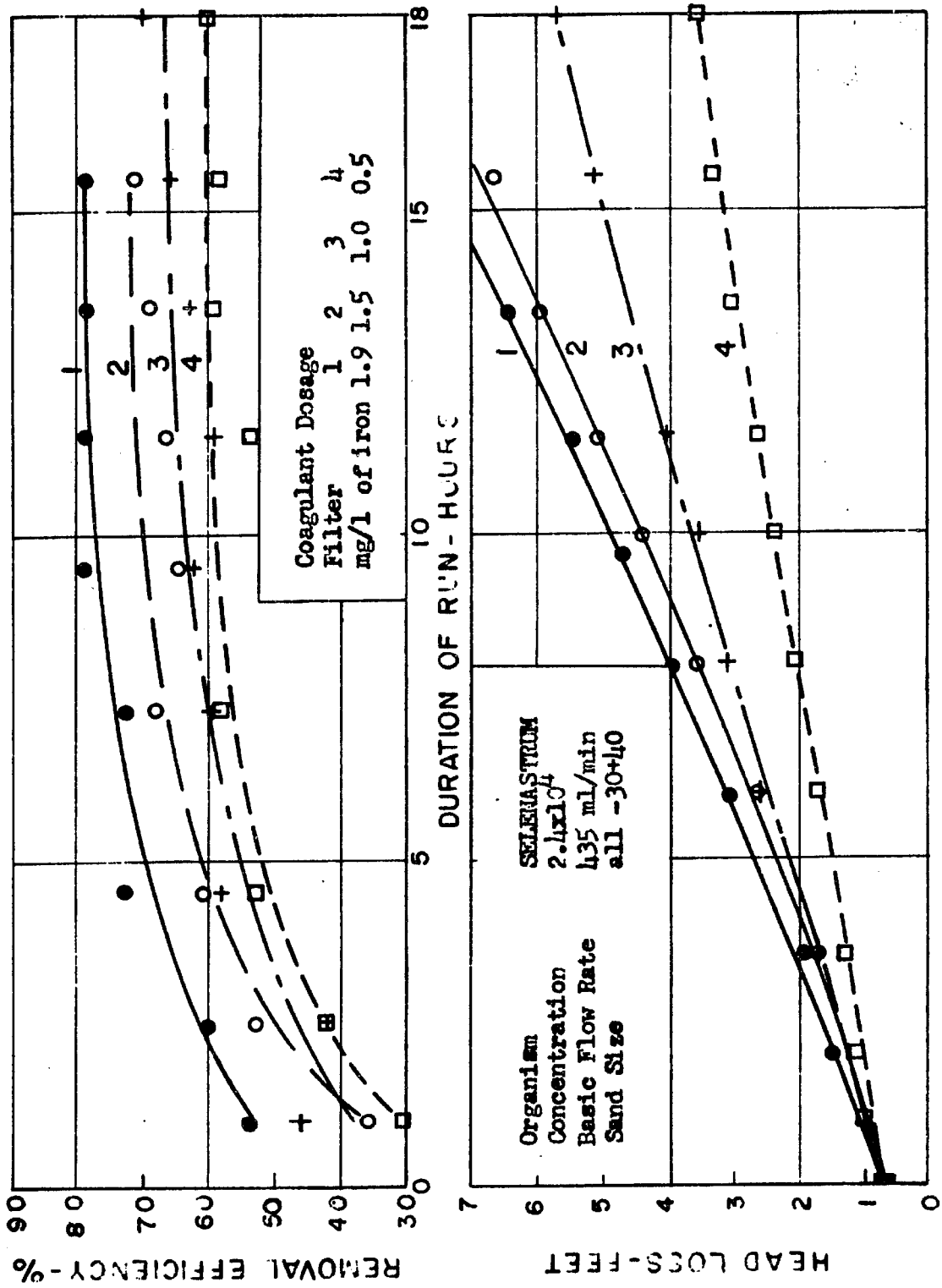


FIGURE 33. Removal Efficiencies and Head Loss Increases Developed During Run C-X

varied from 60 to 75 per cent. Head-loss was nearly linear through the run for filter number 1 and a concave downward pattern developed in the other filters.

During filter run C-X terminal removal efficiencies were in the range of 60 to 80 per cent. The pattern of head loss in run C-X may be seen in Figure 33 to be in agreement with other runs and presented a concave downward pattern.

Organism removals determined twelve hours after commencement of filtration for runs C-5 to C-X are presented in Table 4.

Removal Pattern

The general pattern of increasing removal of organisms was exhibited by all runs regardless of the concentration of organisms in the filter influent and the quantity of coagulant employed.

The greater chance for contact between algae and deposited coagulant material could account for increased removal associated with finer media for the same dose of coagulant, and the same algae concentration in the influent. Depressing of the normal head-loss-increase curve, for reduced coagulant feed rates, into a concave downward type of curve was the result of the presence of algae. It was shown that the depth of penetration of deposited coagulant was increased by the presence of algae in the influent. It is suggested that the presence of algae cause the deposits to penetrate deeper into the bed, reduce the concentration of material in the upper sections, and allow freer passage of the fluid through the filter.

From Table 4 and from Figure 34, a graphical representation of the removals as a function of the coagulant dosages, it appears there is evidence of general conformity within the experimental filter

TABLE 4

Summary of 12 hour Removal Efficiencies

Sand Size	-20+30					-30+40					-40+50				
Run C-	7	6	7	10	13	8	6	8	11	X	9	H	6	9	12
[Org/ml]x10^{-4}	18.6	14	7.6	5.5	1.5	20	14	8	5	2.4	19.4	16	14	9	6
Coag. mg/l															
2.5 2.4 2.3 2.2 2.1		31		35			43		55			33			
2.0 1.9 1.8 1.7 1.6				29	70				50	78		30			56
1.5 1.4 1.3 1.2 1.1	22		30	24	68	30		38	44	70	28	27		38	46
1.0 0.9 0.8 0.7 0.6 0.5 0.45	12	21	17	18	62 58	14		16	39	64 58	16	23	30	20	37

Basic Flow Rate 435 ml/min.

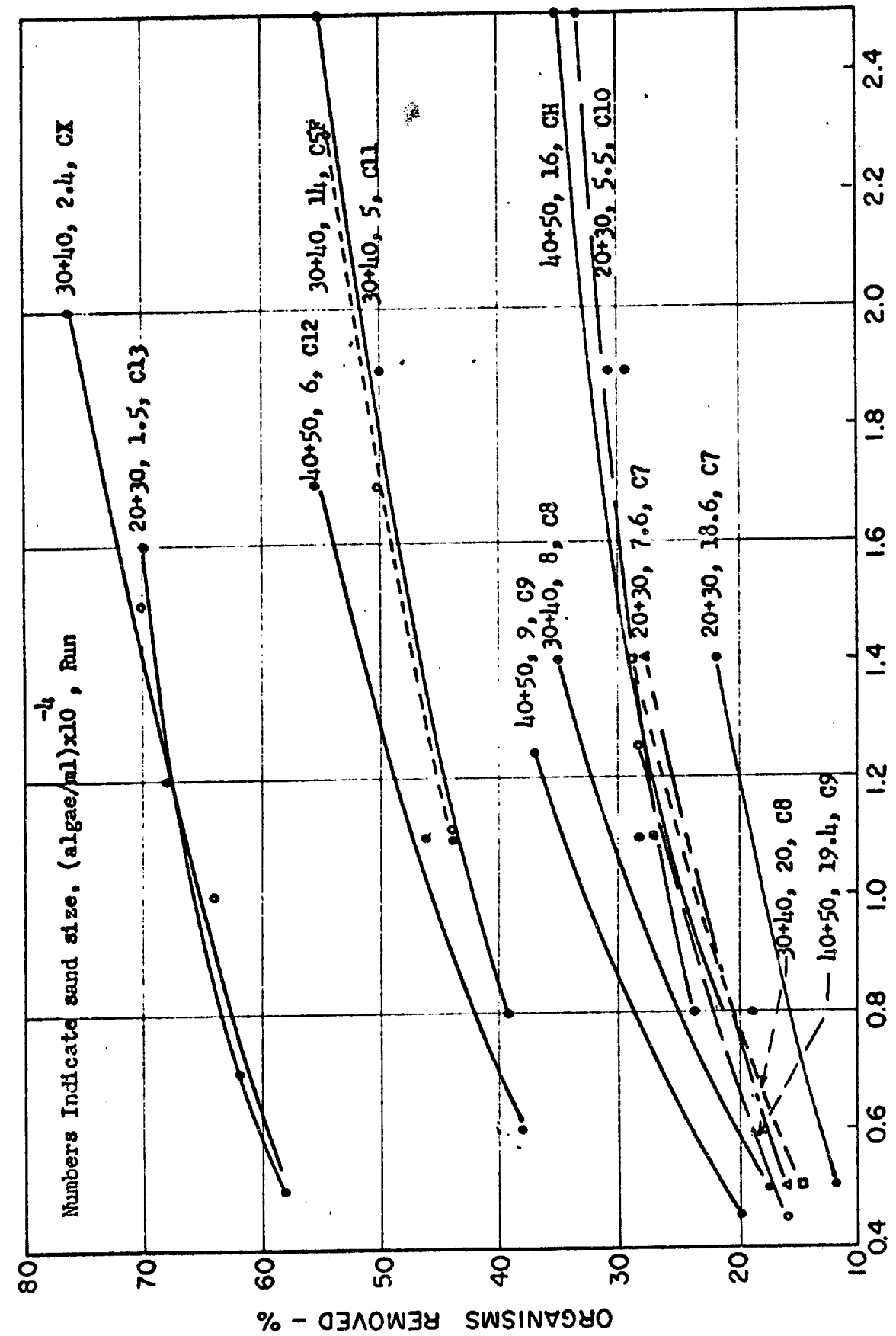


FIGURE 34. Percentage of Organisms Removed as a Function of the Coagulant Dosage Utilized

runs in the pattern of removal of algae in that:

1. For equal coagulant application rates to influents containing similar concentrations of algae there is an increase in the percentage of organisms removed with a decrease in the size of sand employed as the filter media.

2. For a given coagulant dosage and sand size there is an increase in the percentage of organisms removed associated with decrease in the organism concentration in the influent.

3. For any sand size and concentration of algae in the influent there is an increase in the percentage of organisms removed associated with an increase in the amount of coagulant applied.

The removal curve for a run in which the influent contained a mixture of Selenastrum and Schizothrix has been included in Figure 34 and is shown as a dashed line.

In Figure 35 the removal unit "(organisms/ml)$\times 10^{-4}$ per unit of coagulant" is plotted as a function of the coagulant dosage added for a number of runs selected from Table 4. From this figure it is apparent that:

1. For equal coagulant application rates to influent waters containing similar concentrations of organisms, there is an increase in the number of organisms removed, per unit of coagulant, with a decrease in the size of the sand employed as the filter media.

2. For a given coagulant dosage and sand size there is an increase in the number of organisms removed, per unit of coagulant, associated with an increase in the concentration of organisms in the filter influent.

3. For any filter run, regardless of sand size and concen-

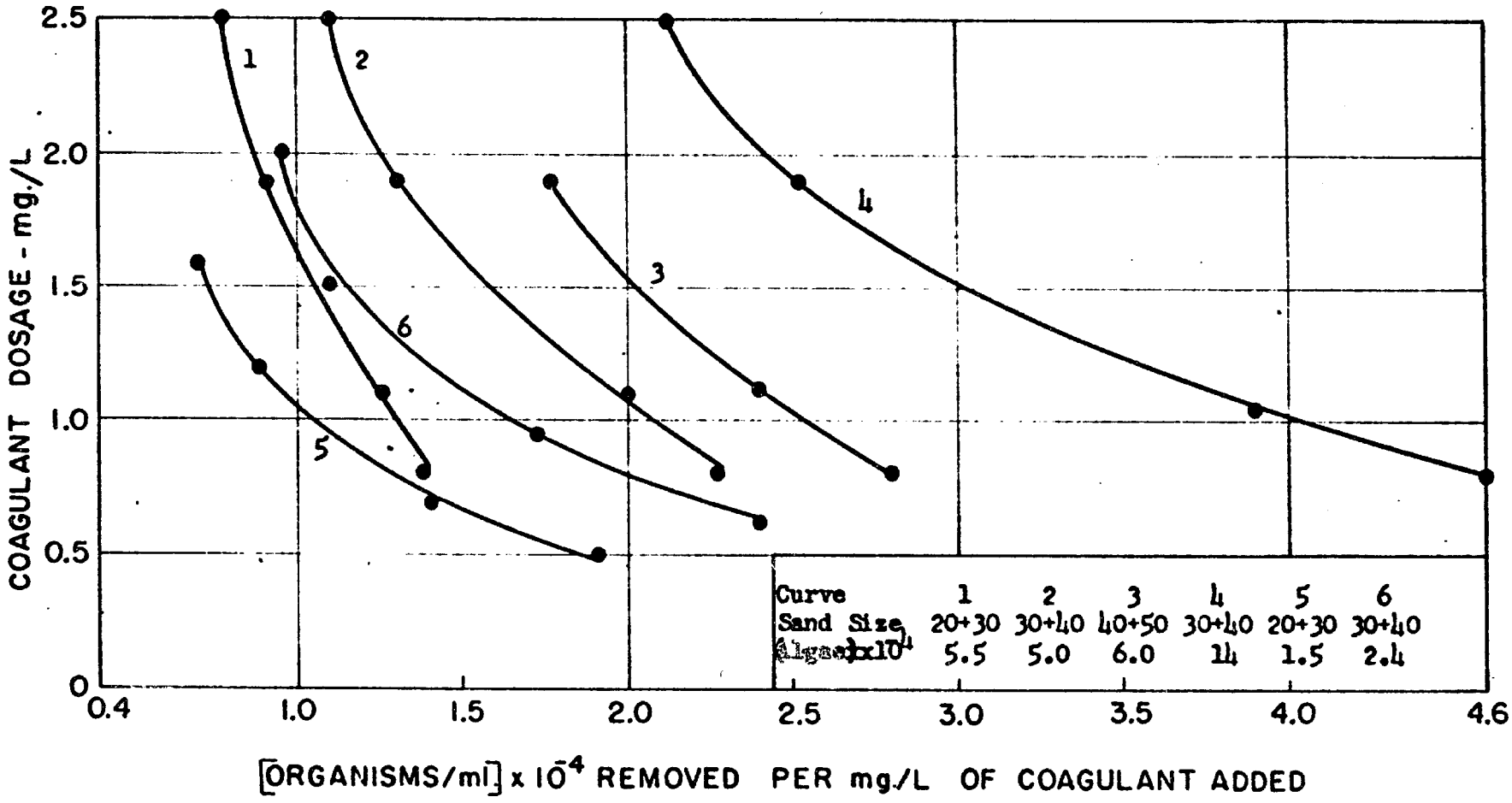


FIGURE 35. Coagulant Dose Employed As a Function of the Organisms Removed Per Unit of Coagulant

tration of organisms in the influent, the number of organisms removed per unit of coagulant applied increased with a reduction in the coagulant application rate. The two latter observations are in accord with the results of runs C-7 to C-9 as shown in Table 3.

The slopes of the curves in Figure 34 suggest the solution to the apparent contradiction between the number three observation above. All of the slopes of the curves are less than forty-five degrees to the horizontal and thus indicate less than proportional removal per unit of coagulant added. All curves tend toward the horizontal with increased application rates, indicating diminishing removal increase with continued coagulant increase.

Figure 36 shows the number of organisms per milliliter removed for various coagulant application rates for selected filter runs.

Values of "percent organisms removed" and "numbers of organisms removed" for the three sand sizes employed for coagulant additions of 0.8 and 1.4 mg/l.were employed to produce Figure 37 which, as a composite, shows the pattern of removal at the concentrations of organisms employed in the research. Whereas the percentage of organisms removed fell off rapidly in a curvilinear manner with an increase in the number of organisms in the filter influent, the actual number of organisms removed increased in an almost linear fashion with an increase in the concentration of algae in the filter influent.

The relationships established would indicate, within the limits of the investigation, that direct application of coagulant to a filter for the purpose of algae removal is a practical procedure which might be expected to yield high removal efficiencies if the

FIGURE 36. Number of Organisms Removed as a Function of the Coagulant Application

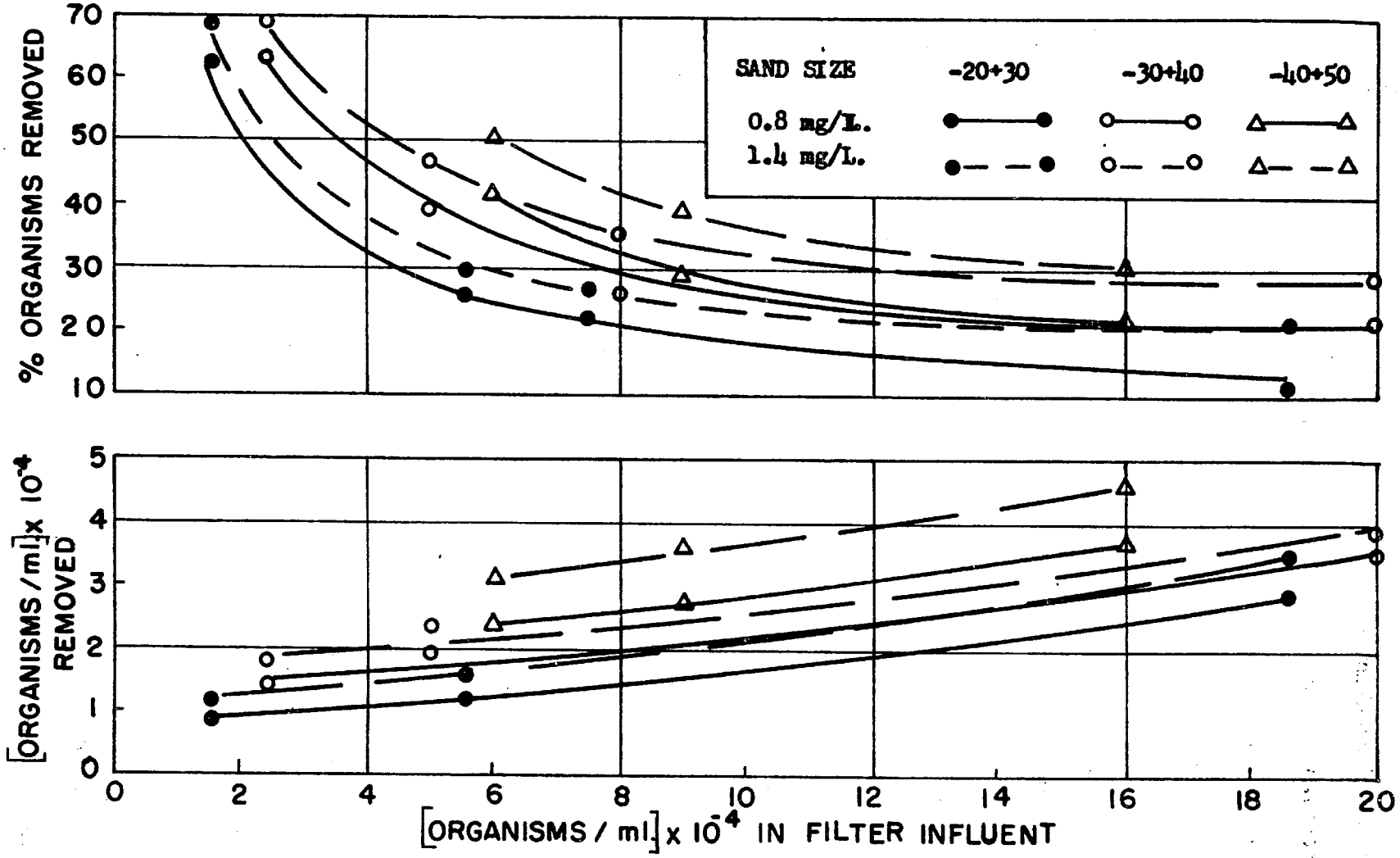


FIGURE 37. Organisms Removed For Two Different Dosages of Coagulant as a Function of the Concentration of Organisms in the Influent

algae content of the influent is of a low order. The point of balance between the flocculant particulate matter added to the filter and a non-flocculant particulate matter in the form of discrete single celled organisms is approached when the influent concentration of organsisms is low. One hundred per cent removal of organisms was not realized in any of the experiments.

Application of this method of particulate control may be limited to waters of naturally low content of algae or those which have had the load of algae substantially reduced by efficient pre-treatment.

Evidence is offered against the feeding of high concentrations of coagulant in order to achieve high removals. A proportional increase in removal is not accomplished by an increase in coagulant and the head loss considerations may be exceeded without a compensating increase in the removal of organisms.

A mixture of organisms which is likely to be found in a water used as a source of supply, would be expected to exhibit a greater tendency to be removed than a uni-algal suspension. The mixed culture removal shown in Figure 34 lends support to this speculation.

PATTERN OF COAGULANT PENETRATION STUDY

The Effect of Algae on Penetration

In order to explain observations made in previous experimental work and gain a broader insight into the process of filtration of particulate matter, a study was conducted of the penetration into sand filters of material of flocculant and non-flocculant nature.

Based on experimental evidence cited previously and upon visual and photographic comparisons it was assumed that penetration into a

3/4" core within a filter was representative of the penetration and deposit within the filter as a whole. Turbidity exhibited by the non-flocculant material retained within the core to visible light was employed as a measure of the quantity of this deposit.

Run P-1 was undertaken to determine if there was any difference in the pattern of penetration into a filter of a preformed floc, similar to that which might carry over from a pretreatment unit, and a floc freshly formed immediately prior to filtration. Coagulant equivalent to 2.5 mg/l was pumped to all four filters. Filters 2 and 3 received preformed floc and filters 1 and 4 received a solution of coagulant. The influent to filters 3 and 4 contained 10×10^4 Selenastrum organisms per milliliter.

The results of iron determinations and turbidity measurements of the material in the filter cores shown as 100-% Transmittance are presented in Figure 38. The quantities determined for each section of the cores are plotted at the midpoint of the sections.

Considering filters 1 and 2, it would appear that the pattern of penetration was identical. The amount of floc retained in the filter fell off logarithmically with depth to a "knee" value where the slope increased greatly. This rapid decrease in deposit was terminated by a "base" value which appeared to persist throughout the remaining depth of the filter. The distribution of the new floc was slightly more uniform and penetrated deeper before the knee break appeared.

The pattern of deposit exhibited for filters 3 and 4 which received influents containing algae showed a reversal in direction of the break at the "knee" and a general flattening of the deposit curve. No downward break was determined in filter number 3 for the coagulant

deposited in the sections sampled, however, such a break must be assumed to exist for no breakthrough of the filter occurred. In this, and subsequent runs, the amount of iron recovered from the cores where no breakthrough of the filter occurred varied between 87 and 103% of that which was theoretically applied.

The amount of algal material deposited within a core section showed similar form to the iron deposit pattern with the break of the curves occurring within the same core section. It is evident that the fresh floc caused the retention of a greater amount of algal material. This is in concurrence with prior experimental results.

Figure 39 for run P-2 shows the influence on penetration and on location of deposited coagulant within a -20+30 sand filter exhibited by varying concentrations of algae. Progressive lowering of the amount of deposit in the upper sections of the filter and deepening of penetration is indicated.

Figure 40 depicts the quantities of algal material recovered from cores for run P-2. These curves are not exactly identical in shape to the iron location curves in figure 39, but do show the general pattern of the breaks occurring in the appropriate core section. The reverse break in filter number 4 did not appear, but rather, the line of best fit through the experimentally determined points was straight. The relative positions of the curves is in order of the numbers of organisms applied in the feed fluid. This is in concurrence with prior determinations in that the numbers of organisms removed for a given coagulant application increased with increased numbers in the influent.

Figure 41 for Run P-8 illustrates the influence on penetration of coagulant into a -30+40 sand filter of varying numbers of organ-

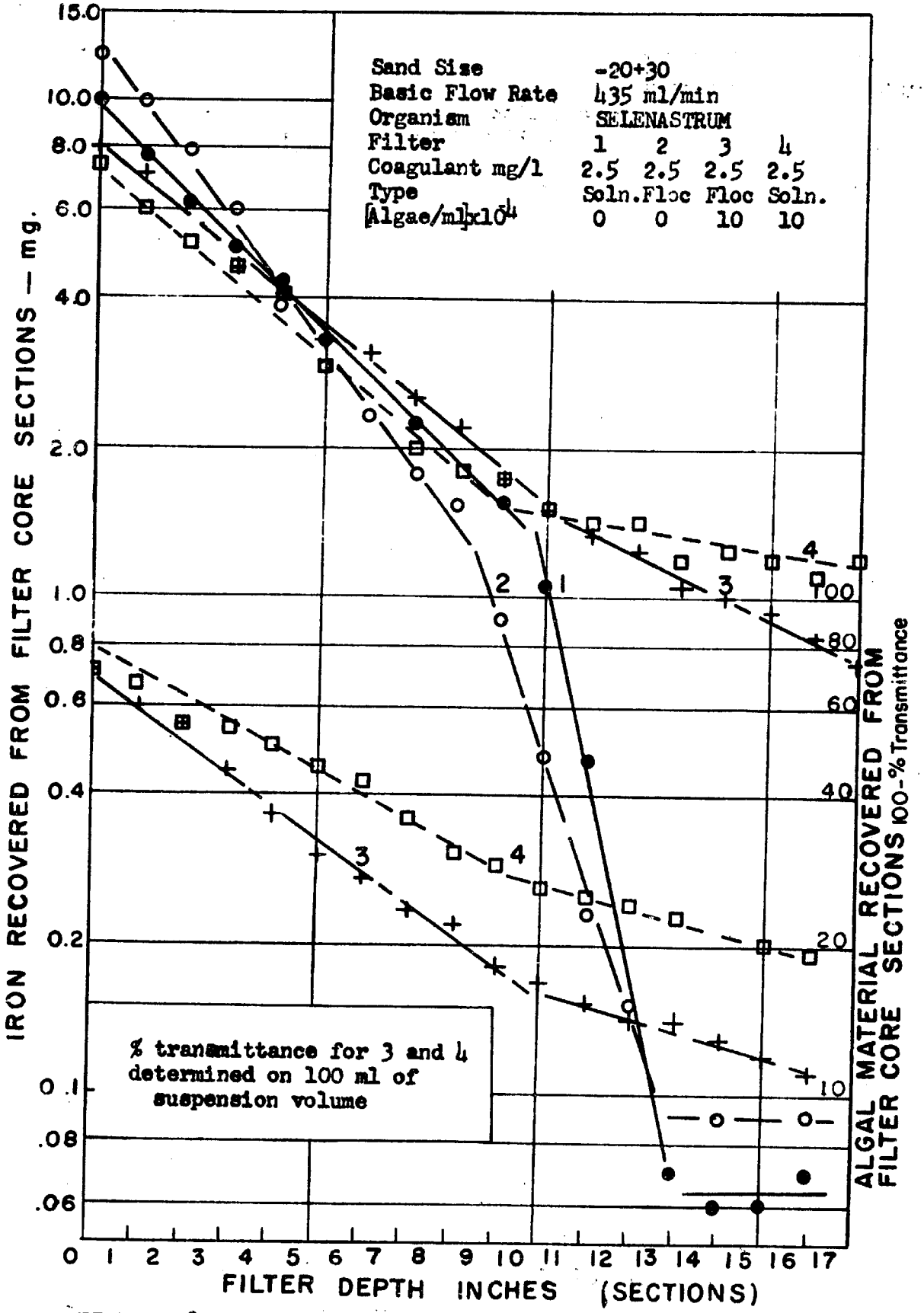


FIGURE 38. Pattern of Penetration of Preformed and Solution Fed Coagulant and Location of Algal Material Removed in Experimental Sand Filters

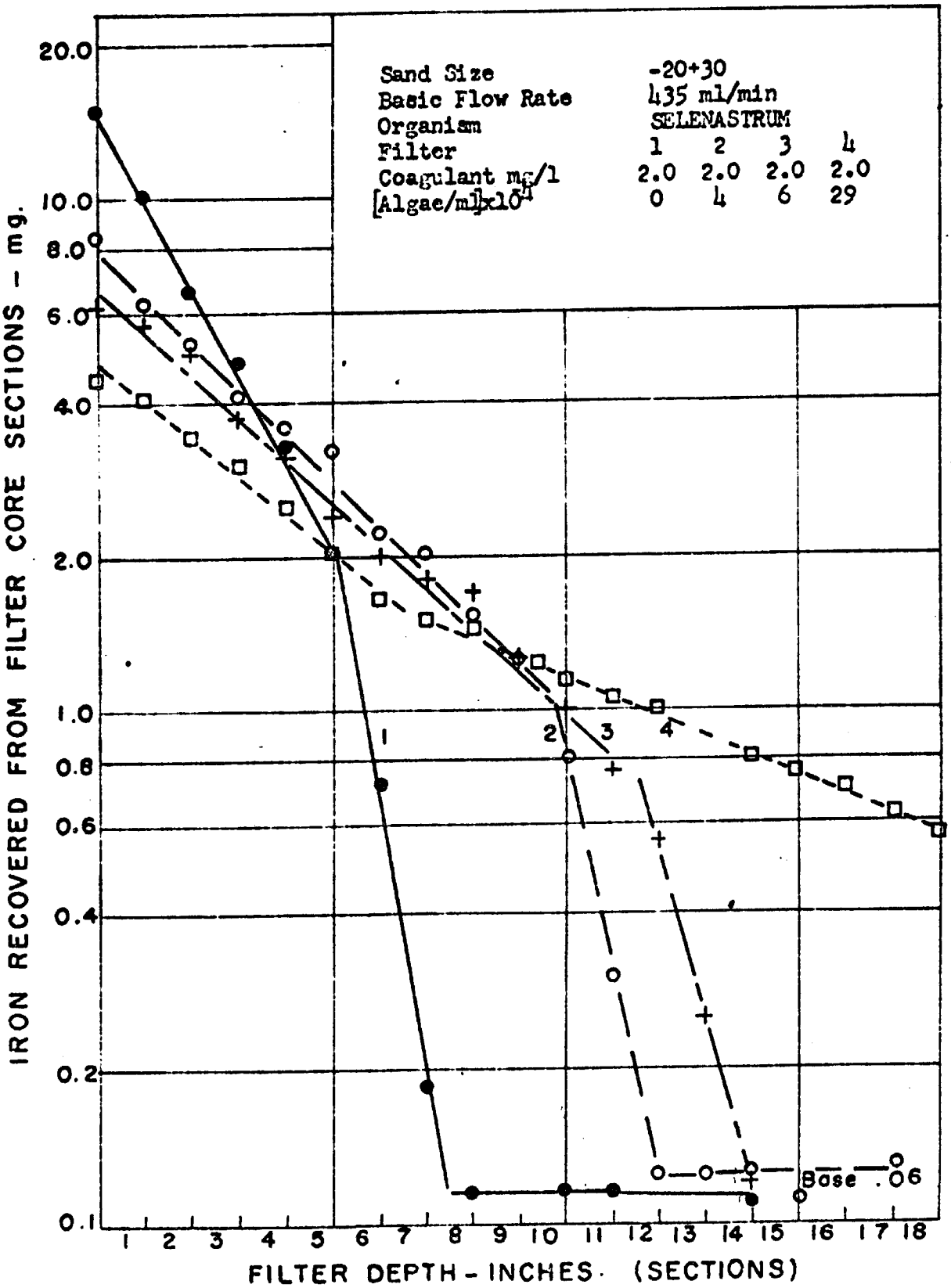


FIGURE 39. The Effect of Varying Concentrations of Algae on the Penetration of Coagulant Into Experimental Filters

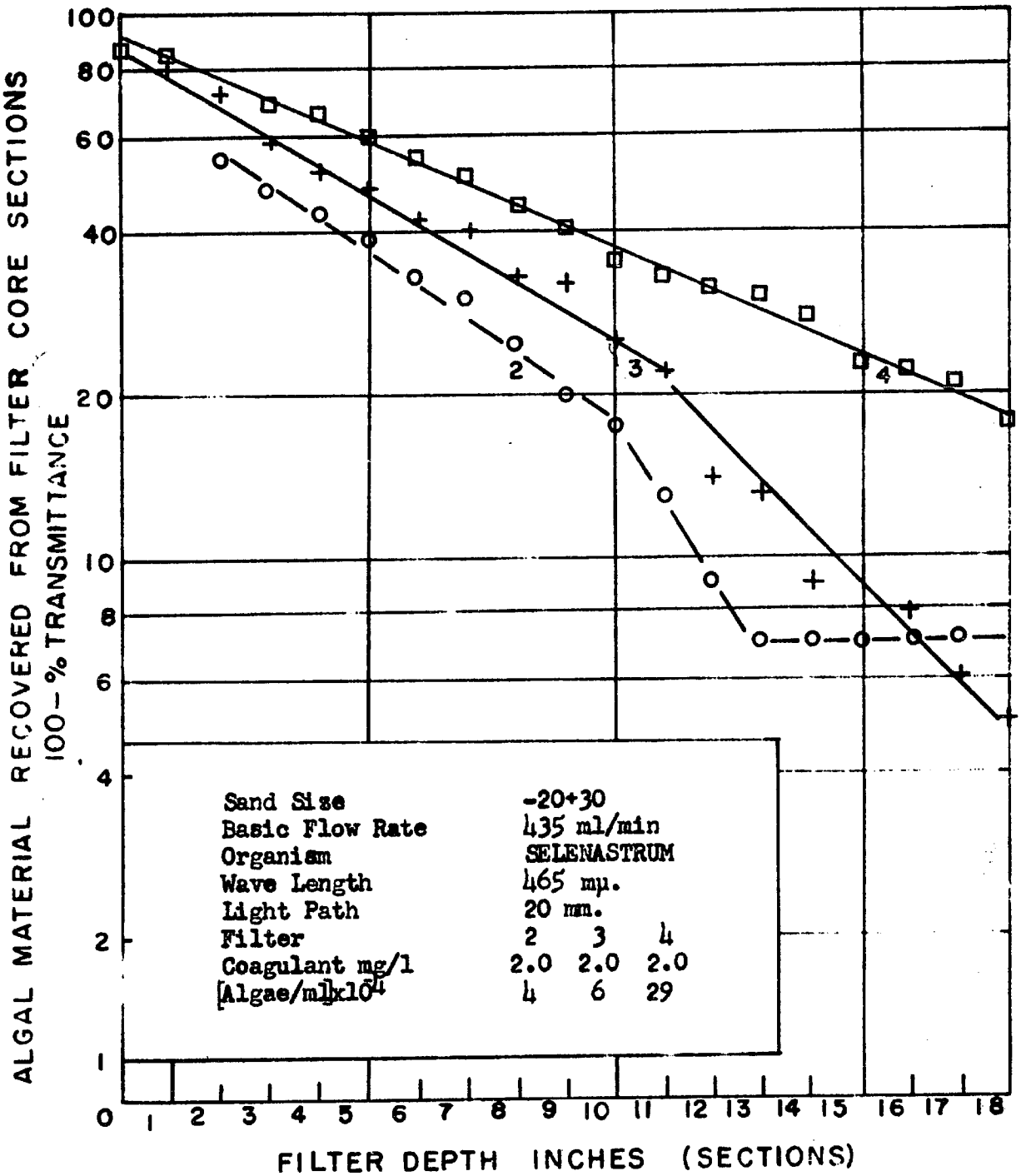


FIGURE 40. Location of Algal Material Deposited in Experimental Filters During Run P2.

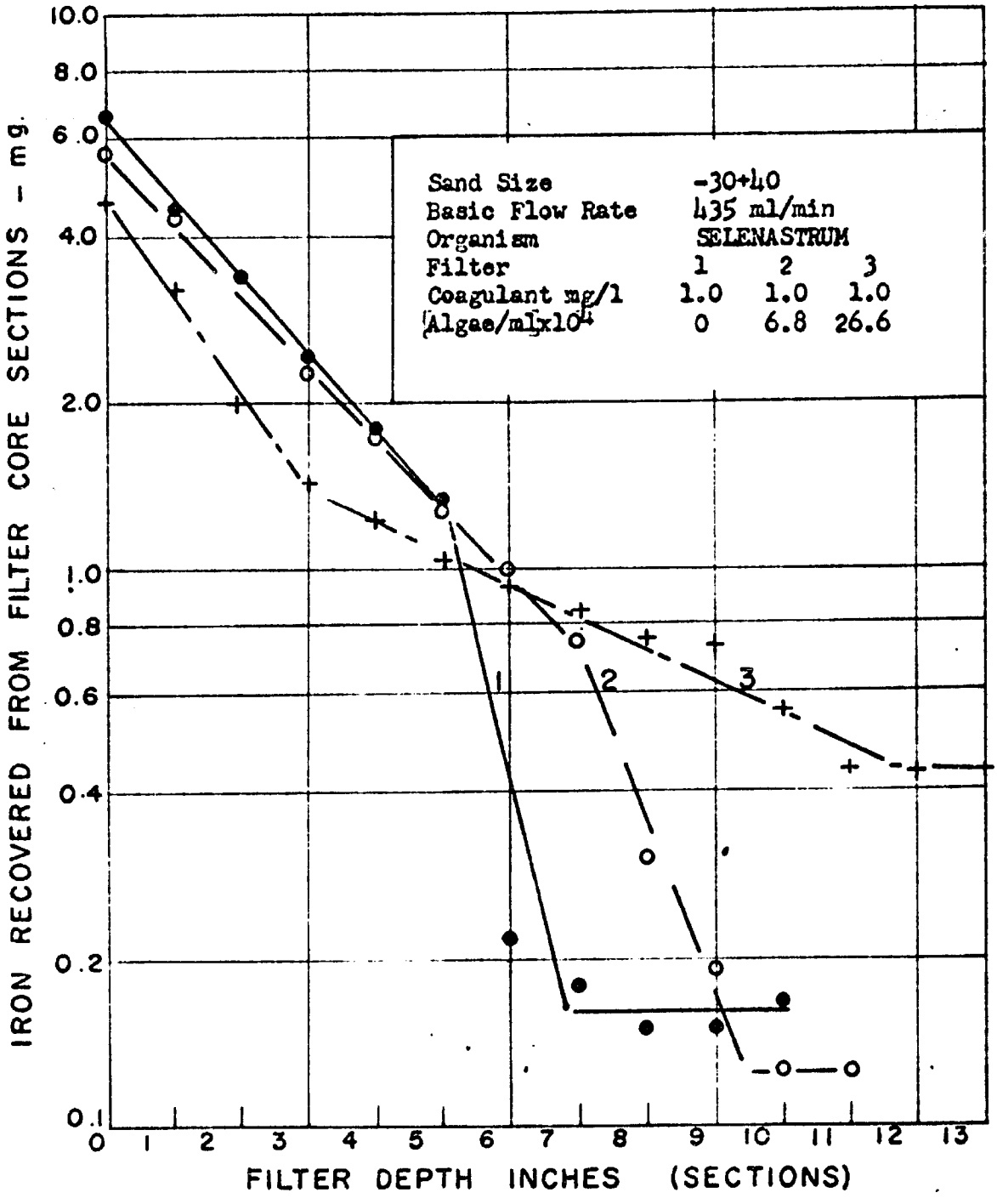


FIGURE 41. The Effect of Varying Concentrations of Algae on the Penetration of Coagulant Into Experimental Filters Run P3.

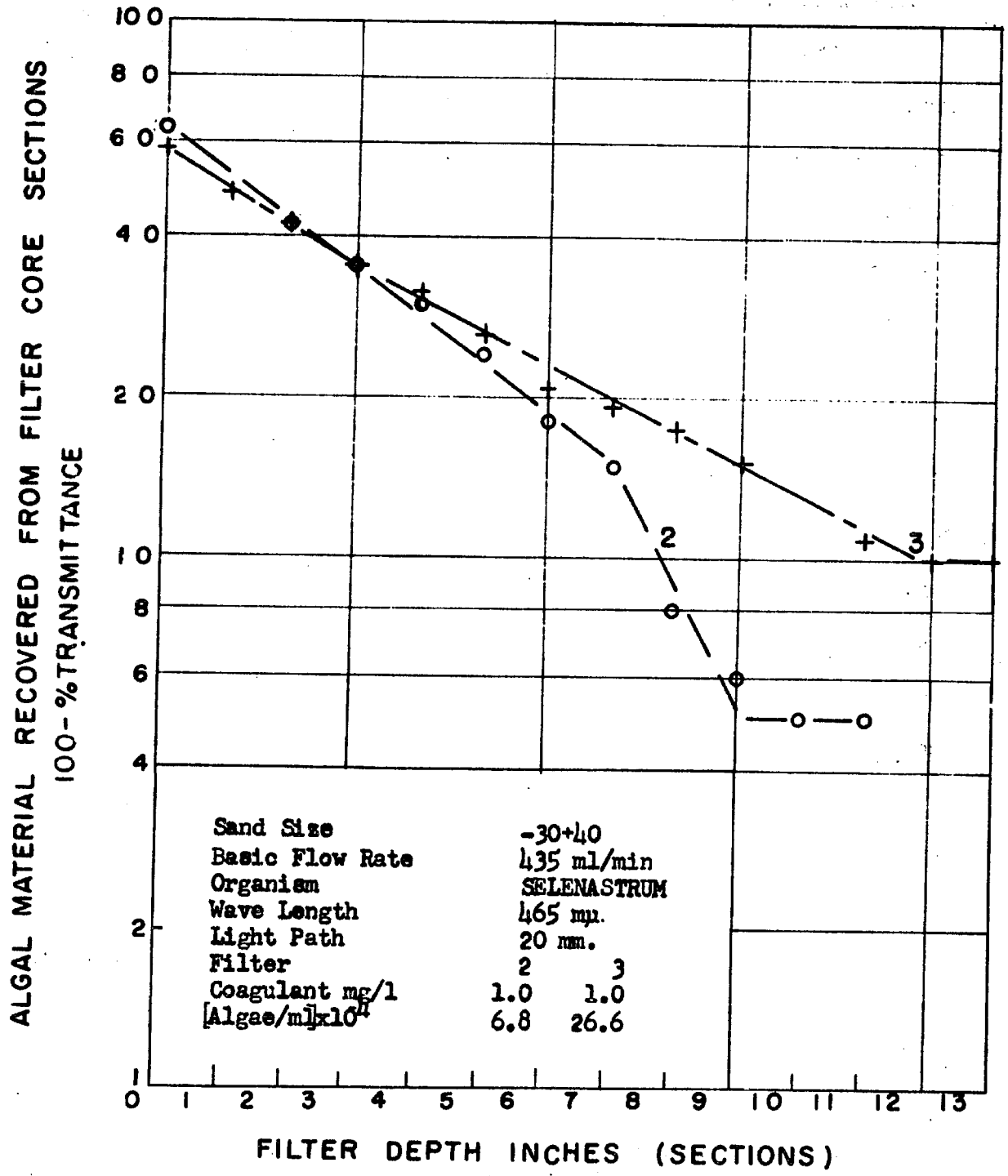


FIGURE 42. Location of Deposit of Algal Material Deposited In Experimental Filters Run P3.

isms. Figure 42 shows the location of the deposited algal material for Run P-3. These curves correspond very closely to their respective coagulant location curves.

The 12 hour removals determined for run P-3 were 16% for filter number 3 and 28% for filter number 2. Extrapolation of the curve of Figure 37 would indicate an expected removal of just under 20% for filter number 3 and 32% for number 4. These values are in reasonable agreement with the determined removals for run P-3. Data from run P-3 was not utilized in the preparation of figure 37.

Penetration patterns were also determined for -40+50 sand filters, and were found to be similar to those for coarser sand except depth of penetration of coagulant was much less. In all penetration pattern runs there was an overall reduction in head loss as well as a concave downward pattern for increased numbers of algae in the influent. This was similar to patterns which had been noted in previous runs.

The Effect of Activated Carbon on Penetration

A study was undertaken to determine if other particulate matter would act, during filtration, in a manner similar to algae. Powdered activated carbon was adopted as the particulate matter. This material was obtained from the Ann Arbor Water Treatment Plant, where it is used in the control of taste and odor. A slurry of the carbon was applied to the filters to give the required dose in the filter influent and coagulant was applied as a solution.

An investigation was conducted to determine if a balance could be reached between coagulant and carbon such that all of the latter would be removed. Sand of -20+30 size was employed as it had been shown

that this size exhibited greatest penetration during filter runs when algae were present in the influent.

The various application rates of coagulant and activated carbon investigated are stated in Table 5. The amount of carbon passing the filters and listed in the body of the table was determined by weighing the carbon deposited from one liter of effluent upon a type HA millipore filter.

It is clear that approximately 1 mg/l of coagulant when applied to a filter of -20+30 size sand resulted in the complete removal of all carbon up to 33 mg/l, a value not often encountered in filtration practice.

From the foregoing it may be surmised for plant operation that direct addition of a small quantity of chemical coagulant prior to the filters would be expected to remove completely any carbon which may be passing pretreatment units or which may have been purposely added before the filters.

The pattern of deposit of coagulant as it was affected by the presence of activated carbon may be seen in Figure 43. Bearing in mind the reduced length of run for filter number 4, due to high head loss, the similarity to the pattern caused by algae as shown in Figure 39 is striking giving strong support to the conclusion that the removal process was similar but modified by the type of suspended matter in the feed fluid.

The interrelationship of the amount and location of deposited coagulant and deposited non-flocculant particulate matter is illustrated in Figure 44. In this figure the coagulant recovered is plotted in conjunction with the amount of light stopped by the carbon

TABLE 5

Activated Carbon Passage Through 24 Inch Filters of -20+30 Sand Under Different Solution Coagulant Applications

Mg/L of Coagulant Applied to Filters	Mg/L Activated Carbon in Filter Effluent									
0.0	1.1					11				
0.2		1.0			1.3			2.7		
0.4		1.1			1.1			2.0		
0.6				.3					.6	
0.8				.2					.3	
1.0		0		0				0		
2.0			0				0			0
Mg/L of Activated Carbon Applied	2	3.3	6	7*	11	12	20	33	45*	94*

Note: All Values in Body of Table and Those Marked With Asterisk Determined by Milliporefilter. All Other Values Calculated

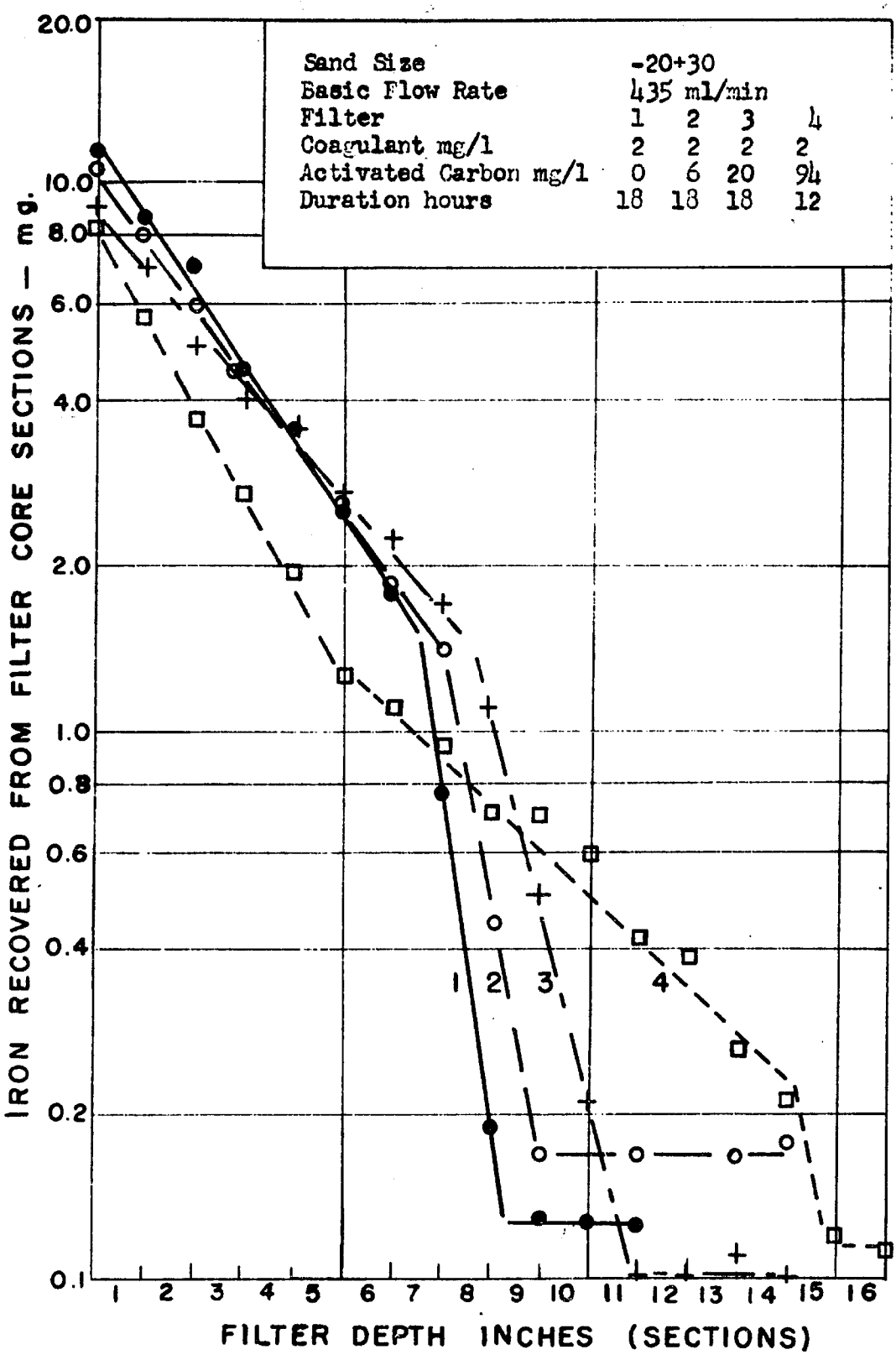


FIGURE 43. The Effect of Varying Concentrations of Activated Carbon on the Penetration of Coagulant Into Experimental Filters

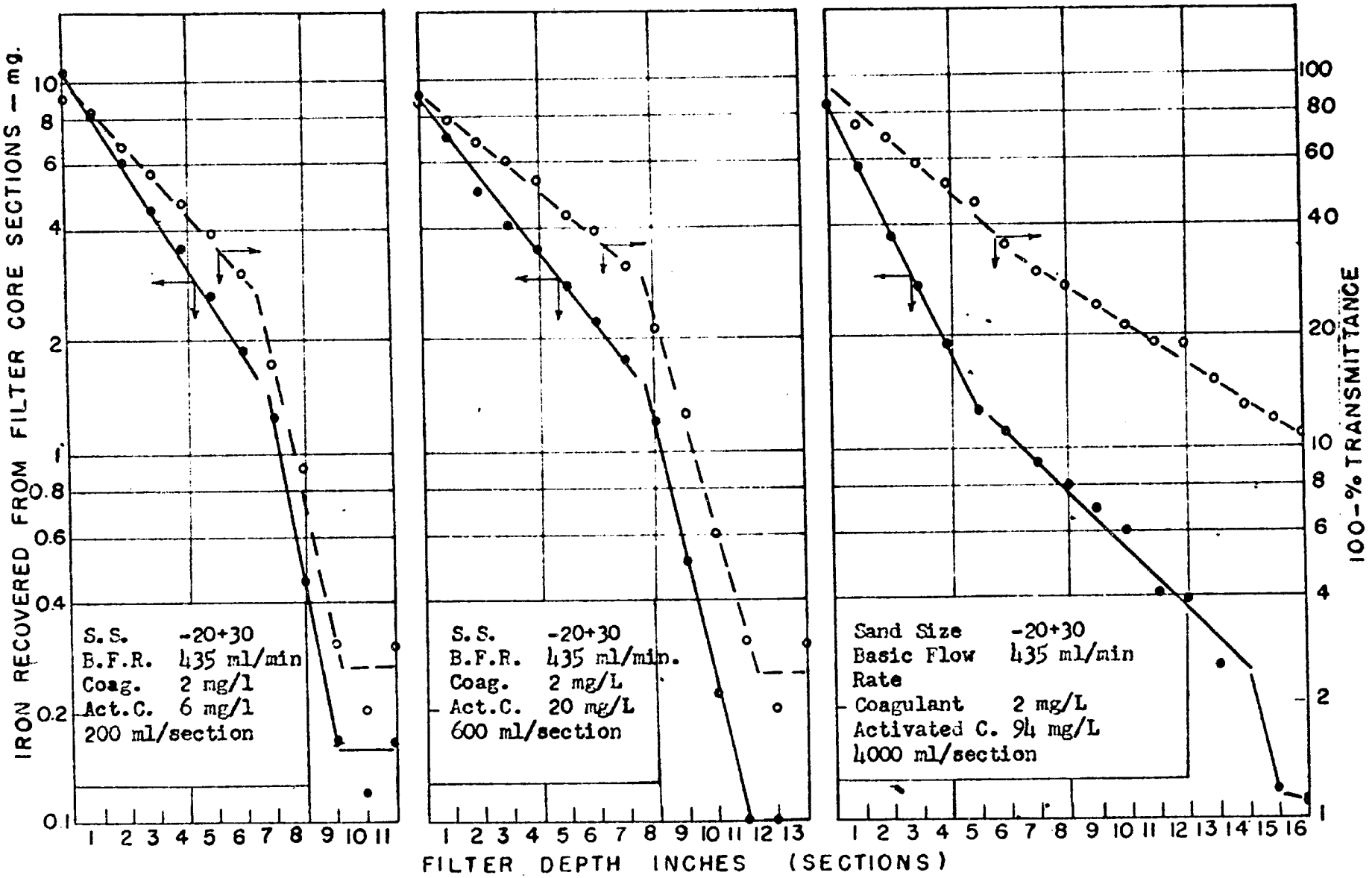


FIGURE 44. The Amount and Location of Deposited Coagulant and Activated Carbon in Experimental Filters

recovered from the same filter sections. The activated carbon was suspended in varying amounts of water depending on the quantity of carbon present. Curves for coagulant and activated carbon show nearly identical form.

The pattern of head-loss increase associated with filtration of activated carbon is presented in Figure 45. A study of this figure reveals that for the application of the same amount of coagulant the rate of increase of head loss increased with greater amounts of activated carbon in the influent. This is in contrast to algae causing a decrease in the rate of increase when they were the non-flocculant particles present in the influent.

The pattern of penetration of coagulant into filters of uniform size sand indicated that removal in the upper portion of the bed was logarithmic with depth. This relation was valid for preformed floc and also for floc formed in filter tubes as a result of addition of solutions of coagulants.

This pattern is verification, in general, under rapid sand filtration conditions, of the theoretical approach to filtration of other investigaters (135, 57, 74). In this experimental undertaking there was no indication of a maximum amount of material being deposited in the upper section of a filter. However, flattening of the deposited coagulant versus depth line may indicate that a terminal deposit might be approached with time. The head loss for the upper section increased throughout the length of a run and the amount of coagulant deposited was always considerably greater in the first than in subsequent sections.

Similar logarithmic patterns of removal have been observed

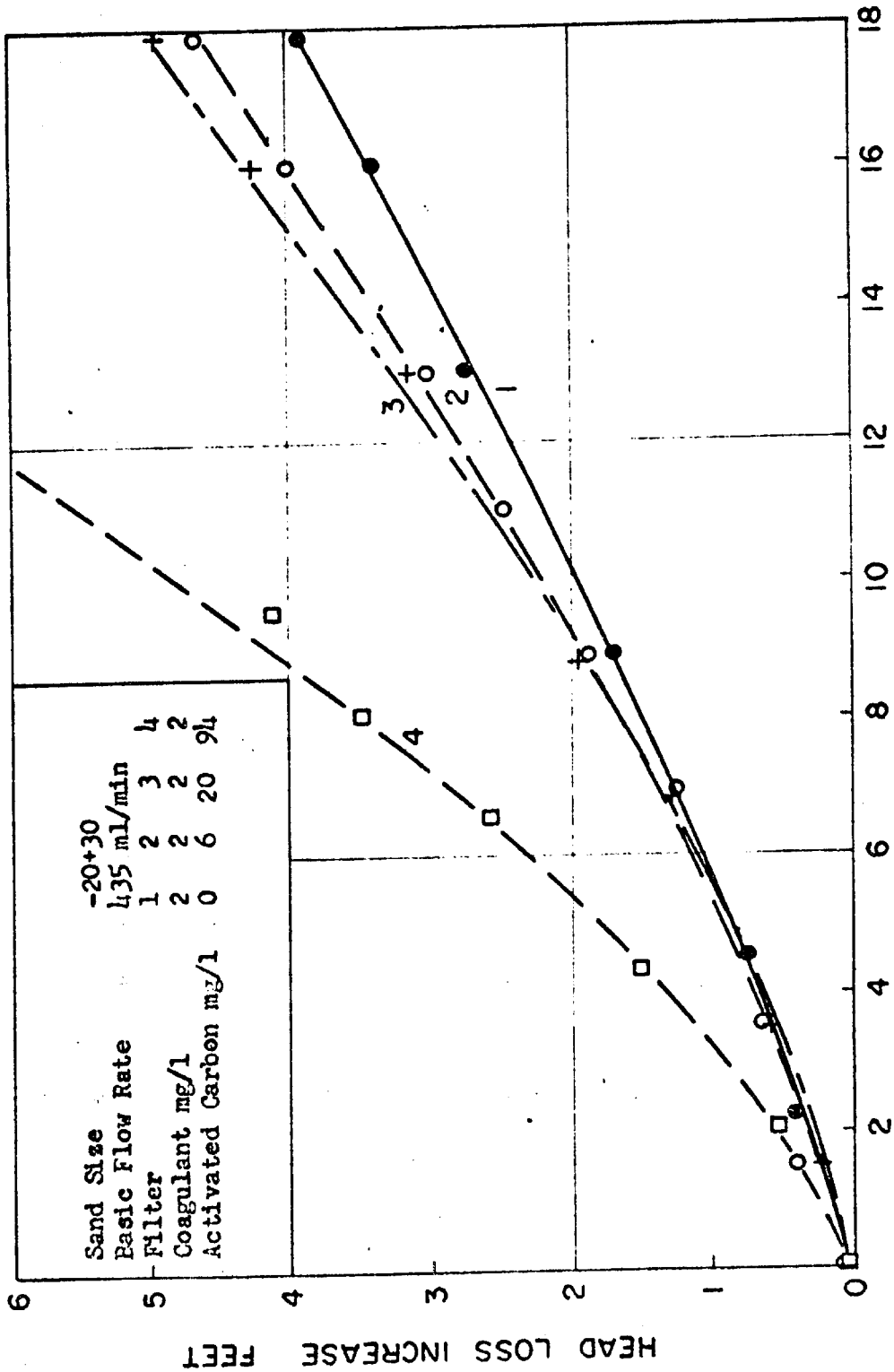


FIGURE 45. The Effect of Increasing Concentrations of Activated Carbon on the Head Loss Developed in Experimental Filters

for the fibrous filtration of bacterial spores (83) and the removal of bacteria in soil (152).

There were no known observations during the experiments which would account for the sharp decrease which occurred in the rate of penetration. Until further study is undertaken to determine the exact cause of this change it might be suggested that differences in size, shape, and perhaps most important, differences in residual charges within one run could be responsible. Floc in the section below the break in slope was active in removing particulate matter as is evidenced by similarities in patterns exhibited by deposited coagulant and suspended matter. More complete neutralization of the charge on the floc particles by increasing concentrations of non-flocculant matter would indicate a flocculant-non-flocculant complex could be carried further into a filter bed before being removed by the sand particles.

That the amount of coagulant did in no case drop to zero indicated a deposit of coagulant on the filter media at least throughout the depth that the filters were sampled. This retention of coagulant is not dissimilar to results determined in the fibrous filtration of bacterial spores and attributed to edge or radial leakage. The parallel operation of two filters of vastly different $\frac{D}{d}$ ratios which yielded similar organism removal results does not rule out wall effects being present but of a similar magnitude, nor does it negate the possibility of penetration of the filter media of both filters by small amounts of coagulant. Evidence as to a source of coagulant deep in filters may be obtained from initial penetration studies (153) and substantiated by observations made during the present investigations.

A short period of high initial breakthrough of coagulant through a filter coupled with a minute amount of material passing the bed could account for a base line of coagulant on the media.

The difference in magnitude of charge on algae, and activated carbon, may be indicative of the tendency with which these non-flocculant particles are removed by oppositely charged flocculant particles. The fact that the activated carbon used was not composed of uniform sized particles might have affected the head-loss increase pattern causing it to be different from the pattern developed when uniform sized algae were the non-flocculant particles used.

The partial removal of algae with penetration of a filter by some organisms at all times, in contrast to the possibility of complete removal of activated carbon suggests further areas of investigation to determine if (i) algal cells once retained by deposited coagulant are held indefinitely or are replaced, (ii) algal cells which pass through a filter show any different characteristics from organisms in the influent, and (iii) the primary reasons to account for complete removal of one type of non-flocculant material and only the partial removal of another.

The Effect of Hexametaphosphate on Coagulant Penetration

The effect of algae in an influent on the location of deposited coagulant within filters is shown in Figure 39. A similar effect caused by the presence of varying concentrations of hexametaphosphate in filter influents may be observed in Figure 46.

This figure presents results of analyses of core sections from six filters which were operated with the amount of phosphate in the influent as the only changeable variable. Concentration of coagulant added to each filter was 2.5 mg/l. Hexametaphosphate, which was

obtained from the Ann Arbor Water Treatment plant where it is utilized in threshold treatment for stabilization, was employed. The weight of chemical introduced into the influent water immediately prior to the runs determined dosages as recorded on Figure 46.

It may be seen that the usual logarithmic pattern of deposit of coagulant was flattened somewhat with an attendant deepening of penetration in those two filters which received influent containing the smallest quantities of hexametaphosphate used in the experiments. It may also be seen that with increasing concentrations of hexametaphosphate in the filter influents, the normal "knee" break pattern straightened and then changed to a reverse break. This pattern was similar to that experienced with heavy feeds of algae or activated carbon. At the highest concentrations of phosphate in the filter influents deposition of the coagulant was severely retarded.

The dramatic effect of hexametaphosphate on the coagulant is shown in Figure 47 which depicts curves for head loss increase and amount of coagulant penetrating the filters. Head loss reduction was nearly uniform for incremental increases of phosphate concentration in the filter influents. For concentrations of hexametaphosphate in the influent in excess of approximately the concentration of coagulant employed there was considerable passage of coagulant through the filter. In all filters this passage was reduced with time.

The application of small quantities of hexametaphosphate to a water for stability control is an accepted practice in water treatment. The adsorption of phosphate on nucleii surfaces as they form, thereby inhibiting precipitation of calcium carbonate, has been discussed by Corsaro (154). Reports on the disturbing action of poly-

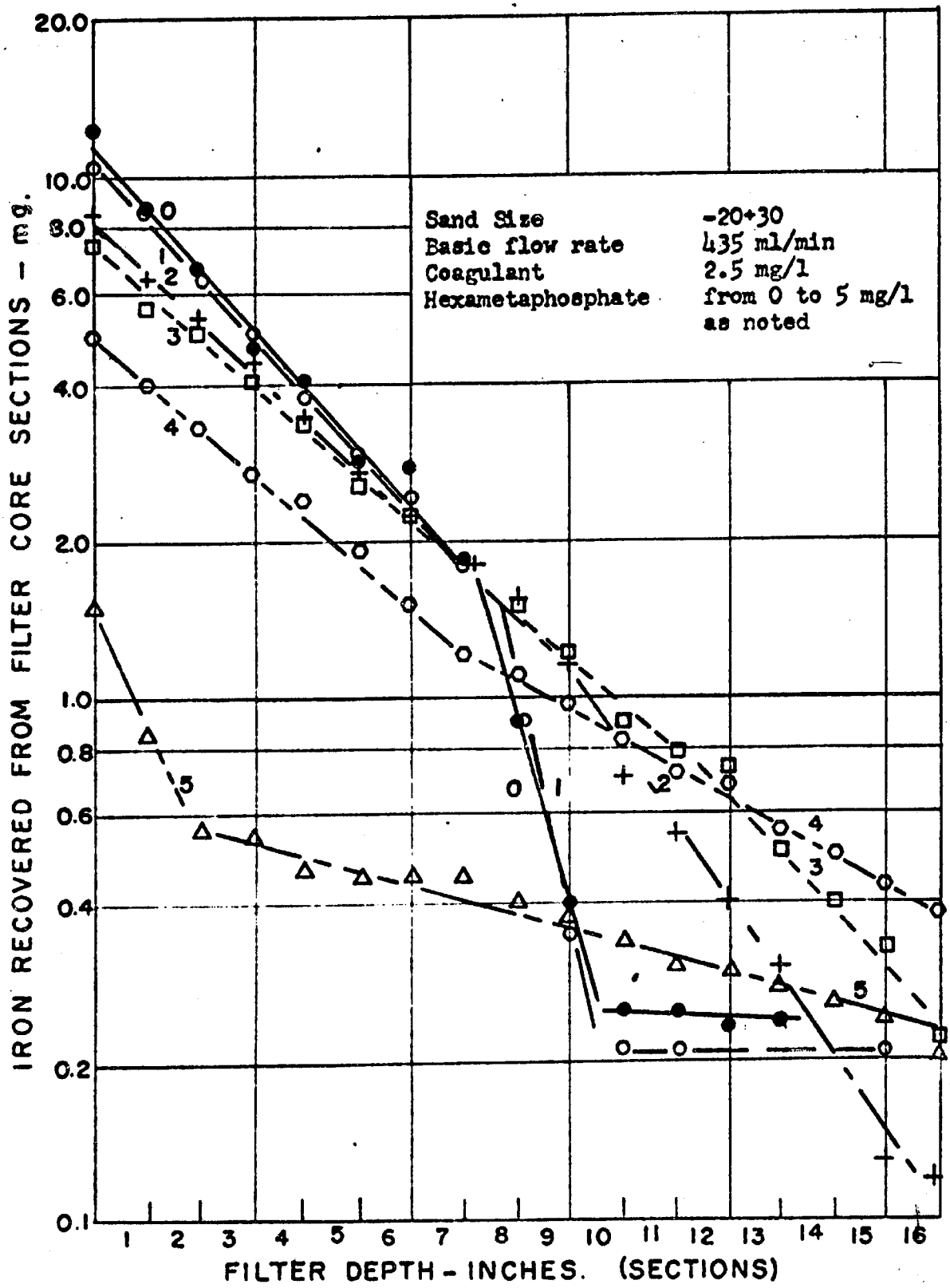


FIGURE 46. The Effect of Varying Concentrations of Hexametaphosphate in the Filter Influent on the Location of Deposited Solution Fed Coagulant in Experimental Filters

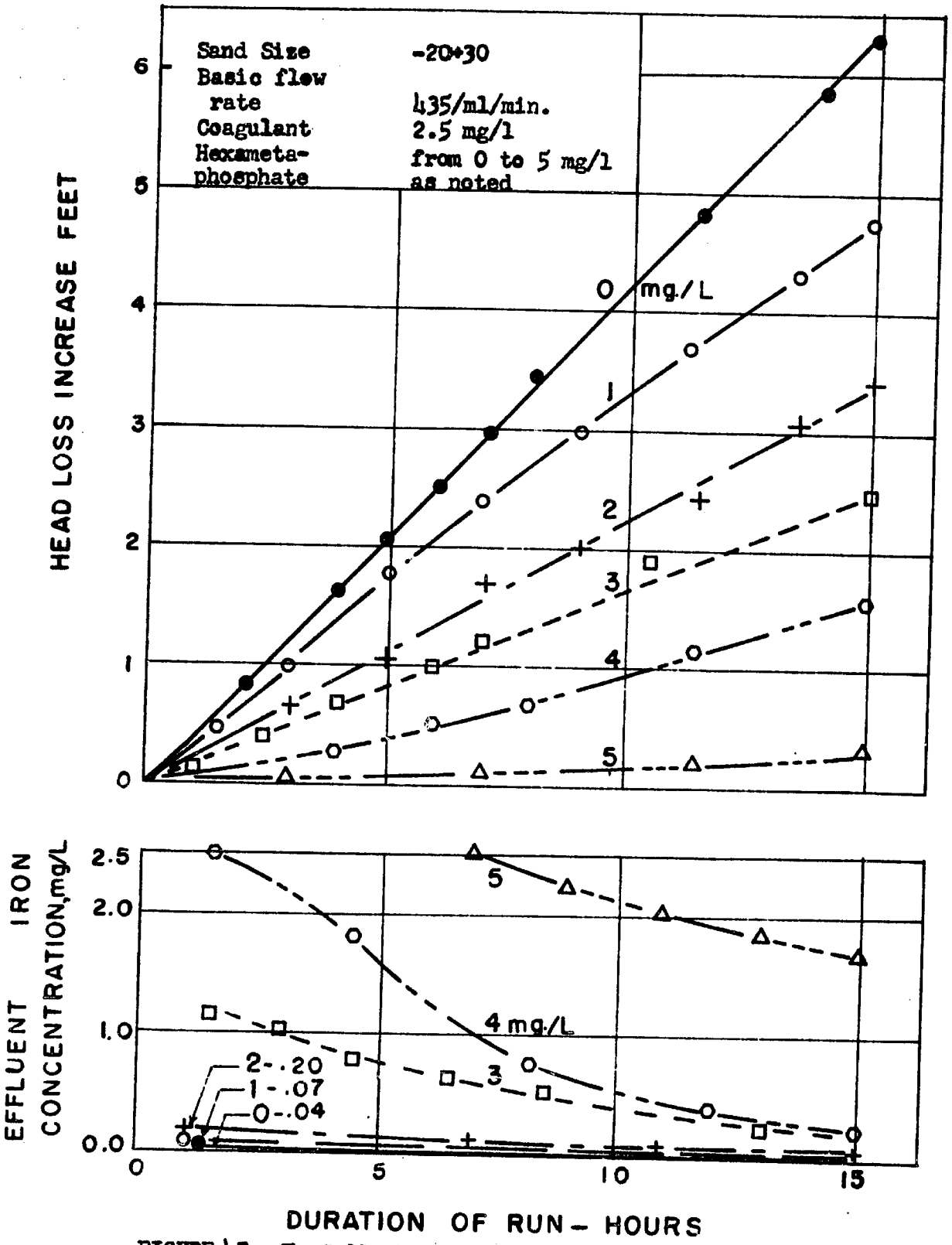


FIGURE 47. The Effect of Varying Concentrations of Hexametaphosphate on the Head Loss Increase and Amount of Coagulant Passing Through an Experimental Filter.

phosphates on coagulant floc have been given by others. Morgan and Englebrecht (155) reported that phosphate content of streams studied in Illinois was generally less than 0.5 mg/l as P_2O_5. Their experimental work indicated that condensed phosphates in reasonably high concentrations were capable of interfering with coagulation and sedimentation processes. Their data indicated studies had been made with concentrations of up to 5 mg/l of phosphate and up to 70 mg/l of coagulant. A decrease in interference was reported to be brought about by an increase in the coagulant dosage. It was reported by Eliassen (156) in connection with jar tests employing alum floc that in concentrations above 0.4 ppm as phosphorous phosphate increasingly inhibited floc formation. It has been shown (120) that floc preformed and aged in water containing a high concentration of phosphate ions penetrated deeper into filters and produced lower head losses than floc formed in water devoid of phosphate.

This experimental work has shown that the presence of 1 to 5 mg/l of hexametaphosphate in the influent caused changes in penetration, head loss and effluent concentration of coagulant when it was fed as a solution to experimental filters. The reduction in the concentration of iron in the filter effluents is not unlike the improvement following initial breakthrough. It may suggest an improvement of removal of coagulant due to previously deposited material, or a reversion of the hexametaphosphate to a less reactive species with time.

The usefulness of the direct addition of coagulant to a water immediately prior to filtration may be limited in those instances where there is a high phosphate content in the raw water or where the addition of polyphosphates to a water is practiced as part of the treatment process.

V. SUMMARY

The object of this investigation was to determine feasible approaches to increase the removal of particulate matter by rapid sand filters, and to expand the knowledge of simultaneous introduction of flocculant and non-flocculant particulate matter to these units. Discrete algae and powdered activated carbon were forms of non-flocculant discrete particules utilized. Ferric chloride was employed as a coagulant chemical.

Plain Filtration of Algal Suspensions

The purpose of this portion of the study was to obtain background information to determine if the organisms employed were responding to filtration in a manner similar to those used in previous investigations, and to determine if the magnitude of removals which might be taking place at normal hydraulic loadings were of significant value.

Removals which took place throughout the depth of the bed were obtained by determining the number of organisms in samples of fluid taken from eight sampling ports in experimental filters and from the filter effluent. These counts were compared to the number of organisms determined to be in the filter influent. A model B Coulter Counter was used to count the organisms in a portion of the samples obtained.

Four twenty-four inch beds of sands of single sieve fractions from -20+30 to -50+60 were employed. Hydraulic loadings of 0.485, 0.97 and 1.87 gpm/sq.ft. were utilized. A green alga, Selenastrum, of proven filter penetrating ability and a blue-green alga, Schizothrix,

were used as the principal organisms.

It was determined that the pattern of removal of the algae was similar under all conditions investigated in that removal was highest at the start of a run and decreased with time at a declining rate. Removals due to filters of small sized media were greater than those for larger sizes and removals of Selenastrum tended toward zero with time. It was also concluded that removal was influenced by hydraulic loading and that removal due to plain filtration after the initial period of a run at rapid sand filter rates was of low order.

Removals of Schizothrix tended to reach a constant but rather low removal with time and gave an indication that different organisms exhibited different resistances to plain filtration.

Simultaneous Filtration of Flocculant and Non-Flocculant Particulate Matter

The direct application of different quantities of coagulant to filters of different sized media operated at different hydraulic loadings was undertaken to study methods to increase removal of discrete particles as the water underwent sand filtration.

Preformed floc was introduced to experimental filters, the influent to which contained a suspension of algae. The suspension was made by introducing a culture of algae, which had been grown on inorganic nutrients, into a supply of stabilized tap water. Solutions of Ferric chloride were pumped to the filters, and the floc was thus formed in the filter tubes. A solution of base was pumped to the filters in sufficient quantity to maintain the pH of the water in the neutral range. The removal of organisms accomplished and the head loss developed by the coagulant fed as a solution were

both greater than for an equivalent amount of coagulant applied as a preformed floc.

The practice of applying coagulant chemicals as solutions was adopted as the preferred application method because it simulated operations which could be carried out in water treatment practice.

Flow rates of 1.04 and 2.0 gpm/sq.ft. were employed. Three sands of -20+30 to -40+50 sieve sizes were utilized. Sands finer than -40+50 size resulted in head losses which were impractically high especially when a solution fed coagulant was added.

Various concentrations of organisms in the feed fluid to the filters were investigated. Head losses due to deposition of material on and in the filter were recorded from the readings of piezometer tubes tapping the filters at eight locations. Organism removal efficiencies were obtained at a number of times throughout the run by counting the algae in an acidified portion of a sample of liquid drawn either from sampling ports or the filter effluent, and comparing this count of algae with the number of organisms determined to be in the filter influent. Iron determinations were made employing a commercial Bipyridine method.

The pattern of removal of organisms was ascertained to be the reverse of that for plain filtration. Percent removal increased rapidly during the first part of filtration and then more slowly with time until a constant removal was established. Proportionally greater percent removals were determined for filters in which the influent had a low concentration of organisms in contrast to those which had high concentrations; the amount of coagulant being constant in both cases.

Plotting the results of percentage of organisms removed against the amount of coagulant employed for all filter runs in which solution fed coagulant was used, produced a series of curves all of which showed similar trends. Regardless of sand size or concentration of algae in the influent, percentage removals of organisms increased at a decreasing rate of removal for an increase in coagulant application. The curves indicated that for equal coagulant application rates to influents containing similar concentrations of algae there was an increase in the percentage of organisms removed with a decrease in sand size of the filter. It could also be seen that for a given sand size and coagulant dosage there was an increase in percent removal of organisms associated with a decrease in concentration of algae in the influent.

By constructing a graph of the removal unit 'organisms/ml$\times 10^4$ per mg/l of coagulant added' as a function of coagulant dosage employed, the following relationships were illustrated. Regardless of sand size and concentration of organisms in the filter influent, the number of organisms removed per unit of coagulant increased with a reduction in the actual amount of coagulant employed. It was evident that for equal coagulant applications to influents having equal concentrations of algae there was an increase in the number of organisms removed with a decrease in the size of the sand used. For any sand size and coagulant dosage there was an increase in the number of organisms removed per unit of coagulant with an increase in the number of algae in the influent.

A summary plot was constructed which illustrated both the percentage and the number of organisms removed as a function of the

concentration of algae in the influent for two coagulant application rates for the three sand sizes studied. A rapidly increasing percentage removal associated with low concentrations of algae in the influent was noted, as was a nearly linear decrease in the actual numbers of organisms removed.

Percentages of removal determined in connection with the pattern of penetration study were in good agreement with removals which would have been indicated from the summary plot.

From the coagulant penetration and head loss data it was shown that for a given sand size, penetration and rate of penetration into an experimental filter increased with an increase in the amount of coagulant applied. For equal coagulant applications the penetration increased with an increase in sand size.

Higher concentrations of algae in the influent caused deeper penetration of coagulant into a filter and this was accompanied by a reduction in head loss increase. Determination of iron in samples drawn from sampling ports of the filters established that penetration of coagulant occurred at a rapid initial rate and then proceeded in a linear manner with time.

A study was conducted in which a three quarter inch diameter filter was operated in parallel with one of standard diameter. On the basis of the removal of organisms no difference was determined between filter units with $\frac{D}{d}$ ratios of 116 and 27. The head loss developed during the operation of these two units was nearly identical.

Pattern of Penetration Study

This study was undertaken to explain certain facts regarding filter penetration and head loss observed in the previous section of investigation.

Twenty inch sections of 3/4"-I.D. plastic tubing of 1/16" wall thickness were suspended in the center of the filters prior to a run. After the completion of filtration the cores were removed, cut into sections and the deposits within the sections analyzed for coagulant and deposited non-flocculant matter. Core samples were taken as being representative of the deposits within the filter as a whole.

The location of deposited coagulant in the cores exhibited a logarithmic decrease with depth. In nearly all cores analyzed, the main logarithmic penetration line was terminated at a knee after which two to three sections showed a log penetration pattern of a much greater slope. This secondary penetration slope was terminated by a base deposit which extended as deep into the filter as the core penetrated. The pattern of penetration was modified by the presence of non-flocculant matter in the filter influent. Greater amounts of particulate material in the influent yielded flatter slopes of penetration line and deeper penetration of coagulant into the filter.

A series of runs were undertaken to establish the pattern of penetration of activated carbon and whether there existed a balance between powered activated carbon and coagulant applied to a coarse sand filter operated at 2 gpm/sq.ft. The addition of 1 mg/l of coagulant caused complete removal within the filters of up to 33 mg/l of activated carbon. 2 mg/l of coagulant removed 94 mg/l of

carbon in a run of twelve hours duration during which there was six feet increase in head loss.

The pattern of coagulant penetration was modified in the same manner by activated carbon as by algae, however, activated carbon caused an increase in head loss whereas the presence of algae in a filter influent caused a reduction in head loss when compared to that for an influent which contained no discrete particles.

The distrubing influence of small doses of Hexametaphosphate upon the deposition of coagulant within a filter was shown to be similar in form to that caused by the presence of activated carbon or algae cells in the filter influent.

VI. CONCLUSIONS

The following conclusions have been reached on the basis of the experimental results obtained in this investigation. They are reported and should be interpreted in appreciation of the limits under which the work was conducted.

PLAIN FILTRATION OF SUSPENSIONS OF ALGAE

1. Suspensions of algae in the influent were considered to be reacting to the filtration process in a manner similar to that associated with organisms which had previously been added directly to a filter as dilutions from cultures in that:

   (a) Removal of organisms increased with a decrease in the size of the filter media employed.

   (b) A considerable amount of the removal accomplished occurred in the upper layers of the sand, and the removal at the surface of the sand increased relative to removal in other sectors of the filter as filtration progressed.

   (c) Organisms penetrated filters of sand of all grain-sizes tested in great numbers at all times.

2. Different organisms and a mixture of organisms exhibited different degrees of removal but the pattern of removal by filters of different sized sands operated at different hydraulic loadings was similar in that removal was highest at the start of the filtering period and decreased with time.

3. The removal of a discrete form of algae, Selenastrum, was related inversely to the flow rate at which the experimental filters were operated.

4. The removal of single celled organisms tended toward zero with time for filters of all sand sizes investigated.

5. The removal of discrete organisms at hydraulic loadings equivalent to rapid sand filtration rates was of minor importance after filtration had been established for a few hours.

THE SIMULTANEOUS FILTRATION OF FLOCCULANT AND NON-FLOCCULANT PARTICLES

1. The removal of organisms associated with the addition of a preformed coagulant increased with time rapidly at first then at a reduced rate until a more or less steady removal was achieved.

2. Removal of organisms by preformed floc was in a non-linear manner, directly proportional to the amount of coagulant added.

3. There was a difference in the susceptibility to removal for different organisms with the addition of preformed coagulant.

4. Organism removals showed no marked difference for flocs prepared and stored under different conditions, and the removal of organisms appeared to be primarily a function of the quantity of coagulant added.

5. Organism removals for coagulant applied as a solution were superior to those achieved by coagulant fed as a preformed floc, but the patterns of removal were similar.

6. The head loss increases due to coagulant fed as a solution were greater than those caused by coagulant fed as a preformed floc.

7. Removal of organisms for the same concentration of coagulant employed, was greater in filters composed of small diameter media than it was in filters of large media. This removal pattern was exhibited by filters receiving coagulant fed as a floc as well as a solution.

8. The penetration and rate of penetration of coagulant into experimental filters when fed as a solution were greater than when coagulant was fed as preformed floc.

9. The patterns of penetration of coagulant fed as a solution and as a floc were similar in that (a) maximum penetration occurred in the early stages of a run, after which the rate of penetration became relatively constant with time, (b) penetration and rate of penetration increased with coagulant dosage for equivalently loaded filters of equal sand size, and (c) penetration increased with an increase in size of sand in filters operating at equivalent loadings and receiving the same dosage of coagulant.

10. No floc particles could be observed from microscopic examination of fluid drawn from directly above filters when coagulant was added as a solution, however, the fluid showed a strong Tyndall effect. The maximum dimension of preformed floc particles observed ranged up to 24 microns.

11. Pre-charging a filter with coagulant prior to introducing it into service for the purpose of removing algae from a subsequently applied influent was an inefficient removal procedure as the organism removal decreased rapidly with time.

12. Filters of 3 3/8"-I.D. and 3/4"-I.D. showed nearly identical head-loss increases when operated at equivalent hydraulic, suspended matter and coagulant loadings. No significant difference was determined between organism removals associated with these filters of greatly differing diameters.

13. The depth of penetration into experimental filters by coagulant fed as a solution, was increased by the presence of algal cells in the influent.

14. A concave downward tendency in the head-loss versus time curve occurred in those filters, the influent to which contained algae.

15. For equal coagulant application rates to influents containing similar concentrations of algae there was an increase in the percentage of organisms removed, and the number of organisms removed per unit of coagulant, with a decrease in the size of sand employed as the filter media.

16. For a given coagulant dosage and sand size there was an increase in the percentage of organisms removed, and a decrease in the number of organisms removed per unit of coagulant, with a decrease in the number of organisms in the influent.

17. For any sand size and concentration of algae in the influent, there was an increase in the percentage, and a decrease in the number of organisms removed per unit of coagulant, associated with an increase in the amount of coagulant applied.

18. A high percentage removal of non-flocculant matter in the form of cells of algae was possible as a result of addition of a solution of coagulant directly to the filter when the influent concentration of organisms was low. The percent removal of algae decreased with an increase in the concentration of organisms in the influent.

19. A proportional increase in organisms removed did not accompany an increase in the amount of coagulant applied.

Pattern of Penetration of Coagulant Study

1. The pattern of removal in a uniform size sand filter for equal amounts of coagulant added as preformed floc or as solution was similar. The preformed floc was removed at a faster rate, and did not penetrate as deeply into filters as did the coagulant fed as a solution.

2. Removal of both preformed floc and coagulant fed as a solution were logarithmic with depth in the upper sections of the filters. This was followed by a section of rapid decrease in the amount of deposited material which terminated in a base value of coagulant which existed throughout the depth at which the filters were sampled.

3. The amount of algal material recovered from cores of filters receiving a solution of coagulant was greater than that from filters receiving preformed floc.

4. The pattern of the location of algal material recovered from filter cores showed strong similarities to the pattern of deposited coagulant.

5. Increased numbers of algae in the influents of filters receiving a solution of coagulant resulted in lowering of the quantity of deposit in the upper section of the filter, and increasing the penetration into the filter.

6. Increasing quantities of powdered activated carbon in the influent affected the pattern of deposit of coagulant fed as a solution in a manner similar to that of increasing concentrations of algae.

7. For filters receiving identical quantities of coagulant fed as a solution, the rate of head loss increased with an increase in the amount of activated carbon in the fluid reaching the filters.

8. One mg/l of coagulant applied as a solution to a filter of -20+30 sand resulted in complete removal of activated carbon up to an influent concentration of 33 mg/l.

9. Increasing amounts of hexametaphosphate in the filter influent changed the usual pattern of removal of coagulant fed as a solution to a filter in a manner similar to that which was caused by increasing concentrations of particulate matter and at higher dosages the deposition of coagulant was severely retarded.

10. The reduction in head loss in filters receiving coagulant fed as a solution was proportional to the concentration of hexametaphosphate in the influent.

REFERENCES

1. Baker, M. N., "The Quest for Pure Water," The American Water Works Association, New York, 1948.

2. Fuller, G.W., "Purification of Ohio River Water at Louisville, Kentucky," D. Van Norstrand & Co., New York, 1898.

3. Fuller, G.W., "Progress in Water Purification," Journal American Water Works Association, 25:1566-1576, 1933.

4. Bell, T. J., "History of the Water Supply of the World," Peter G. Thomson, Publisher, Cincinnati, 1882.

5. Hazen, A., "Filtration of Water Supplies," John Wiley & Son, New York, 1900.

6. Hartung, H. O., and Tuepker, J. L., "Use of Submerged Filters," Journal American Water Works Association, 55: 1165-1173, 1963.

7. Baylis, J. R., "Experiences in Filtration," Journal American Water Works Association, 22: 1010-1048, 1937.

8. Baylis, J.R., "Continued Tests on High Rate Filtration," Pure Water, 6:111-122, 1954.

9. Baylis, J. R., "Experience with High Rate Filtration," Journal American Water Works Association, 42:687, 1950.

10. Baylis, J.R., "Silicates as Aids to Coagulation," Journal American Water Works Association, 29:1355-1396, 1937.

11. Baylis, J.R., "Seven Years of High Rate Filtration," Journal American Water Works Association, 48:585-596, 1956.

12. Baylis, J.R., "Chicago South District Filtration Plant," Journal American Water Works Association, 41:599-615, 1949.

13. Hudson, H. E., "Rates of Filtration," Water Filtration, University of Michigan continued Education Series, 82:69-76, 1959.

14. Cox, C.R., "High Rate Filtration of Water in Rapid Sand Filters," Water and Sewage Works, 100:400-402, 1953.

15. Brown, W.G., "High Rate Filtration Experiences at Durham," Journal American Water Works Association, 47:243-247, 1955.

16. Jackson, N. E., "Study of High Rate Filtration at the Dalecarlia Plant, Washington," Journal of American Water Works Association, 47:129-141, 1955.

17. Hazen, R., "Elements of Filter Design," Journal of American Water Works Association, 43:208-218, 1951.

18. Allen, L.F., "Filter Sand Experiments," Journal of American Water Works Association, 35:205-219, 1935.

19. Hudson, H. E., "Discussion: Fundamental Factors Governing the Streamline Flow of Water Through Sand," Journal of American Water Works Association, 25:1563-1565, 1933.

20. Carman, P. C., "The Determination of the Specific Surface of Powders," Journal of the Society of Chemical Industry, 57:225-233, 1938.

21. Rose, H. E., "An Investigation Into the Laws of Flow of Fluids through Beds of Granular Materials," Proceedings, Institution of Mechanical Engineers, 153:141-148, 1945.

22. Fair, G. M., and Geyer, J. C., "Water Supply and Waste Water Disposal," New York, John Wiley & Son, 1954.

23. Schlichter, C. S., "Theoretical Investigation of the Motion of Ground Water," U.S. Geological Survey, 19th Annual Report, Part 2, 1899.

24. Brown, J. J., "Unit Operations," New York, John Wiley & Sons, 1950.

25. McCabe, W. L., and Smith, J. C., "Unit Operations of Chemical Engineering," McGraw-Hill Book Co., Inc., New York, 1956.

26. Ives, K. J., "New Concepts in Filtration," Water and Water Engineering, (a) 65:307-308, 1961. (b) 65:341-344, 1961. (c) 65:383-388, 1961.

27. King, H. W., "Handbook of Hydraulics," 6-7, 4th edition, 1954, McGraw-Hill, New York.

28. Hudson, H. E., "Discussion: Media Characteristics in Water Filtration," Proceedings of American Society of Civil Engineers, 84:No. SA3, 1958.

29. Rich, L. G., "Unit Operations of Sanitary Engineering," John Wiley & Son, New York, 1961.

30. Brownell, L. E., and Katz, D. L., "Flow of Fluids Through Porous Media," Chemical Engineering Progress, 43:537-544, 1947.

31. Fancher, G. H., and Lewis, J. A., "Flow of Simple Fluids Through Porous Materials," Industrial and Engineering Chemistry, 25: 1139-1147, 1933.

32. Blake, F. C., "The Resistance of Packing to Fluid Flow," Transactions of American Institute of Chemical Engineers, 14:415-421, 1921-22.

33. Carman, P. C., "Fluid Flow Through Granular Beds," Transactions of the Institute of Chemical Engineers, 15:150-166, 1937.

34. Burke, S. P., and Plummer, W. B., "Gas Flow Through Packed Columns," Industrial and Engineering Chemistry, 20:1196-1200, 1928.

35. Harwoor, R. M., "Measurement and Control of Particulate Matter in Filter Effluents," Journal of American Water Works Association, 55:487-489, 1963.

36. Robeck, G. G., et al, "Effectiveness of Water Treatment Processes in Virus Removal," Journal of American Water Works Association, 54:1275-1292, 1962.

37. Robeck, G. G., Dostal, K. A., and Woodward, R. L., "Studies in Modifications in Water Filtration," Journal of American Water Works Association, 56:198-213, 1964.

38. Riddick, T. M., "Zeta Potentials and Its Application to Difficult Waters," Journal of American Water Works Association, 53:1007-1030, 1961.

39. Gosh, G., "Media Characteristics in Water Filtration," Proceedings of American Society of Civil Engineers, 84, SAI: 1533-1543, 1958.

40. Ives, J. K., "Filtration Using Radio-Active Algae," Proceedings of American Society of Civil Engineers, 87 SA3:23-37, 1961.

41. O'Melia, C. R., "Sand Filtration of Algal Suspensions," unpublished Ph.D. Dissertation, University of Michigan, 1963.

42. Stanley, D.R., "Sand Filtration Studied with Radio Tracers," Proceedings of American Society of Civil Engineers, 81, No. 592, 1955.

43. Ling, J. T., "A Study of Filtration Through Uniform Sand Filters," Proceedings of American Society of Civil Engineers, 81:No. 751, 1955.

44. Hoel, P. G., "Introduction to Mathematical Statistics," John Wiley & Sons, Inc. New York, 1958.

45. Hazen, A., "Some Physical Properties of Sands and Gravels with Special Reference to Their Use in Filtration," 29th Annual Report, Mass. State Board of Health, 1892.

46. Hulbert, R., and Feben, D., "Hydraulics of Rapid Filter Sand," Journal of American Water Works Association, 25: 19-54, 1933.

47. Hulbert, R., and Feben, D., "An Improved Method for Measuring Porosity of Sand," Journal of American Water Works Association, 34:271-274, 1934.

48. Fair, G. M., and Hatch, L. P., "Fundamental Factors Governing the Streamline Flow of Water Through Sand," Journal of American Water Works Association, 25:1551-1565, 1933.

49. Kozeny, J., "Mathematisch-Naturwissenschaftliche Klassen Sitzungberichte," Akademie der Wissenschaften Vienna, 136a:271, 1927.

50. "Water Treatment Plant Design," Manual of Engineering Practice #19, American Society of Civil Engineers, New York, 1939.

51. Cohen, J. M., et al, "Natural and Synthetic Polyelectrolytes as Coagulant Aids," Journal of American Water Works Association, 50: 463-478, 1958.

52. Black, A.P., et al, "Effectiveness of Polyelectrolyte Coagulant Aids in Turbidity Removal," Journal of American Water Works Association, 51:247-263, 1959.

53. Borchardt, J.A., "Coagulant Aids," Coagulation of Water for Filtration, University of Michigan Continued Education Series, 42:39-48, 1962.

54. Henderson, C. R., "Experiences with Algae at Davenport," Journal of American Water Works Association, 9:622-623, 1922.

55. Baylis, J. R., "Microorganisms in the Baltimore Water Supply," Journal of American Water Works Association, 9:712-730, 1922.

56. Purdy, W. C., "Results of Algal Activity," Journal of American Water Works Association, 27:1120-1133, 1935.

57. Palmer, C. M., "Algae and Other Organisms in Water of the Chesapeake Area," Journal of American Water Works Association, 50:936-950, 1958.

58. "Filter Sand for Water Filtration Plants," Proceedings of American Society of Civil Engineers, 62:1543-1580, 1936.

59. Vaughn, J. C., "Coagulation Difficulties at the South District Filtration Plant," Pure Water, 13:45-49, 1961.

60. Gamet, M. B., and Rademacher, J. M, "Study of Short Filter Runs with Lake Michigan Water," Journal of American Water Works Association, 52:137-152, 1960.

61. Palmer, C. M., "Algae in Water Supplies," Public Health Service Publication 657.

62. Palmer, C. M., "Specific Problem in Rivers Algae and Metropolitan Wastes," Public Health Service Publication, Sec. T.R.W 61-3 p.

63. Palmer, C. M., "Algae and Other Interference Organisms in the Waters of the South Central United States," Journal of American Water Works Association, 52:897-918, 1960.

64. Metzler, D. F., et al, "Emergency Use of Reclaimed Water for Potable Supply at Chanute, Kansas," Journal of American Water Works Association, 50:1021-1060, 1958.

65. Dillenberg, H. O., and Dehnel, M. K., "Toxic Water Bloom in Saskatchewan, 1959," Canadian Medical Association Journal, 83:1151-1154, 1960.

66. Leva, M., "Flow Through Packing and Beds," Chemical Engineering, 64 263-268, 1957.

67. Rose, H. E., "Fluid Flow Through Beds of Granular Material," Chapter VIII, Some Aspects of Fluid Flow, Edward Arnold and Co., London, England, 1951.

68. Rose, H. E., and Rizk, A., M., A., "Further Researches In Fluid Flow Through Beds of Granular Material," Proceedings of Institution of Mechanical Engineers, 160:493-503, 1952.

69. Hudson, H. E., "Operating Characteristics of Rapid Sand Filters," Journal of American Water Works Association, 51:114-122, 1959.

70. Furnas, C. C., "Flow of Gases through Beds of Broken Solids," U.S. Bureau of Mines Bulletin 307, 1929.

71. Jordan, R. M., "Electrophoretic Studies of Filtration," Journal of American Water Works Association, 55:771-782, 1963.

72. Grace, H. P., "Structure and Performance of Filter Media, II. Performance of Filter media in Liquid Service," Journal of the American Institute of Chemical Engineers, 2:316-336, 1956.

73. Feben, D., "Theory of Flow in Filter Media," Journal of American Water Works Association, 52:940-958, 1960.

74. Hall, W. A., "An Analysis of Sand Filtration," Proceedings of American Association of Civil Engineers, Separate SA3, 1276-1, 8, 1957.

75. Cleasby, J. L., and Bauman, E., R., "Selections of Optimum Filtration Rates for Sand Filters," Iowa Engineering Experiment Station Bulletin No. 198, Iowa State University, Ames, Iowa, 1962.

76. Eliassen, R., "Clogging of Rapid Sand Filters," Journal of American Water Works Association, 33:926-942, 1941.

77. Metcalf, L, and Eddey, H. P., "American Sewerage Practice," Vol. III, Disposal of Sewage, McGraw-Hill Book Co., Inc., New York, 1935.

78. McGauhey, P. H., "Theory of Sedimentation," Journal of American Waterworks Association, 48:437-448, 1956.

79. Graton, L. C., and Frazer, H. J., "Systematic Packing of Spheres with Particular Relation to Porosity and Permeability," The Journal of Geology, 43 (No. 8 Part I) 785, 1935.

80. Hazen, A., "On Sedimentation," Trans. American Society of Civil Engineers, 53:45-71, 1904.

81. Stein, P. C., "A Study of the Rapid Filtration of Water Through Sand," Ph.D. Dissertation, Massachusetts Institute of Technology, 1939.

82. Boreli, M., "Clogging of Porous Media," Proceedings of the 9th General Assembly, International Association for Hydraulic Research, 516-520, 1961.

83. Humphrey, A. E., and Gaden, "Air Sterilization by Fibrous Filters," Industrial and Engineering Chemistry, 47:924-931, 1958.

84. Wolff, W. F., "Flocculation Deflocculation in Agitated Suspensions," Journal of Physical Chemistry, 63, 653-659, 1959.

85. Hackh's Chemical Dictionary, The Blakstone Company, Philadelphia, 1944.

86. McCabe, J., and Eckenfelder, W. W., "Biological Treatment of Sewage and Industrial Wastes," Reinhardt Publishing Corp., New York, 1956.

87. Markle, V., and Markle, S., "Adhesion in Filters," Proceedings of the American Society of Civil Engineers, 87:SA5, 1961.

88. Ives, K. J., "Rational Design of Filters," Proceedings of the Institution of Civil Engineers, 16:189-193, 1960.

89. Dean, R. B., "Modern Colloids," D. Van Norstrand Co. Inc., New York, 1949.

90. Hendricks, S. B., "Base Exchange of Crystalline Silicates," Ind. Eng. Chem., 37:625-630, 1945.

91. Gaudin. A. M, et al, "Adsorption of Sodium Ion on Quartz," Mining Engineering, 4:693-696, 1952.

92. Greenland, D. J., and Russel, E. W., "Organo Clay Derivatives and the Origin of the Negative Charge on Clay Particles," Transactions of the Faraday Society, 51:1300-1307, 1955.

93. O'Connor, D. J., and Buchanan, A.S., "Electrokinetic Properties and Surface Reactions of Quartz," Transactions of the Faraday Society, 52:397-402, 1956.

94. Sandford, L. H., "The Effect of Synthetic Detergents on Rapid Sand Filter Performance," unpublished Doctoral Thesis Cornell University, 1955.

95. Douglas, H. W., Walker, R. A., "The Electrokinetic Behaviour of Island Spar Against Aqueous Electrolyte Solutions," Transactions of the Faraday Society, 46:559-568, 1950.

96. Douglas, H. W., and Adair, D., "The Electrokinetic Behaviour of Minerals in Aqueous Electrolyte Solutions," Part 2, Flurospar, Transactions of the Faraday Society, 50:1251, 1954.

97. Cashen, G. H., "Electric Charge of Kaolin," Transaction of the Faraday Society, 55:477-486, 1957.

98. Kraemer, E. O., "Treatise on Physical Chemistry," edited by H. S. Taylor, D. Van Nostrand Co., Inc., New York, 1936.

99. Vaughn, J. C., et al, "Effects of Synthetic Detergents on Water Treatment," Journal of the American Water Works Association, 48:30-44, 1956.

100. Ewing, B. B., "Retention of ABS on Soils and Biological Slimes," Robert A. Taft Sanitary Engineering Center, Teaching Bulletin W61-5:166-177, 1961.

101. Watman, Cooper H., "Adsorption of Anionic Detergent on Solid Mineral Surfaces," U.S. Geological Survey, Professional Papers No. 450-C, 137-139, 1962.

102. Sandford, L. H., and Gates C. D., "Effects of Synthetic Detergents on Rapid Sand Filter Performance," Journal of American Water Works Association, 48:45-54, 1956.

103. "Handbook of Chemistry and Physics," Chemical Rubber Publishing Co., Cleveland, Ohio, 1927.

104. Camp, T. R., Root, D. A., and Hoota, B. V., "Temperature and Floc Formation," Journal of American Water Works Association, 32:1913-1940.

105. Hudson, H. E., "Declining Rate Filtration," Journal of American Water Works Association, 51:1455-1463, 1959.

106. McCall, G. B., et al, "Effectiveness of Sand Filters in Removing Floc," Journal of American Water Works Association, 32:147-1940.

107. Gosh, G., "Mechanism of Rapid Sand Filtration," Water and Water Engineering, 62:147-153, 1958.

108. Palin, A. T., "Controlled Filter Break-through by Addition of Activated Silica to Settled Water," Water and Water Engineering, 63: 258-259, 1959.

109. Ives, K. J., "The Significance of Surface Electrical Charge on Algae in Water Purification," Journal of Biochemical and Micro-Biological Technology and Engineering, 1;37, 1959.

110. Ives, K. J., "Electrokinetic Phenomena of Planktonic Algae," Proc. Society of Water Treatment and Examination, 5: 41-58, 1956.

111. Wallwork, S. C., "Physical Chemistry," Longmans Green & Co., London, 1956.

112. Conway, B. E., et al, "The Dielectric Constant of the Diffuse and Helmholtz Double Layer," Transactions of Faraday Society, 47:756-766, 1951.

113. Eliassen, R., "An Experimental and Theoretical Investigation of the Clogging of a Rapid Sand Filter," unpublished Ph.D. Dissertation Massachusetts Institute of Technology, 19

114. Hudson, H. E., "A Theory of Functioning of Filters," Journal of American Water Works Association, 40:868-872, 1948.

115. Hudson, H. E., "Factors Affecting Filtration Rates," Journal of American Water Works Association, 48:1138-1154, 1956.

116. Hudson, H. E., "Functional Design of Rapid Sand Filters," Proceedings of the American Society of Civil Engineers, 89:SA1, 1963.

117. Cleasby, J. L., et al, "Effect of Filtration Rate Changes on Quality," Journal of the American Water Works Association, 55:869-880, 1963.

118. Black, A. P., and Hannah, S. A., "Electrophoretic Studies of Turbidity Removal by Coagulation with Aluminum Sulfate," Journal of American Water Works Association, 53:438-452, 1961.

119. Black, A. P., "Theory of Coagulation," Coagulation of Water for Filtration, University of Michigan Continued Education Series 92: 10-26, 1962.

120. O'Melia, C. R., Private Communication.

121. Pilipovich, J. B., et al, "Electrophoretic Studies of Water Coagulation," Journal of American Water Works Association, 50:1463-1482, 1958.

122. Black, A. P., and Walters, J. V., "Electrophoretic Studies of Turbidity Removal with Ferric Sulfate," Journal of American Water Works Association, 56:99-110, 1964.

123. Bier, M., "Electrophoresis," Academic Press, Inc., New York, 1959.

124. Douglas, H. W., Shaw, D. J., "Electrophoretic Studies on Model Particles," Transaction of the Faraday Society, 53:512-522, 1957.

125. Dickensen, W., "The Electrophoretic Mobility of Certain Hydrocarbons," Transaction of the Faraday Society, 37:140-148, 1941.

126. Douglas, H. W., "Electrophoretic Studies on Bacteria," Transaction of the Faraday Society, 53:1494- , 1957.

127. Henley, A., "Electrophoresis Bibliography," Electrophoresis Division, American Instrument Co. 1953.

128. Thornton, W. N., "The Apposite Electrification Produced by Animal and Vegetable Life," Proceedings of the Royal Society (London), B.82:638, 1910.

129. Kolin, A., "A New Approach to Electrophoretic Separation," Proceedings of the National Academy of Science, 41: 110, 1955.

130. Kreger, D. R., "Cell Walls, Chapter 19," Physiology and Biochemistry of Algae - R. A. Lewin, editor, Academic Press, New York, 1962.

131. Nicolai, E., and Preston, R. D., "Cell Wall Study in the Chlorphyceae," Proceedings of the Royal Society (London) B 140: 244-274, 1952.

132. O'Colla, P.S., "Mucilages, Chapter 20," Physiology and Biochemistry of Algae - R. A. Lewin, editor, Academic Press, New York, 1962.

133. Wolff, W. F., "The Structure of Gas Adsorbent Carbons," Journal of Physical Chemistry, 62:829-833, 1958.

134. Terzaghi, K., and Peck, R. B., "Soil Mechanics in Engineering Practice," John Wiley and Sons, Inc., New York, 1948.

135. Iwasaki, T., "Some Notes on Filtration," Journal of American Water Works Association, 29:1591-1597, 1937.

136. Ives, K. J., "Simulation of Filtration on Electronic Digital Computer," Journal of American Water Works Association, 52:933-939, 1960.

137. Hudson, H. E., "Factors Affecting Filtration Rates," Journal of American Water Works Association, 50:271-277, 1958.

138. Sawyer, A. W., "Functional Design of the Wayne County Filtration and Pumping Plant," Journal of American Water Works Association, 51: 761-767, 1959.

139. Katz, W. A., and Myers, J., "Nutrition and Growth of Several Blue Green Algae," American Journal of Botany, 42:282-287, 1955.

140. Gates, W. E., "The Influence of Substrate Nutrient Concentration and Induced Turbulence on the Growth of Algal Cultures," Ph.D. Thesis, University of Michigan, 1963.

141. Northcote, D. H., "The Biology and Chemistry of the Cell Walls of Higher Plants, Algae, and Fungi," International Review of Cytology, Academic Press, 14:232-265, 1953.

142. Clark, N. A., and Chang, S. L., "Enteric Viruses in Water," Journal of American Water Works Association, 51:1299-1317, 1959.

143. Camp, T. R., "Discussion - Anthracite Sand Filters," Journal of the American Water Works Association, 53:1478-1483, 1961.

144. Baylis, J. R., "Discussion - Filter Evaluation," Journal of American Water Works Association, 52:214-218, 1960.

145. Conley, W. R., and Pitman, R. W., "Test Program for Filter Evaluation at Hanford," Journal of American Water Works Association, 52:205-215, 1960.

146. Conley, W. R., "Experience with Anthracite Sand Filters," Journal of American Water Works Association, 53:1473-1478, 1961.

147. Iler, R. K., "The Colloid Chemistry of Silica and Silicates," Cornell University Press, Ithaca, New York, 1955.

148. Moore, W. J., "Physical Chemistry," 3rd Edition, Chapter 16, Prentice-Hall Inc., Englewood Cliffs, N.J. 1963.

149. Echelberger, W. F., "The Influence of Lighting Conditions and Liquid Depth on the Growth Activity of Environmentally Controlled Algal Cultures," unpublished Ph.D. Dissertation, University of Michigan, 1964.

150. Clark, H. W., "A New Method of Purifying Water," Journal of New England Water Works Association, 36: 385-390, 1922.

151. Clark, H.W., "Further Studies of Water Purification by Filters Charged With Al or $FeOH_3$," Journal of New England Water Works Association, 38: 84-89, 1924.

152. Krone, R. B., Orlob, G.T. and Hodgkinson, Carl, "Movement of Coliform Bacteria Through Porous Media," Journal of Sewage and Industrial Wastes Associations, 30: 1-13, 1958.

153. Cleasby, J. L. and Baumann, E.R., "Selection of Sand Filtration Rates," Journal of American Water Works Association, 54: 579-602, 1962.

154. Corsaro, G. et al, "Mechanism of Polyphosphate Threshold Action," Journal of American Water Works Association, 48: 683-699, 1956.

155. Morgan, J.J., and Engelbrecht, R.S., "Effects of Phosphates on Coagulation and Sedimentation of Turbid Waters," Journal of American Water Works Association, 52: 1303-1314, 1960.

156. Eliassen, R., et al, "Studies on Radioisotope Removal by Water Treatment Process," Journal of American Water Works Association, 43: 615-637, 1951.

APPENDIX I

Synthetic Nutrients for Algae Cultures

MEDIA

Chemical	Concentration in mg/l of culture
KH_2PO_4	50
$MgSO_4 \cdot 7H_2O$	100
KNO_3	100

$FeCl_3 \cdot 6H_2O$	3.50 g/l
Fe Citrate	1.00 g/l
Citric acid	1.00 g/l

Dissolve in one liter of distilled water and add at rate of .2 ml per liter of culture

---

MICRO NUTRIENTS

Chemical	Concentration
H_3BO_4	2.86 g/l
$Mn \cdot SO_4 \cdot H_2O$	1.58 g/l
$ZnSO_4 \cdot 7H_2O$	0.222 g/l
$CuSO_4 \cdot 5H_2O$	0.079 g/l

Dissolve in one liter of distilled water and add at rate of 0.4 ml per liter of culture

---

APPENDIX II

Specific Gravity of Sand

Prior to Use		After Use	
Sieve size	S.G.	Sieve size	S.G.
-20 +30	2.65	-20 +30	2.63
-30 +40	2.65	-30 +40	2.64
-40 +50	2.65	-40 +50	2.63
-50 +60	2.65		

APPENDIX III

Sand Size Determination

Sieve Fraction	Manufacturer's Rating	Count & Weigh Method	Microscopic Measurement
-20 +30	.711	.770	.746
-30 +40	.503	.509	.541
-40 +50	.358	.403	.395
-50 +60	.275	.308	.294

APPENDIX IV

Sampling and Testing Procedures

1. Sample Collection

During the sampling period, the discharge from the sampling ports was directed to 60 ml screw top test tubes which were placed in a removable rack at the front of the filters. The sampling period required was about thirty minutes as the flow from the ports was controlled by needle valves to be less than 2 ml per minute.

The discharge for the first two minutes was wasted to ensure flushing of any material deposited in the rubber tubing. Failure to observe this procedure resulted in erroneously high determinations, especially of the iron content.

A 50 ml portion of the filter effluent was taken as a representative sample from one gallon of the effluent collected during the sampling period. A 50 ml sample was also taken from the constant head box for each different feed water algae concentration under investigation. This was required as a check on the validity of the count of organisms in the water reaching the filters.

The size of the samples collected was sufficient to allow (i) determination of numbers of algae (ii) determination of iron content and (iii) determination of pH with sufficient allowance for a duplicate sample if so required.

2. Procedure for Algae Counting

Samples obtained from the top sampling ports of the filter during a run contained precipitated iron floc as well as algae. The floc particles could cause the Coulter Counter to register. The counts produced by the floc particles increased as the particles were reduced

in size by the physical agitation afforded the sample. It was therefore necessary to dissolve the floc prior to counting the algae. The procedure finally developed was as follows:

(a) The test tube containing a sample was shaken ten times to resuspend sedimented matter and break up floc particles.

(b) A 24 ml portion of the sample was withdrawn from the test tube with a volumetric pipette and discharged into a 50 ml beaker and the pipette was cleaned of adhering liquid before being used to draw another sample. The order of withdrawal was from the filter effluent to the filter influent or in approximate increasing concentration of iron and algae.

(c) 1 ml of the acid solution used in the Bipyridine determination of iron was added from an automatic burette to the 24 ml portions and the samples stirred with a clean glass rod. The acidified solution was allowed to react for one hour.

(d) 1 ml of the reacted acidified algal suspension was withdrawn from the beaker by pipette after stirring and transferred to a 15 ml plastic vial. The pipette was cleaned before use in subsequent samples. 9 ml of 1% sodium chloride solution were added to the plastic vial to make a 10:1 dilution of the algal suspension and produce a 0.9% salt solution required for operation of the Coulter Counter. It is here restated that the passage of the solutions through a millipore filter prior to use resulted in a great reduction in background counts and produced more reproduceable determinations especially in studies dealing with low concentrations of algae.

(e) The samples were counted in sequence from filter effluent to filter influent, and to ensure a representative count the samples

were poured back and forth five times between two vials. Prior to the counting of a sample the drop of liquid adhering to the orifice chamber and electrode was wiped off in accordance with the instructions for the instrument. After counting a sample containing a high concentration of algae the electrode and tip of the orifice chamber were washed with distilled water and rinsed with 0.9% salt solution.

The Coulter Counter settings employed throughout the study were :

The reciprocal of the aperture current - 1/2
The reciprocal of the amplification - 1/8
Lower threshold - 60
Upper threshold - out.

The organism Selenastrum was of extremely uniform size from run to run and none of the distribution curves indicated that a change in instrument settings was required.

A minimum of three representative counts were recorded for each sample and five for the dilution electrolyte, filter influent and feed water. Average count values corrected for dilution, background and coincidence, when necessary, were used for final determinations.

All beakers, vials, pipettes and stirring rods were washed in distilled water after each use. The equipment which was used with electrolyte was rinsed with that solution.

3. Iron Determination

(a) Samples from Filter - The remaining chemical solution required for color development in the iron determination was added to the 24 ml of acidified sample remaining from step (d) above. The samples were mixed and allowed to stand for ten minutes to ensure maximum color development.

The reduction in transmittance due to the color was determined with a Coleman spectrophotometer against a blank of distilled water and the same amount of test solutions as were added to the sample. Quantities of iron present were determined from a curve developed from known quantities of iron in solution and treated in a manner similar to the samples. The wave length utilized was 500 millimicrons. The curve developed was linear for readings of 30% transmission and greater. Where necessary, dilutions were made so that the readings obtained for the sample were in excess of 30%.

(b) Samples from Core - The filter sand and adhering material was washed from the sections cut from the filter core with distilled water. 1 ml of acid solution was added for each 24 ml of water used. The acidified solution was allowed to react for six hours to dissolve all the iron, during which time the sample beakers were covered with a plastic film to prevent losses due to evaporation. Iron determinations were conducted as above. Iron concentrations were obtained from values on the standard curve with corrections being made for dilutions of the sample.

4. Suspended Material

The suspended matter from the filter core sections which was freed of iron in 3(b) was subjected to turbidity analysis utilizing 20 mm light path and a wave length of 465 millimicrons. Dilutions were required on most runs, especially so where activated carbon was utilized, to prevent saturation values being reached.