

FISHERIES RESEARCH INSTITUTE
College of Fisheries
University of Washington
Seattle, Washington 98195

SEA WATER FILTRATION AND FOULING CONTROL IN A MODEL RAPID-SAND
FILTER FOR EXCLUSION OF FISH FROM POWER PLANT COOLING SYSTEMS

by

Quentin J. Stober,

Charles H. Hanson,

and

Peter B. Swierkowski

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Director

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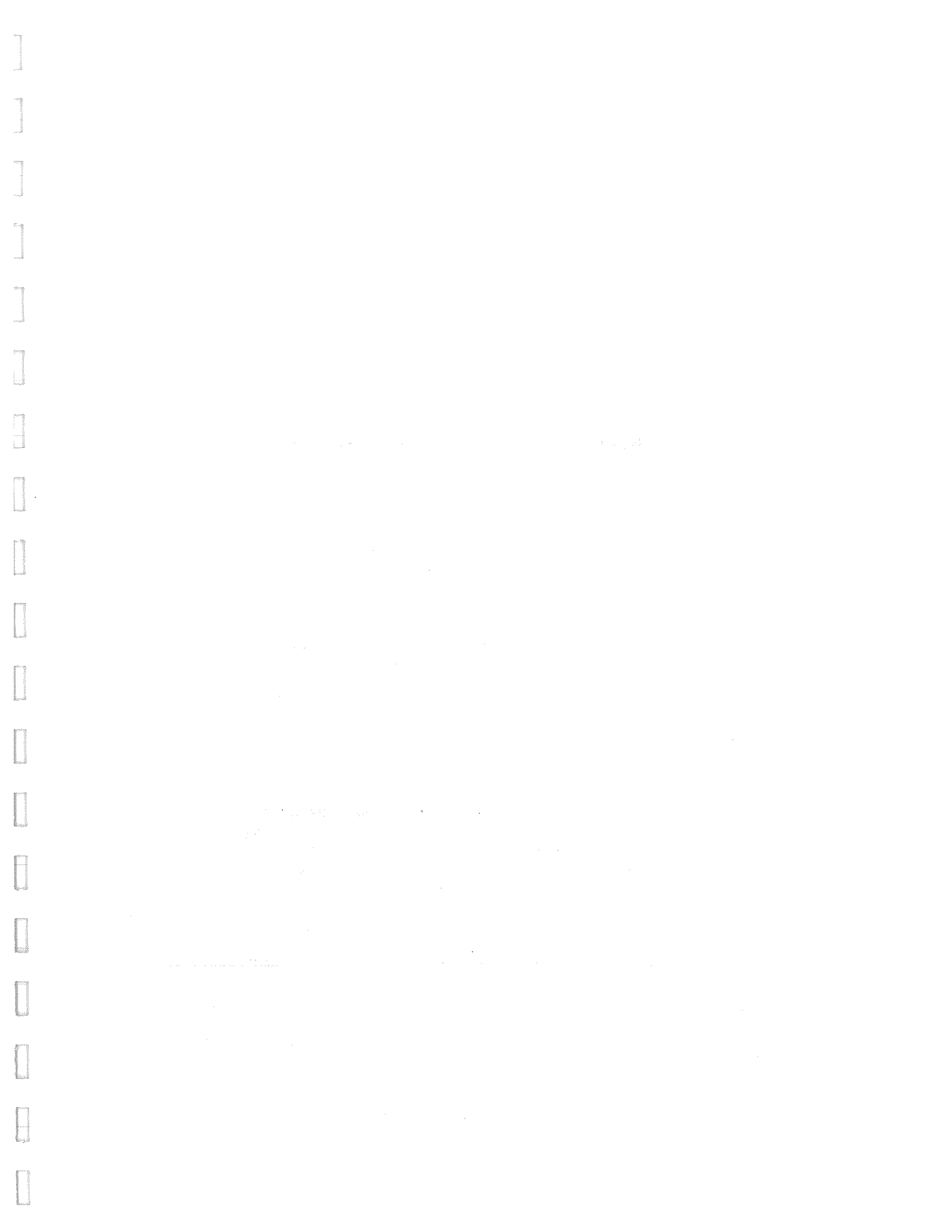
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Peter B. Swierkowski



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SEA-WATER FILTRATION AND FOULING CONTROL IN A MODEL RAPID-SAND FILTER
FOR EXCLUSION OF FISH FROM POWER PLANT COOLING SYSTEMS

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1.0 SUMMARY AND CONCLUSIONS

The entrainment of larval or juvenile fishes in once-through cooling systems is a major problem encountered in the siting of thermal power plants particularly in estuaries. The larval and juvenile fishes (e.g., pink and chum salmon in Pacific Northwest estuaries where this investigation was conducted) are of economic importance to the sport and/or commercial fishery and if lost at these life history stages require a minimum regeneration time of one year. The traveling screen is perhaps the most advanced device in use for the exclusion of larger fish; but has not been entirely satisfactory for preventing the passage of pelagic eggs and larval fishes.

A model rapid sand filter was tested as a positive method for the exclusion of larval fish from thermal power plant cooling system intakes. Some hydraulic aspects of sea water filtration through an anthracite-gravel filter were established during studies conducted near Kiket Island, Puget Sound, Washington, in 1971 and 1972. The optimal size for the anthracite media was found to be between 3/32 and 5/16 inches. The coarseness of the media was restricted by the quantity and velocity of backwash water required to achieve bed expansion.

Filter flow velocities of 0.01 to 0.02 ft/sec which fall within the range of acceptable filtration rates of 5 to 10 gpm/ft² will not result in sink flow rates affecting the mobility of juvenile fishes and larger invertebrates (e.g.,

Neomysis awatschensis) above the filter surface. The exclusion of plankton including the larval stages of marine fouling organisms was not practical.

The seasonal changes in water quality (turbidity, temperature, and salinity) were determined on-site. Turbidity was subject to seasonal variations due primarily to planktonic organisms during most of the year and silt during the winter and spring floods from the Skagit River. Silt appeared to have the greatest effect in reducing filter performance.

A filtration rate of 6 gpm/ft² yielded a mean volume of over 2.5 million gallons per run. The average run time was 260 hours to a head loss through the filter of 52 inches. Filtration time ranged from 5.4 to 20 days depending on influent turbidity.

Marine fouling was expected to cause the most serious operational difficulty in a rapid sand filter. Population dynamics and succession of colonial diatoms (*Melosira* sp.) and barnacles (*Balanus crenatus* and *B. cariosus*) were assessed. Mussels (*Mytilus edulis*) did not set due to the limited exposure period.

Six fouling control techniques were evaluated, including backwash with ambient sea water; anoxia; single-dose chlorination; heat treatment; chlorination and heat treatment during backwash; and daily 2-hr chlorination. Based on barnacle abundance and growth rates, the most effective fouling control techniques tested were backwashing with heated sea water daily chlorination, and anoxia.

The test data developed are sufficient to determine engineering feasibility and the probable requirements for construction, operation, maintenance, and fouling control, although model tests over one annual cycle would be desirable to provide operating experience prior to final design or construction.

2.0 ACKNOWLEDGMENTS

This investigation was sponsored in a contract with Seattle City Light and Snohomish County P.U.D. Dr. E. O. Salo was co-principal investigator of the biological investigations under which this was a subproject. Mr. H. V. Strandberg provided valuable engineering assistance throughout this study. The assistance of Hal Beattie, Brenda Leistikow, Eric Meyer, Tom Northup, Cliff Olds, and Matt Salo is greatly appreciated. We wish to thank Professor Milo C. Bell for his critical review of the manuscript.

3.0 INTRODUCTION

The impact of conventional thermal power plant intake structures on fishery resources and other aquatic organisms has been a neglected aspect in the design and construction of some once-through cooling water systems. The resulting fish kills have aroused public concern for the conservation of natural resources, and much effort has been directed toward improving the hydraulics of intake structures and the design of screens and by-pass channels to minimize the impingement and entrapment of entrained fish.

These efforts have met with varying degrees of success because many have not been geared to the requirements of the specific site and related to the characteristics of those species to be protected. In the utilization of water for the dilution, dispersion, and dissipation of waste heat, the user has an obligation to insure that other resources are not destroyed. These concerns have resulted in a growing body of laws and regulations having as their objective the conservation of resources forcing the consideration of a systems approach and the application of innovative design concepts.

Although considerable effort has been expended to perfect means of preventing fish entry, very few have proven successful. Perhaps the most advanced device in use is the traveling screen; however, when large water volumes are required it has not proven entirely satisfactory to exclude pelagic eggs and larval fishes (e.g., pink and chum salmon). The intake of delicate juvenile fishes is a serious problem due to their high vulnerability during early life stages and long regeneration times. It is especially serious in estuaries since they serve as breeding and nursery grounds for many valuable

species. Little information exists on the application of rapid sand filters in salt water or on a scale that would ensure a supply of 1,500 cfs, the volume required by a 1,000-Mw nuclear power station. Rapid sand filters have been applied almost exclusively to municipal water supply systems until recently, and are now being considered for use in the sewage treatment process. Studies on the use of a rapid sand filter as a positive means of excluding pelagic eggs, larval fishes, and large invertebrates from the cooling water of the proposed power plant are described.

The work was carried out in two phases. Phase I (1971) was concerned with a determination of the hydraulic characteristics of filtration through four configurations of a multimedia filter in order to optimize the size and configuration of the media. The effects of the filter face velocities on marine organisms were observed and the degrees of reduction of marine zooplankton in the filtrate were determined and reported by Stober, Salo, and Swierkowski (1971). In phase II of the investigation (1972) the extent of marine fouling on the media during continuous filtration was assessed. Six fouling control techniques were evaluated, including backwash with ambient sea water; anoxia; single-dose chlorination; heat treatment; chlorination and heat treatment during backwash; and daily 2-hr chlorination.

4.0 MATERIALS AND METHODS

Filter tests were conducted on a prototype filter aboard the research barge R. V. *Kumtuks* off the northwest shore of Kiket Island in Similk Bay, Puget Sound, Washington (Fig. 4-1). This site was chosen because of the relatively higher turbidities due to plankton blooms as compared to the waters

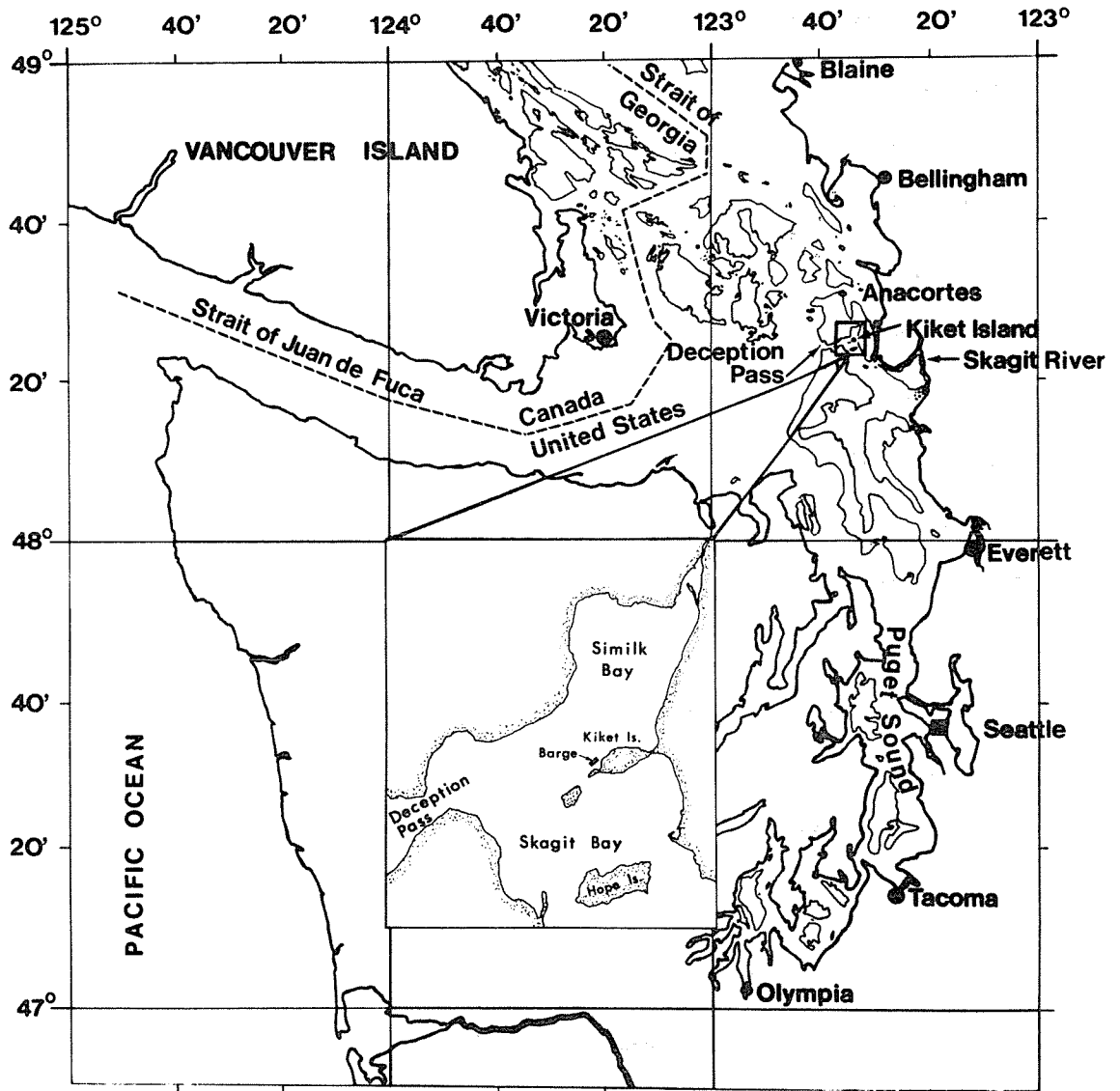


Figure 4-1. Map of western Washington, with the study area shown in inset.

of Skagit Bay. This condition was prevalent throughout the period of experimentation in phase I, from August 20 to October 10, 1971. During phase II filter tests were conducted from April 10 to July 5, 1972, during which most marine fouling organisms were known to set and turbidity was believed to be at a maximum because of runoff from the Skagit River.

4.1 Filter

The main filter was contained in a 5-x 5-ft (25-ft²) steel box 8 ft deep. Six plexiglass tubes (five with a diameter of 4.5 inches and one with 5 inches) 5 ft long were attached to one side of the main filter to provide additional filters for the fouling control treatments tested. These collectively increased the filter surface area by 0.688 ft². A schematic of the entire test system and its arrangement aboard the barge is shown in Fig. 4-2. A porous steel grate was installed to support the media in the main filter to provide an underdrainage 18 inches deep. The media were supported at the same level in the tubes by porous plexiglass plates as illustrated in Fig. 4-3. Each tube was connected with the overflow and underdrainage of the main filter by 2-inch pipes and could be operated independently when required by means of the valves at each end. Inflow was pumped to the top of the main filter at a rate of about 350 gpm from an intake located 5 ft below the waterline in the barge hull. This intake was perforated with holes 1 inch in diameter. Water in excess of that passing through the filters was discharged through a 4 inch-diameter overflow pipe. Water was pumped through the filters by means of a single-stage, 5-HP centrifugal pump with a capacity of 153 gpm. A filtration rate of 6 gpm/ft² was maintained. The system was controlled through a pressure valve on the discharge line. Filtrate was directed to a 3,000-gal storage tank on the barge house and to a 200-gal hot water

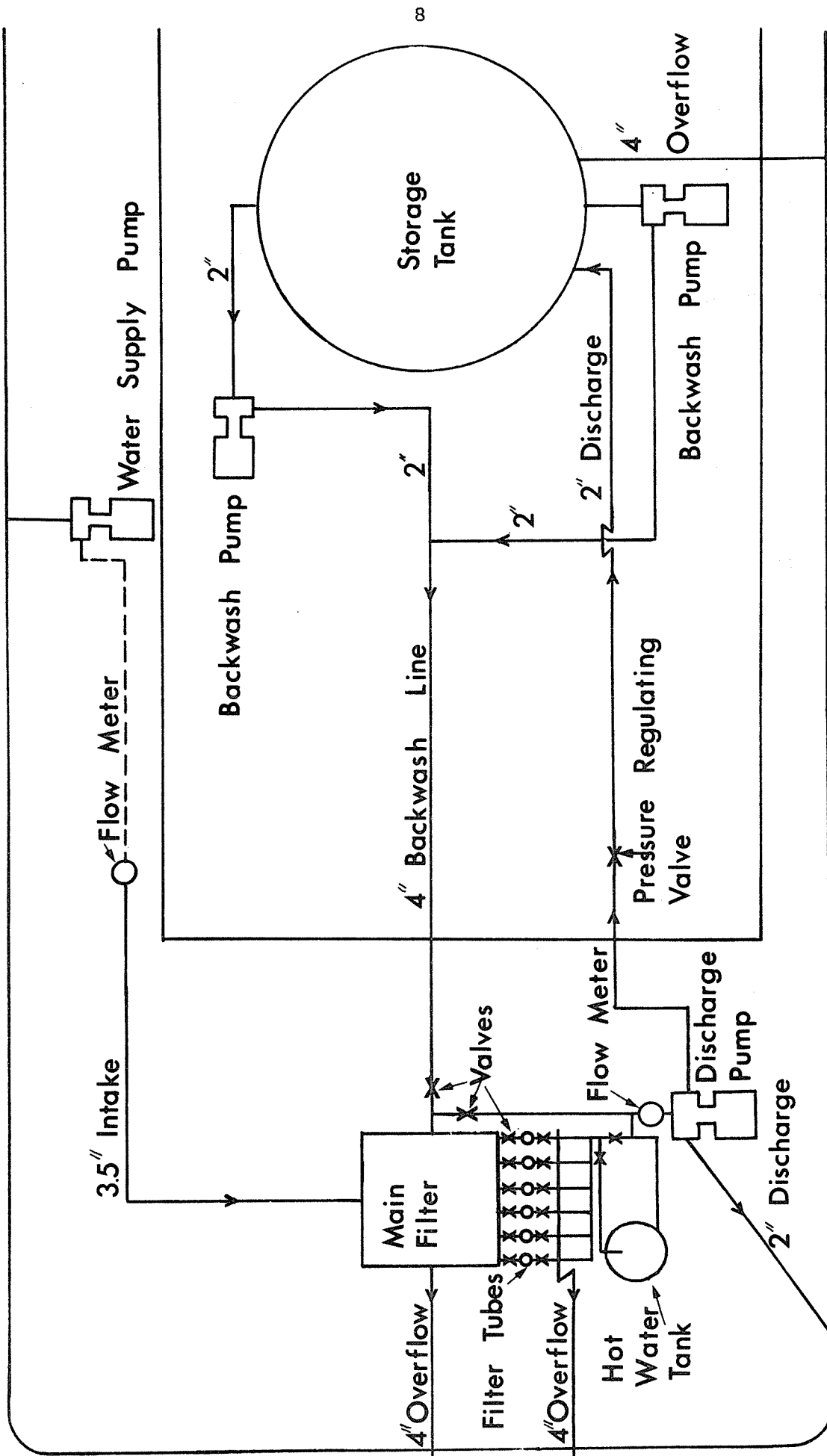


Figure 4-2. Plan view of entire filter test system aboard R.V. Kumtiks.

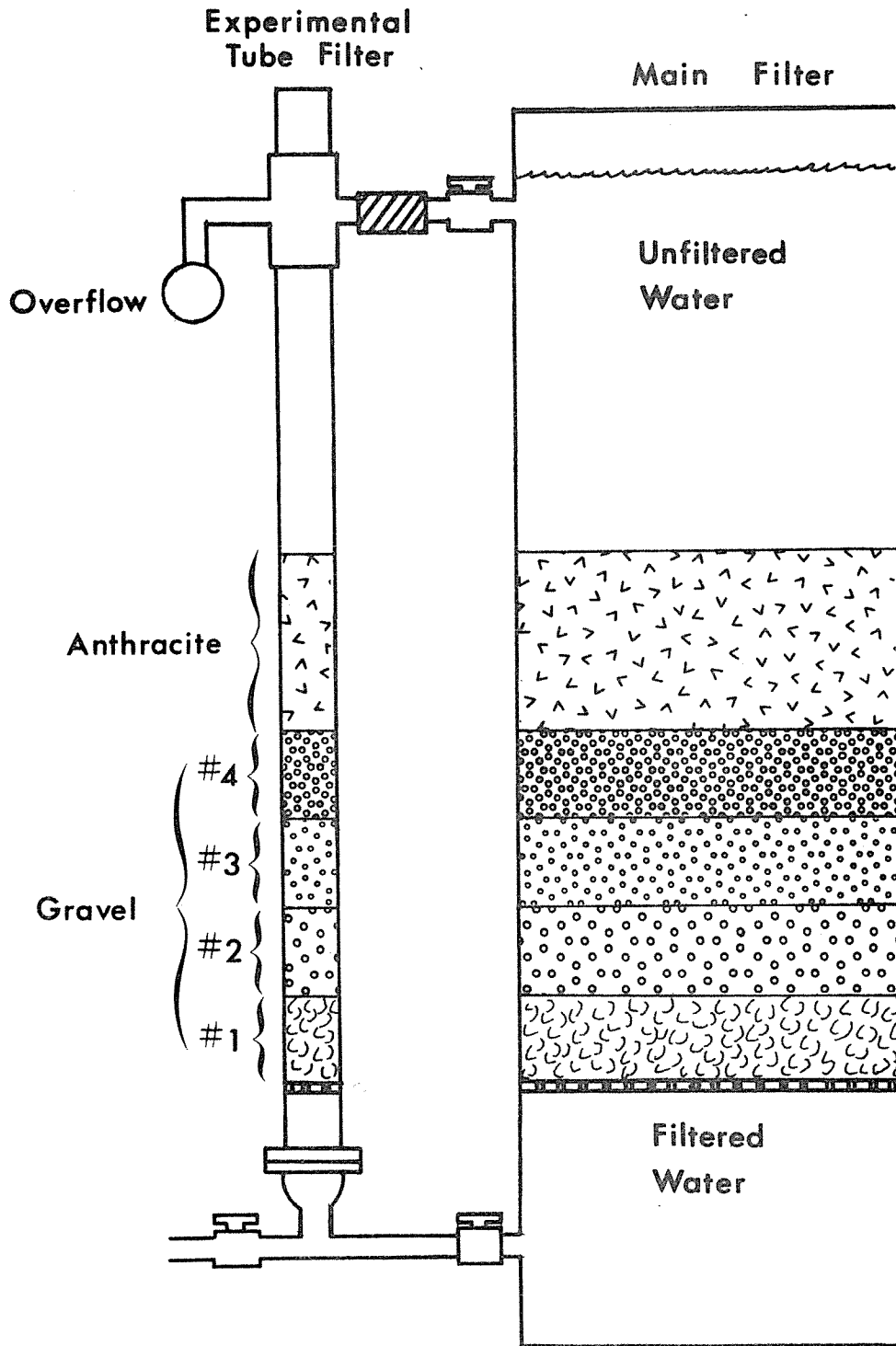


Figure 4-3. Side view of main filter and one tube with media configurations.

tank and the excess was discharged overboard. PVC pipe and valves were used throughout the system. The volume of the filtrate was measured continuously with a flowmeter (Sparling model 474).

4.2 Backwash System

The stored filtrate was used to backwash the main filter. It was pumped by single-stage centrifugal pumps (2 HP, 10 HP) through a 4-inch-diameter line to the filter underdrainage at an average rate of about 12 gpm/ft². The backwash system for the tubes was independent and drew its supply of filtrate from the operating main filter. A 1-inch diameter line supplied the distribution manifold used to backwash each tube individually and also to supply a 200-gal glasslined hot water tank. The hot water tank was fitted with stainless steel elements so that heavy metal contamination of the heated wash water would be minimized. Each column could be treated independently with ambient, chlorinated, or heated sea water as prescribed. The backwash water was sampled and discharged overboard.

4.3 Instrumentation

The rate of head loss was recorded with a pressure recorder (Rustrak Model 2162) connected to the underdrainage. A direct-reading, well-type manometer was installed on the main filter as well as on each tube to provide comparable measurements of loss of head. Turbidity of the inflow and filtrate was automatically monitored during alternate 30-min intervals with a Hach Model 2426 "surface scatter" turbidimeter. The automatic valves were controlled with a time clock to select the flow of either inflow or filtrate to separate 3-gal containers. Two small submersible pumps (Teel Model #IP598) connected to the automatic switching system pumped the desired water to a small head tank (volume 0.16 gal) which maintained a constant flow rate

and sample size through the continuous-reading turbidimeter. The output was recorded on a potentiometric recorder (Texas Instr. Model #PS01W68). Individual turbidity measurements were made with a Hach Model DR-EL photometer. Temperature was measured continuously with a resistance thermometer (YSI Model #43TD) and recorded with a potentiometric recorder (ARA Model #400). Salinity was determined with a modified Goldberg refractometer calibrated with standard NaCl solutions. The pH was measured with a Model 21 Scientific Equipment meter. Settleable solids were collected manually from the backwash and quantified with Imhoff cones (Standard Methods, 1971). Dissolved oxygen determinations were made with the Alsterberg modification of the standard Winkler titration.

4.4 Media

The design and physical properties of the media were determined. The media configuration used in the second phase of the study was selected to maximize filtrate volume and at the same time retain a low density and gradation to achieve expansion at a backwash rate of about 12 gpm/ft². The media configurations tested in phase I and phase II are shown in Table 4-1. The quality of the resulting filtrate was not a criterion in selecting the media since any medium that could be expanded would effectively exclude larval fish. It was not found to be practical to attempt removal of the plankton. Anthracite was selected as a medium in order to allow greater particle penetration and therefore minimize rapid surface cake formation (Conley and Hsiung, 1969).

The results of the tests on the media configurations used in 1971 served as a practical guide in determining the bed composition in 1972. The filter tested in this year was composed of four layers of graded gravel each 6 inches

Table 4-1. Filter media configurations, including size and depth, tested in phase I (1971) and phase II (1972)

Phase I								
Media type	Group E		Group A		Group B		Group C	
	Size ¹	Depth (inches)	Size ¹	Depth (inches)	Size ¹	Depth (inches)	Size ¹	Depth (inches)
<u>Filter media:</u>								
Anthracite			0.6-0.8 mm	20	3/32-3/16 in	12	5/16x9/16 in	12
Sand	0.45-0.55 mm	24	1 mm	4	2 mm	4		
<u>Support media:</u>								
Gravel #4	1/8x1/4 in	4	1/8x1/4 in	2	1/8x1/4 in	4		
Gravel #3	1/4x1/2 in	4	1/4x1/2 in	2	1/4x1/2 in	4		
Gravel #2	1/2x3/4 in	4	1/2x3/4 in	2	3/4x1-1/2 in	4	1/2x3/4 in	12
Gravel #1	3/4x1-1/2 in	6	3/4x1-1/2 in	6	3/4x1-1/2 in	6	3/4x1-1/2 in	12
Phase II								
<u>Filter media:</u>								
Anthracite					3/16x5/16 in	12		
<u>Support media:</u>								
Gravel #4					1/8x1/4 in	6		
Gravel #3					1/4x1/2 in	6		
Gravel #2					1/2x3/4 in	6		
Gravel #1					3/4x1-1/2 in	6		

¹Mfg. specifications.

deep, decreasing in particle size toward the surface and topped with a layer of crushed anthracite 12 inches deep. The anthracite had a sphericity of 0.30, whereas the gravel was 0.59; thus the anthracite was of greater angularity.

The anthracite particles were measured in order to determine the coefficient of the effective particle size. A sample weighing 804.5 g was passed through a series of U.S. Standard sieves with openings of 0.5, 1, 2, 4, and 8 mm. Each portion of anthracite held between adjacent sieves was weighed and converted to a percentage of the total sample by weight. A cumulative log-probit curve was plotted (Fig. 4-4). The coefficient of uniformity (U) was determined from this curve by the equation $U = P_{60}/P_{10}$. Cleasby (1970) chose P_{10} per cent as the (hydraulically) effective size because he observed that the head loss due to resistance was unaffected by the size variation up to a uniformity coefficient of 5. The ideal coefficient of uniformity occurs when the ratio $P_{60}/P_{10} = \text{one}$. The coefficient of uniformity for the anthracite tested was 1.37, indicating a negligible hydraulic influence of variation in media size. The effective size (P_{10}) was 2.1 mm, and the geometric mean size was 2.74 mm.

The initial head losses for the media (clean) were calculated at filtration rates of 3, 6, 9, and 12 gpm/ft² and are presented in Table 4-2. Initial head loss through the 1-ft depth of anthracite was most significant, whereas initial head loss through the gravel layers was negligible; thus the gravel served as support for the anthracite. Effective filtration was achieved only in the anthracite. The decrease in initial head loss through each layer from top to bottom indicates that the combination was excellent for this multilayer filter. Initial head loss was proportional to the square of the average velocity as expressed by the Carman-Kozeny equation (Craft, 1966). It varied

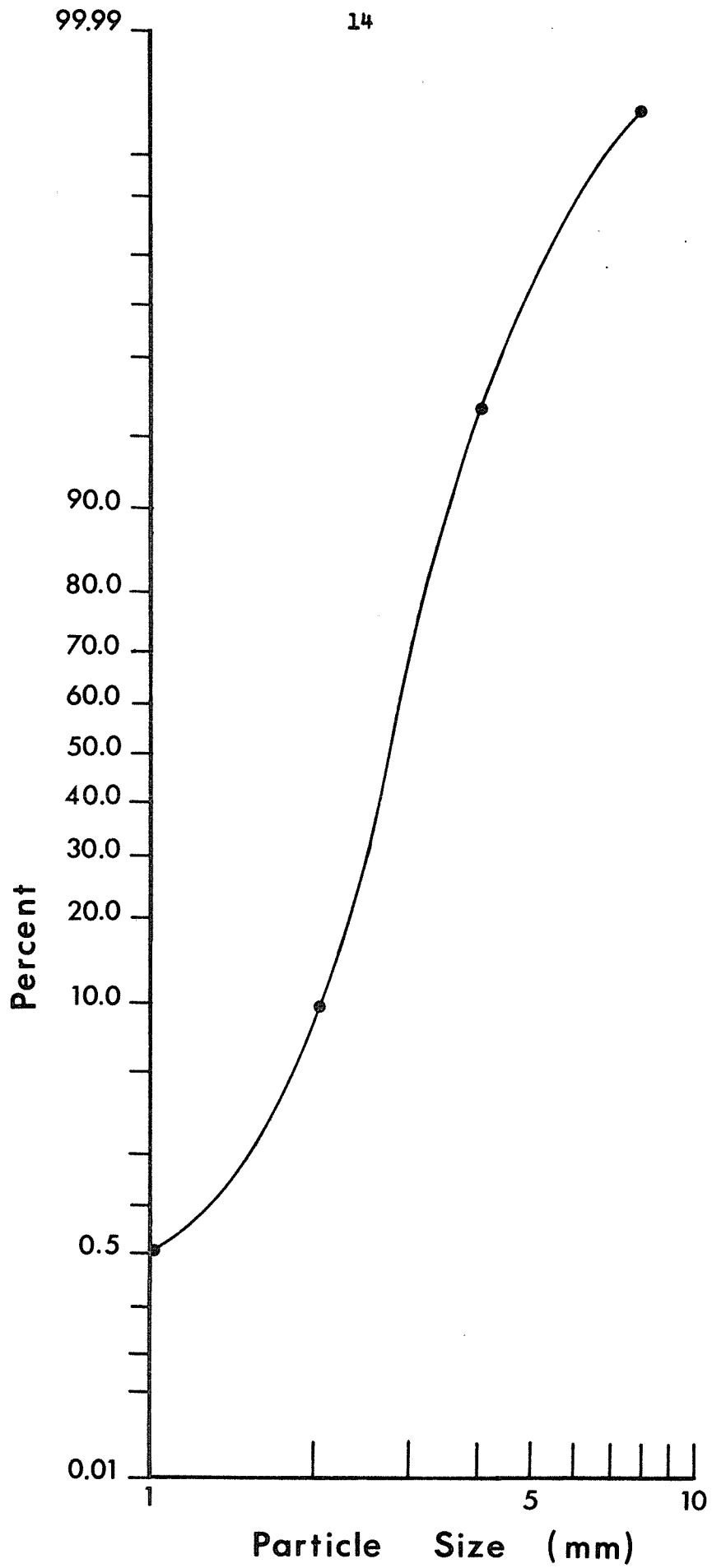


Figure 4-4. Cumulative percentages of particle size, from which the coefficient of uniformity for anthracite was determined.

Table 4-2. Initial head losses through the clean media, calculated with the Carman-Kozeny equation (Craft, 1966)

Rate of filtration gpm/ft ²	Size of media				
	Anthracite 4 mm .157 ft /12	Gravel 4 .25 ft /12	Gravel 3 .5 ft /12	Gravel 2 .75 ft /12	Gravel 1 1.5 ft /12
	Calculated head loss in ft (A)				
3 gpm/ft ²	.117	.014	.002	.001	.000
6 gpm/ft ²	.243	.031	.005	.002	.001
9 gpm/ft ²	.378	.050	.009	.003	.001
12 gpm/ft ²	.524	.073	.014	.005	.002

directly with the depth of the media and could be interpolated. The data in Table 4-2 can be corrected for temperature through the equation $HL = A \times 60 / (o_F + 10)$, where o_F is the filtration temperature, and A the value in Table 4-2.

The backwash velocity at which bed expansion begins (U_{mf}) and the terminal velocity (U_t) were calculated with the following equations (Zerz and Othmer, 1960) for anthracite:

U_t = terminal velocity (ft/hr),

U_{mf} = velocity at which bed expansion begins (ft/hr),

V = actual velocity observed (ft/hr),

$$U_t = \left[\frac{3D_p (P_s - P)}{P} \right]^{1/2},$$

$$U_{mf} \Rightarrow (P_s - P)g = \frac{150(1-E)\mu(U_{mf})}{D_p^2 E^3} + \frac{1.75 P (U_{mf})^2}{D_p E^3},$$

$$V = 0.4058 G D^{-2} (3,600).$$

Definitions:

P_s = density of solid (lb/ft³),

P = density of water (lb/ft³) = 62.4,

g = gravity (ft/hr²) = 4.16×10^8 ,

G = flow rate (U.S. gal/min),

D = diameter of passage,

E = Porosity or void fraction,

D_p = diameter of particle (ft),

μ = kinematic viscosity.

Most passages are circular in cross section, therefore all equations were derived in terms of diameters. When the flow area is noncircular, the

diameter of the equivalent circular cross section can be derived as follows:

$D = 1.128 A$, where A equals surface area of the filter (Sverdrup, 1962).

Specific gravity, particle diameter (ft), and porosity for each medium are given in Table 4-3 for the media tested in 1972. The backwash rate, velocity, and filter diameter are given in Table 4-4. The calculated U_{mf} and U_t are listed in Table 4-5 for each type of media.

The U_{mf} and U_t were plotted (Fig. 4-5) for all five media so that the required ranges of superficial velocity could be determined. The U_{mf} was compared with that provided the main filter during these tests. A minimal velocity of 266 ft/hr was required to fluidize the anthracite; however, a velocity ranging from 96.5 to 120 ft/hr was provided in the main filter (Table 4-4). The minimal U_{mf} for the tubes was exceeded in all cases. These calculations indicate that the main test filter was not sufficiently backwashed. Subsequent testing and filter design must correct this deficiency.

4.5 Operation and Treatments

The hydraulic test procedure was designed so that maximum marine fouling would be achieved on the filter media. This effect was achieved by continuously operating until head loss across the main filter reached 52 inches, then all filters were backwashed and the filtration procedure repeated. This sequence was repeated six times during the 84-day test period.

Six fouling control techniques were evaluated. Each filter tube was backwashed separately after isolation from the rest through a series of controlling valves. The filter bed of each tube was expanded 15 per cent for a period of 15 min (15 gpm/ft²) during backwash. The duration of backwash for the main filter was restricted to about 8 min because of the limited capacity of the storage tank and the consequent limitation of backwash velocity to approximately 12 - 15 gpm/ft². Most fouling control techniques were

Table 4-3. Parameters of the various media utilized in the filter

	Anthracite	Gravel #4	Gravel #3	Gravel #2	Gravel #1
Specific gravity	1.6	2.6	2.6	2.6	2.6
Particle diameter (ft)	.157 /12	.25 /12	.5 /12	.75 /12	1.5 /12
Porosity	0.42	0.35	0.4	0.45	0.45

Table 4-4. Backwash volumes, for the various filter units used (note the variation in the main filter); the diameters for the various filter passages; and the resulting backwash velocities that occur from those volumes per unit of time being passed through their respective passages

	Col 1 to 5	Col 6	Main filter (range)
Backwash gpm/ft ²	15	15	12 - 15
Diameter of filter ($D=1.128 \sqrt{A}$)	4.5 in	5 in	67.7 in
Velocity (ft/hr)	520	413	96.5 to 120

Table 4-5. Velocities required for initial bed expansion (U_{mf}) and velocities beyond which the media will be carried off (U_t)

	Anthracite	Gravel #4	Gravel #3	Gravel #2	Gravel #1
U_{mf}	266.0	533.4	982.5	1455.7	2071.9
U_t	3120	6450	9121	11171	15799

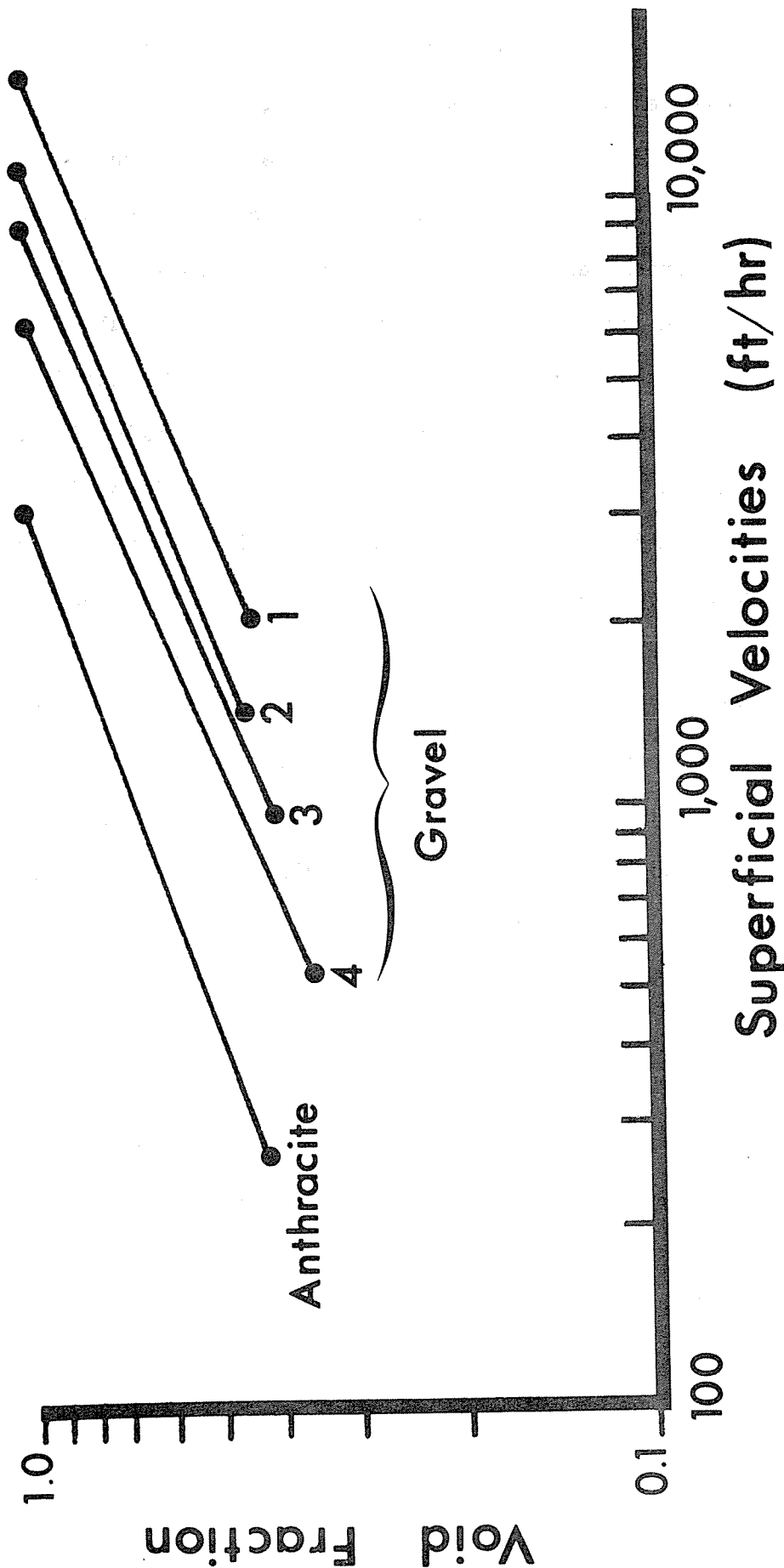


Figure 4-5. Ranges of superficial velocities required to expand media used in the filter.

implemented during the backwash process. First, the main filter and one tube were backwashed at the end of each run with filtrate. This was the minimum control required in operation of the filter and constituted no special technique; however, the results were considered to be representative of the control that mechanical abrasion between particles might afford. Second, a tube was sealed off at the end of each run so that anoxia would occur. The biological oxygen demand of organic matter accumulated on the filter bed determined the rate and degree of anoxia. The rate of decline in dissolved oxygen was periodically monitored from a sampling port located in the filter underdrainage. After a predetermined length of time, the column was backwashed with ambient sea water. A third tube was backwashed with sea water heated to an average maximum of 43 C. The temperature of the backwash water was monitored at the anthracite surface by means of a telethermometer with stainless steel probe. Chlorine was applied as a fouling control agent in three conditions. Chlorine at residual concentrations of 0.89 and 0.95 mg/l was introduced to two columns backwashed with ambient and heated sea water (average maximum 35 C), respectively. The final tube was chlorinated for 2 hr per day at a residual concentration of 0.21 mg/l. In this case, introduction was made at the anthracite surface and chlorine samples were taken from a port in the filter tube underdrainage. This filter tube was backwashed only with ambient sea water. A Sigmamotor finger pump (Model T65) was used to introduce the chlorine solution at a controlled rate. The filtrate was pumped directly overboard so that chlorine contamination of the filtered water stored for backwashing would be avoided. Filtration was resumed in each tube immediately after the control technique had been applied. Control techniques were applied consistently to a single filter throughout the study, and each method was evaluated at the end of the 84-day period.

The effectiveness of a wider range of chlorine concentrations in preventing the accumulation of sedentary fouling organisms was tested through continuous-flow bioassays in a simulated low-velocity marine cooling water circuit. The experimental apparatus consisted of six aquaria. Each aquarium contained a series of 36 plexiglass plates 10 cm², to serve as a fouling substrate. Water was supplied from the filter storage tank by means of a gravity system to a constant-head tank. Water flow through the aquaria was maintained at 0.5 liters per minute by restriction valves. Each aquarium was enclosed in black plastic in order to exclude extraneous light. Bioassays were run continuously for a period of 67 days. Four of the six aquaria were chlorinated at specific levels for 2 hr per day, the remaining two were not, to serve as controls. Chlorine was introduced at the inflow to each of the test aquaria with a Sage proportionating (Model 375) or a Sage syringe pump (Model 234-5). Chlorine solution was prepared from a calculated volume of sodium hypochlorite (Bakers analyzed reagent) and a volume of distilled water. This solution was kept in glass flasks in a dark place until needed. A fresh solution was prepared before each introduction. Residual chlorine concentrations were measured at the outflow.

Residual chlorine concentrations were quantified through the orthotolidine method (Standard Methods, 1971). Samples of unreacted chlorine were held in dark amber glass bottles cleaned and rinsed with chlorine-demand-free water. Samples were tested with the orthotolidine indicator within 1 min of sampling and held in a darkened water bath at 20 C for 2-5 min to allow for complete color development. Colorimetric measurements were made with a Bausch and Lomb spectrophotometer (Spectronic 20) and a Hach Model DR-EL photometer. Preliminary tests indicated that the Hach photometer was not as sensitive as the spectrophotometer but had an accuracy within that of the experimental

procedure. Residual concentrations were checked periodically with the Spectronic 20. Chlorine determinations were found to be minimally affected by changes in pH, turbidity, and salinity during the study period.

Control methods were evaluated and the variability in distribution and size was quantified under the various treatments. *Balanus crenatus* was selected as the index organism because it was the most abundant of the barnacles colonizing the filters, it was observed easily both during and after the tests could be more reliably counted and measured than other organisms present. During the period of filter operation the accumulation and growth rate of *Balanus crenatus* on the walls of each filter tube were observed. The longitudinal basal diameters of individuals in the population of each filter tube were measured weekly. Thus the effect of each fouling control method on the prevention of settlement or restriction of the subsequent growth rate was determined. Upon conclusion of the filtration, the test filters were dismantled and the contents examined. One cubic foot of each media from the main filter and the entire contents of each tube filter were examined. The media were washed and hand sorted. Only those organisms that were directly attached to media particles were weighed and measured. The wall and unattached populations were not determined. Standard analysis consisted of identification of organisms associated with the filter media and determination of their abundance. Longitudinal basal diameter was measured on each barnacle.

5.0 RESULTS

5.1 Filtration

The design of a rapid sand filter is directly dependent on the quality of the water to be filtered; therefore, on-site filtration tests are the most direct means of determining the critical water quality parameters as well as the related operational characteristics of the filter. Filter

performance was evaluated on the basis of rate of head loss, effluent quality (turbidity), and length of filter run. The timing of each filter run (A-G) and associated mean ambient turbidity, temperature, and salinity measurements are presented in Fig. 5-1. A general increase in mean daily turbidity was observed during runs C-G (May 29-July 3), which coincided with the spring runoff from the Skagit River. Increased turbidity during runoff was primarily due to the greater silt load carried by the freshwater into the bay and resulted in shorter run times (C-G). Runs A and B were conducted in water with relatively high salinity and low turbidity and resulted in correspondingly longer filtration times. Plankton appeared to be mainly responsible for the turbidity during runs A and B. Salinity showed a general depression during high river runoff whereas temperatures increased gradually throughout the study period. These environmental parameters illustrate the water quality conditions near the surface (at a depth of 5 ft). The actual filter would probably be placed on the bottom; and, if the surface of the filter were deep enough to remain below the pycnocline, the turbidity and temperature would remain consistently lower and salinity higher and water quality would be under relatively less influence from runoff from the Skagit River and therefore more consistent.

The rate of head loss for each run is plotted against the volume of filtrate in Fig. 5-2. At a filtration rate of 6 gpm/ft², this media configuration yielded an average volume of 2,636,306 gal per run, a larger volume than Media Group B yielded during the 1971 tests. The shortest filtration time occurred during the highest turbidity conditions (Run D). This indicates an "extreme case" and is most important for design considerations. Approximately 300,000 gal were filtered in all runs before rapid decrease in head loss began. The results of the seven consecutive filter

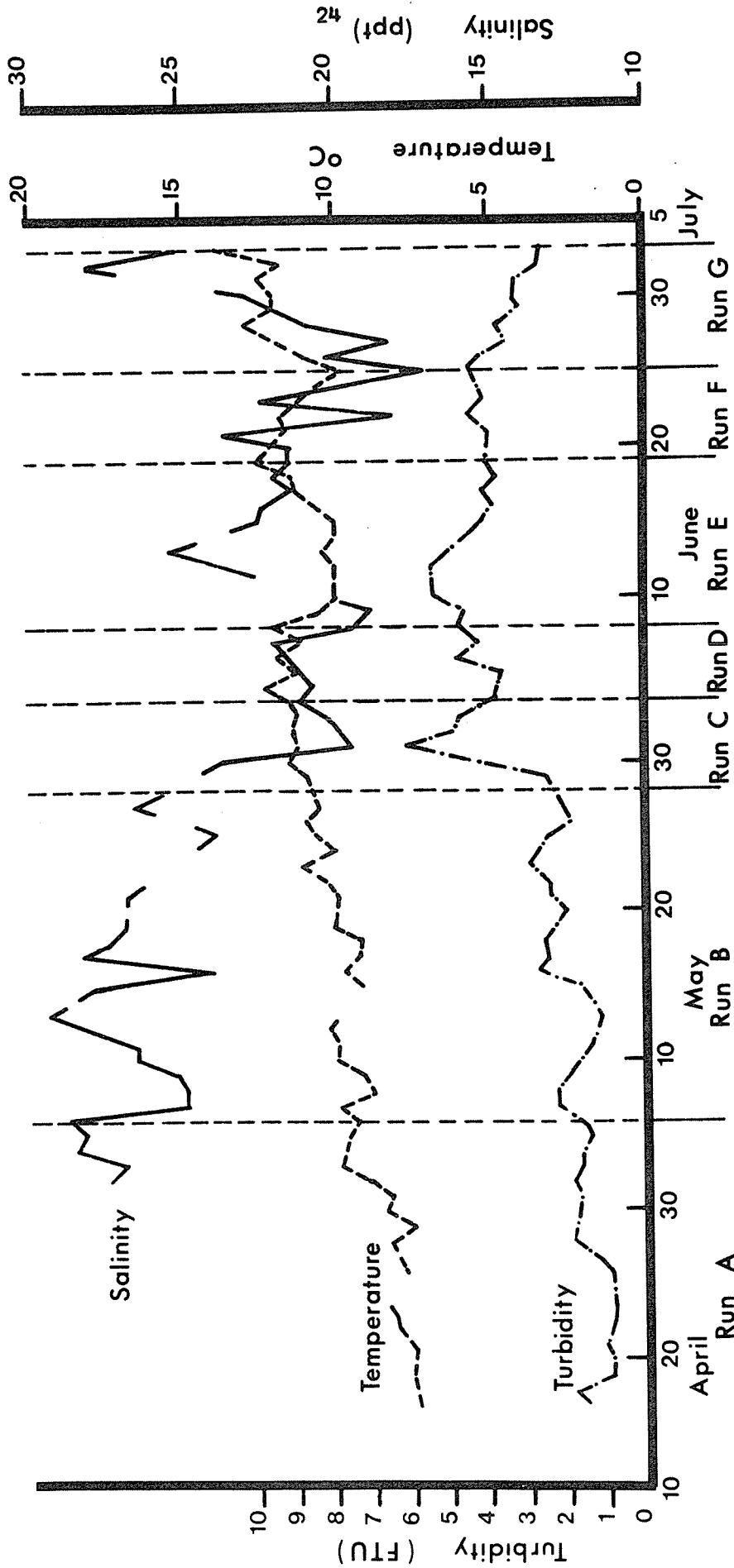


Figure 5-1. Mean daily turbidity, temperature, and salinity measurements recorded during the filter test and timing of each successive filter run (A-G).

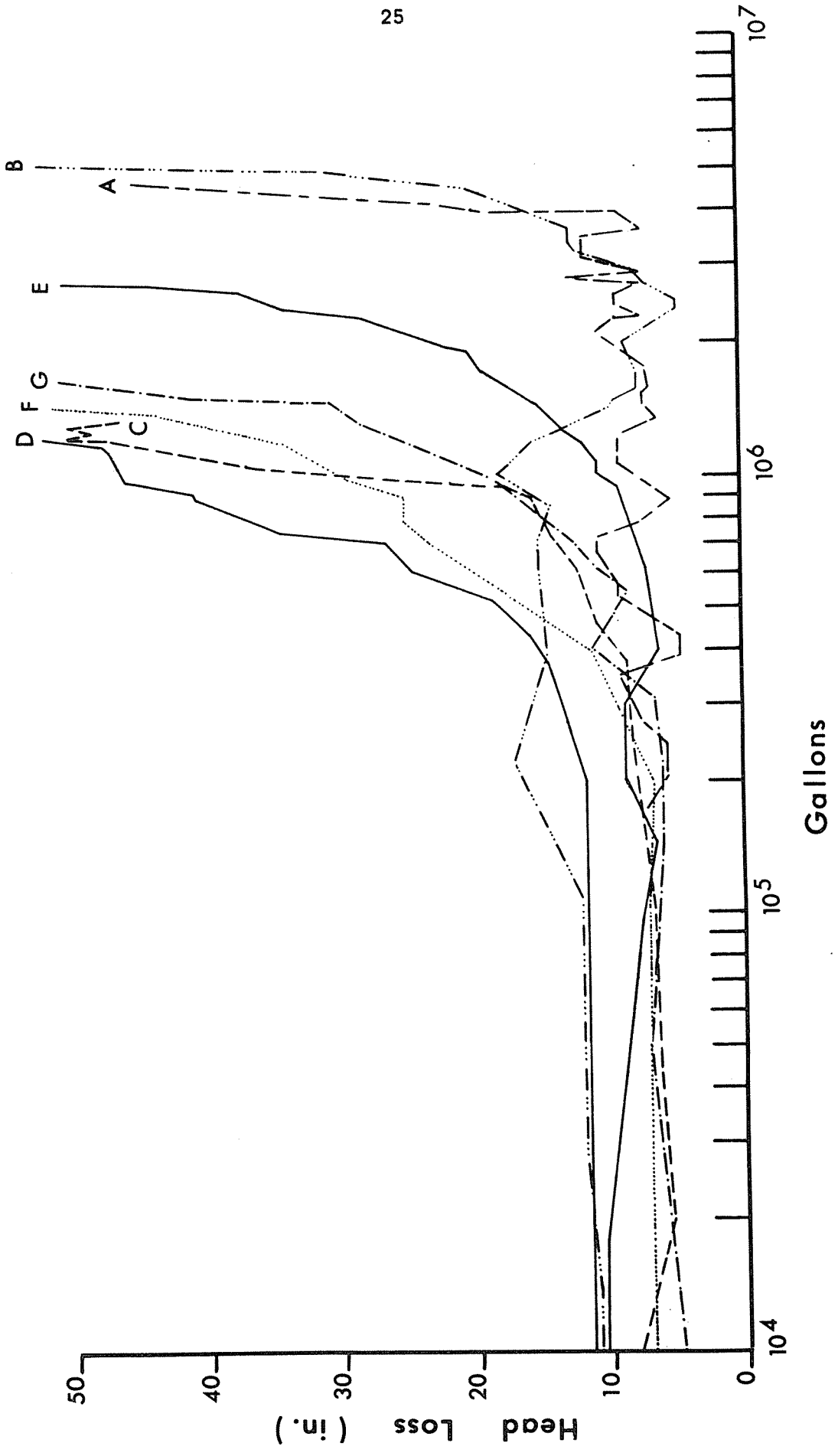


Figure 5-2. Rates of head loss for filter runs A-G, 1972.

runs are summarized in Table 5-1. The run time to a loss of head of 52 inches varied from a minimum of 119 to a maximum of 513 hr during the test with a mean time of 260.6 hr. Initial head loss ranged from 4 to 11.5 inches and did not increase with successive runs. The mean turbidity was reduced an average of 19.2 per cent throughout the test period.

The head loss rate curves indicate a sharp increase in head loss near the end of each run. Variations in the level of deposition of suspended matter within the bed created a negative head which appeared at different depths in the filters. Toward the end of each run the bottoms of the filter beds were under a partial vacuum and dissolved air was released. The static pressure was reduced to the vapor pressure of the water and the released air began to fill the pore space of the filter, causing the filter to become air-bound. This phenomenon would be avoided in normal filter operation by suspension of filtration prior to a critical degree of head loss.

5.2 Backwash

In order to effectively clean a rapid sand filter the backwash flow must be sufficient to expand and actively tumble the filter media so that silt, algae, slime, and other attached material are loosened effectively, but it must not be so great as to wash the media out of the filter. The calculations presented earlier indicated that the U_{mf} was not sufficient to backwash adequately the main filter since it caused only a partial expansion of the bed. The backwash velocity through the tubes was higher and sufficient to expand the anthracite and the No. 4 gravel. The velocity through the main filter would have to be increased by at least a factor of 2.8 times for the filter media to be expanded adequately.

Table 5-1. Filter performance during consecutive runs at a filtration rate of 6 gpm/ft²

Date: Start to finish	Run	Initial HL (inches)	Run time (hours)	Gallons filtered	\bar{X} turbidity at inlet (FTU)	\bar{X} turbidity at outlet (FTU)	Per cent reduction turbidity
4/12 to 5/6	A	7.0	480	4,642,520	1.3	1.1	15
5/6 to 5/28	B	11.0	513	5,190,650	2.2	1.6	27
5/28 to 6/3	C	8	130	1,334,780	4.5	3.6	20
6/3 to 6/8	D	11.5	119	1,219,120	4.2	3.8	10
6/8 to 6/19	E	4	257	2,720,350	4.7	3.3	30
6/20 to 6/25	F	7	152	1,567,300	4.2	3.7	12
6/26 to 7/3	G	5	173	1,779,420	3.4	2.7	21
			$\Sigma 1824$	$\Sigma 18,454,140$			$\bar{X} = 19.2$
			$\bar{X} = 260.6$	$\bar{X} = 2,636,306$			

The mean amounts of settleable solids measured in the backwash effluents for the treatment methods are presented in Table 5-2. Maximum turbidity was measured during the first minute of backwash in all filters (Table 5-3); however, a lag was more apparent in the main filter, indicating inadequate backwash. The settleable solids exhibited trends similar to turbidity. The media tended to rise as a piston when the backwash began. After the piston action had been broken up (approximately 1 min) backwashing could be maintained at a steady rate. No practical method of calculating the load accumulated on the filter was found, except for the model proposed by Ives (1965). The composition of the material deposited on the filter was highly variable and difficult to describe quantitatively from either settleable solids or turbidity measurements as pointed out by Duehrow and Everhart, 1971. The Ives model has potential for providing a mathematical approach to the evaluation of filter performance which would be helpful in arriving at a design concept. A simplification of this model was applied to the initial data obtained during filter Run A given in Appendix A.

5.3 Fouling

The accumulation and ecological succession of biological fouling organisms in the filter tubes were observed throughout the test period. Colonization of the filter media commenced with an accumulation of a brown organic detrital film on each particle together with an associated bacterial slime. A filamentous algae (*Enteromorpha* sp) and a diatom (*Melosira* sp) colonized the anthracite surface 16 days after filter operation was begun. As floral density increased, invertebrate crustaceans (copepods and amphipods) became more frequent above the surface of the anthracite. Barnacles (*Balanus crenatus* and *Balanus cariosus*) were first observed on the anthracite and large gravel 47 days after filtration had been initiated. Ecosystem

Table 5-2. Mean settleable solids measured in the backwash effluents in tests of the six treatment methods

Backwash time	Settleable solids (ml/l)						Continuous 2-hr daily chlorination tube
	Main filter	Ambient sea water tube	Anoxic tube	Heated sea water tube	Heated sea water + chlorine tube	Ambient sea water + chlorine tube	
0:00	3.0	16.5	22.0	17.0	21.0	15.0	40.0
0:15	4.75		6.5				
0:30	8.18	4.0	4.1	3.0			0.1
0:45	6.25		2.0				
1:00	4.17	3.0	1.8	1.0	1.8		0.1
1:15							
1:30	2.6					0.1	0.1
1:45							
2:00	2.9	0.8	0.9	0.5	0.8	0.3	0.1
2:15							
2:30							29
2:45							
3:00	2.6	0.2	0.1	0.25	1.0	0.1	0.1
3:30			0.1				
4:00	0.54	0.15	0.1	0.6	0.1	0.1	0.1
4:30							
5:00	0.70	0.1	0.2	0.1	0.2	0.1	
5:30							
6:00	0.26	0.1		1.8	0.4	0.1	0.1
6:30							
7:00	0.20	0.1	0.1				
7:30							
8:00	0.23	0.1		1.5	0.35	0.1	0.1
8:30							
9:00	0.16						
10:00	0.2	0.1	0.2	0.8	0.4	0.1	0.1
11:00							
12:00			0.1				
13:00			0.1				
14:00			0.1				
15:00			0.1				

Table 5-3. Mean turbidity measured in the backwash effluents in tests of six treatment methods

Backwash time	Turbidity (J. T. U.)						
	Main filter	Ambient sea water tube	Anoxic tube	Heated sea water tube	Ambient sea water + chlorine tube	Heated sea water + chlorine tube	2 hr daily chlorination tube
0:00	235	970	975	850	896	884	1560
0:15	545		240				
0:30	596	326	206	130	86	225	70
0:45	538						
1:00	149	174	147	38	43	64	31
1:15	292						
1:30	181	66	84	25	12	47	27
1:45	144						
2:00	94	78	47	49	21	41	21
2:15	112						
2:30	97	50	46	70	13	24	21
2:45	78						
3:00	77	43	42	39	17	32	17
3:30	81	30	34	43	15	15	14
4:00	52	29	20	56	12	23	
4:30	68						
5:00	57	24	18	50	12	21	14
5:30	50						
6:00	29	22	13	94	8	23	13
6:30							
7:00	28	19	18	46	10	19	14
7:30							
8:00	25	19	11	72	12	17	11
9:00	28	17	17	22	9	21	10
10:00	24	15	11	49	10	15	14
11:00	15	13	15	21	10	12	11
12:00	13	15	13	38	10	12	10
13:00		13	15	19	10	9	10
14:00		15	13	28	10	11	11
15:00		13	17	25	10	11	12

development and species diversity continued through July 3, when filter operation was terminated. The degree of development of the fouling population in each filter tube was dependent on the effectiveness of the specific control treatment to which it was exposed.

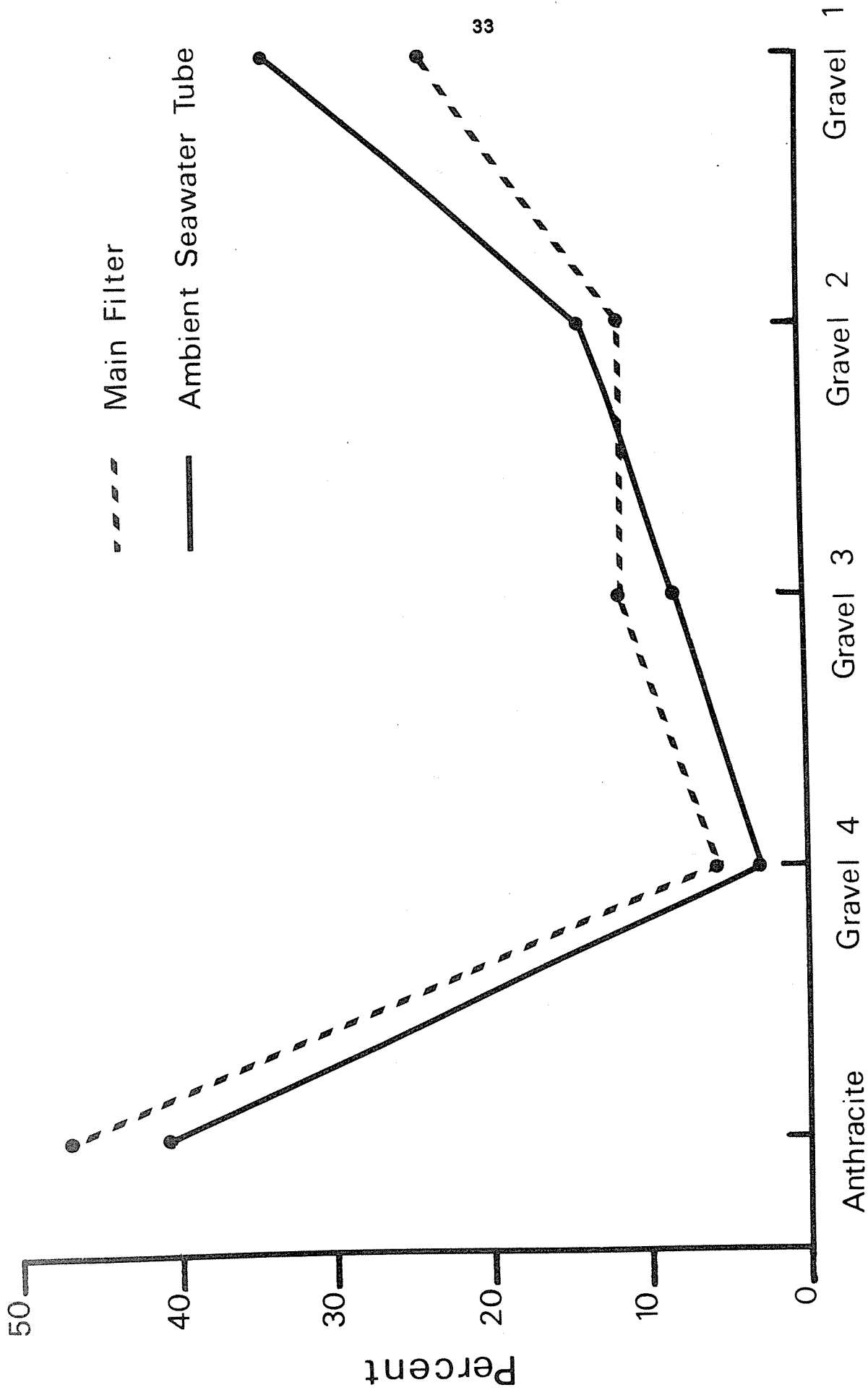
5.3.1 Ambient Sea Water

Analysis of the abundance and distribution of *Balanus crenatus* within the filters backwashed with ambient sea water is presented in Table 5-4. A total of 19 barnacles per 572 cubic inches of media was observed in the main filter sample population, as compared to 76 individuals present on the filter tube media; and the difference was found to be significant (.05 level). The distribution was calculated as a percentage of the organisms in a particular filter tube associated with a specific medium. Although the relative abundances differed, the distributions through the media of both filters were comparable (Fig. 5-3). Relative distributions of 47.4 and 40.8 per cent of the barnacles, respectively, in the anthracite layer of the main filter and ambient filter tube were observed. Abundance of barnacles was moderate ($\bar{x} = 29.4\%$) in the larger size supportive gravel, and least (an average of 9.1%) in the small size gravel.

The size distributions of *Balanus crenatus* associated with the media and fouling control techniques tested are presented in Table 5-5. The relative growth rates of those individuals that successfully settled on the walls of filter tubes with populations greater than 5 were determined. No successful settlement occurred on the plexiglass walls of filter tubes treated with hot water, hot water with chlorine, and daily chlorination. Relative growth in the filter tubes treated with anoxia and ambient sea water + Cl_2 is compared with growth among the control populations maintained in the filter tube treated with ambient sea water and growth in the filter head tank in Fig. 5-4. Regression lines were fitted to the data by the

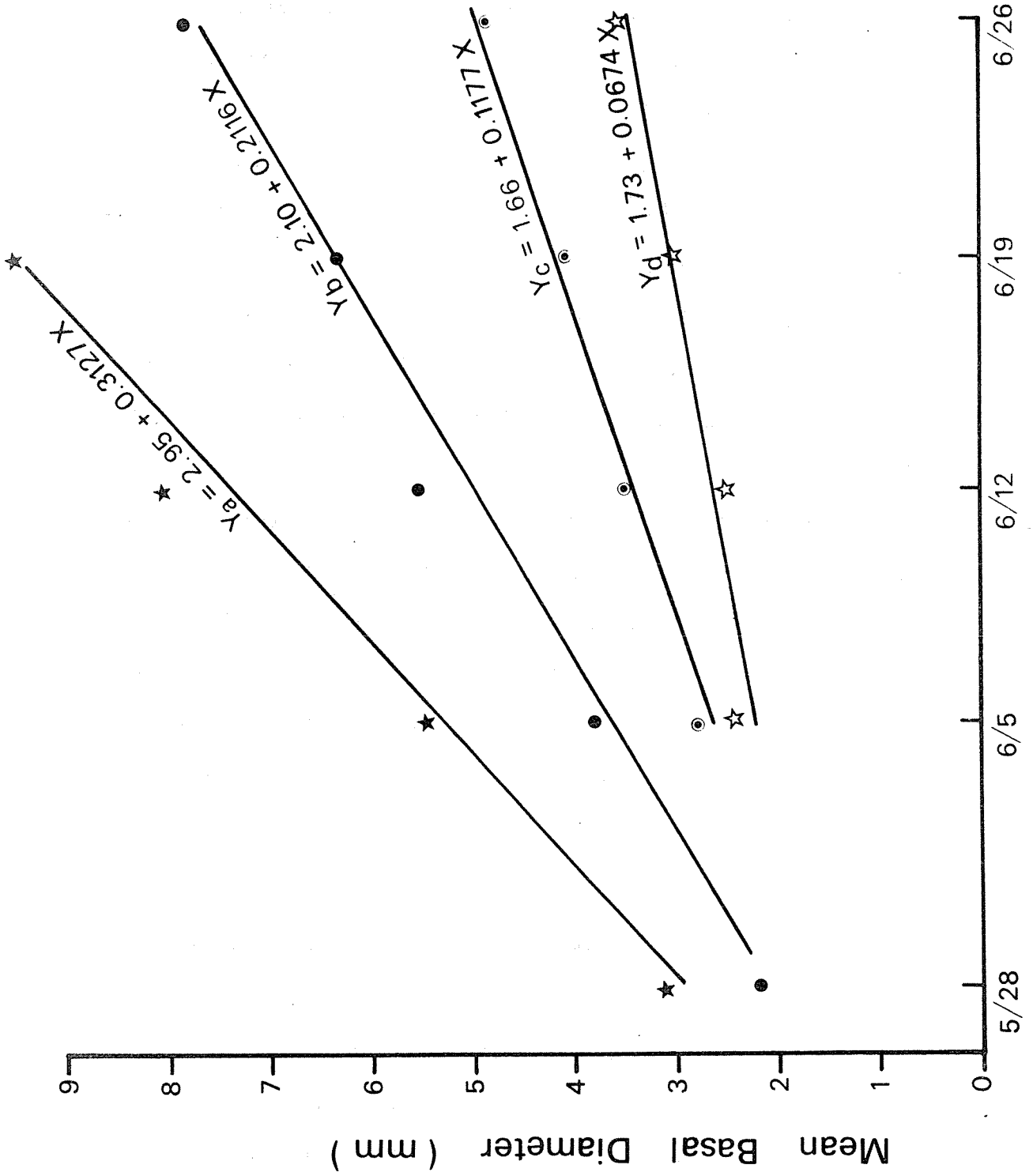
Table 5-4. Abundance and distribution of *Balanus crenatus* within the media of filters tested with six fouling control techniques

Media	Main filter	Ambient sea water tube		Anoxic tube		Heated sea water tube		Ambient sea water + Cl ₂ tube		Heated sea water + Cl ₂ tube		2 hr daily chlorination tube		
		n	per cent	n	per cent	n	per cent	n	per cent	n	per cent	n	per cent	
Anthracite	27	47.4	31	40.8	1	6.7	3	42.9	13	26.5	46	63.0	0	0
Gravel #4	3	5.3	2	2.6	6	40.0	4	57.1	4	8.2	10	13.7	4	25.0
Gravel #3	7	12.3	6	7.9	6	40.0	0	0	18	36.7	2	2.7	4	25.0
Gravel #2	7	12.3	11	14.5	1	6.7	0	0	1	2.0	10	13.7	5	31.2
Gravel #1	14	24.6	26	34.2	1	6.7	0	0	13	26.5	7	9.6	3	18.8
Total number	58	76	15	7	49	75	16							



Media Types

Figure 5-3. Comparison of barnacle distribution within the media of the main filter and the filter tube backwashed with ambient sea water.



Date (1972)

Figure 5-4. Relative growth rates of *Balanus crenatus* where y_a = control; y_b = ambient sea water tube; y_c = anoxic tube; y_d = heated water-chlorine tube.

method of least-squares. The slopes indicate the relative growth rates of individuals for the test populations. The growth rates of the filter tube population treated with ambient sea water ($b = +1.2116$) were not significantly different from those of the filter tank control population ($b = +0.3127$) at the 0.05 level; thus backwashing with only ambient sea water had little effect on the growth rate of *Balanus crenatus*.

A comparison of the sizes of individuals in the main filter (mean basal diameter = 4.86 mm, SD 2.00) and the filter backwashed with ambient sea water (mean basal diameter = 3.31 mm) showed that the former averaged 1.55 mm larger than the latter.

The barnacle size distributions through the filter media, unlike the population distributions, showed the occurrence of the smaller organisms in anthracite in both the main filter and filter tube treated with ambient sea water (basal diameter = 3.86 mm and 2.46 mm, respectively). Barnacles were consistently greater in size by approximately 1.50 mm in the gravel media, with a maximum mean basal diameter of 6.45 mm in the largest size (size #1) gravel in the main filter.

5.3.2 Anoxia

This control technique was based on the use of the biological oxygen demand of the organic matter accumulated in the filter bed. Depletion of the dissolved oxygen supply of the water within the filter created conditions favorable for anoxia and conditions unfavorable for aerobic organisms. Dissolved oxygen concentration declined below 1.0 mg/l only after run B. Minimum dissolved oxygen concentrations of 2.5, 0.5, 8.3, and 8.0 were obtained after runs A, B, D, and E, respectively. Duration before backwashing ranged from 69-147 hr.

A survey of the abundance and distribution of *Balanus crenatus* within the media of the filter tube in which low oxygen stress was applied indicated a total of 15 barnacles in the filter tube population (Table 5-4). Of the barnacles observed, 80 per cent were present in the #3 and #4 gravels and 6.7 per cent in each of the remaining media.

The mean basal diameter of *Balanus crenatus* in the anoxia-treated filter tube was 3.68 mm (Table 5-5). Size distribution within the filter media excluding the largest size gravel was 3.30 ± 0.30 mm. The only individual observed in the large-size supportive gravel had a basal diameter of 6.95 mm.

The slope of the regression line for the relative growth curve of the barnacle population treated by anoxia was +0.1177 as compared to +0.3127 for the control population (Fig 5-4). This difference was determined to be significant (.05 level); thus the application of low dissolved oxygen stress appeared to be an effective means of limiting the growth rate of *Balanus crenatus*.

5.3.3 Hot Water

Backwashing with heated sea water at a maximum average temperature of 43 C was tested as a possible control technique. The average application of heat as well as the maximum and minimum range of the backwash water are given in Fig. 5-5. In general, the backwash temperatures within the filter tube rose rapidly to the maximum, remained above 40 C for approximately 4 min, and then declined gradually to 15 C during the 15 min backwash. Ambient temperature averaged about 10 C.

Observations at the conclusion of the filter test showed a total of seven barnacles associated with the media in the filter tube backwashed with heated sea water (Table 5-4). Distribution was restricted to the

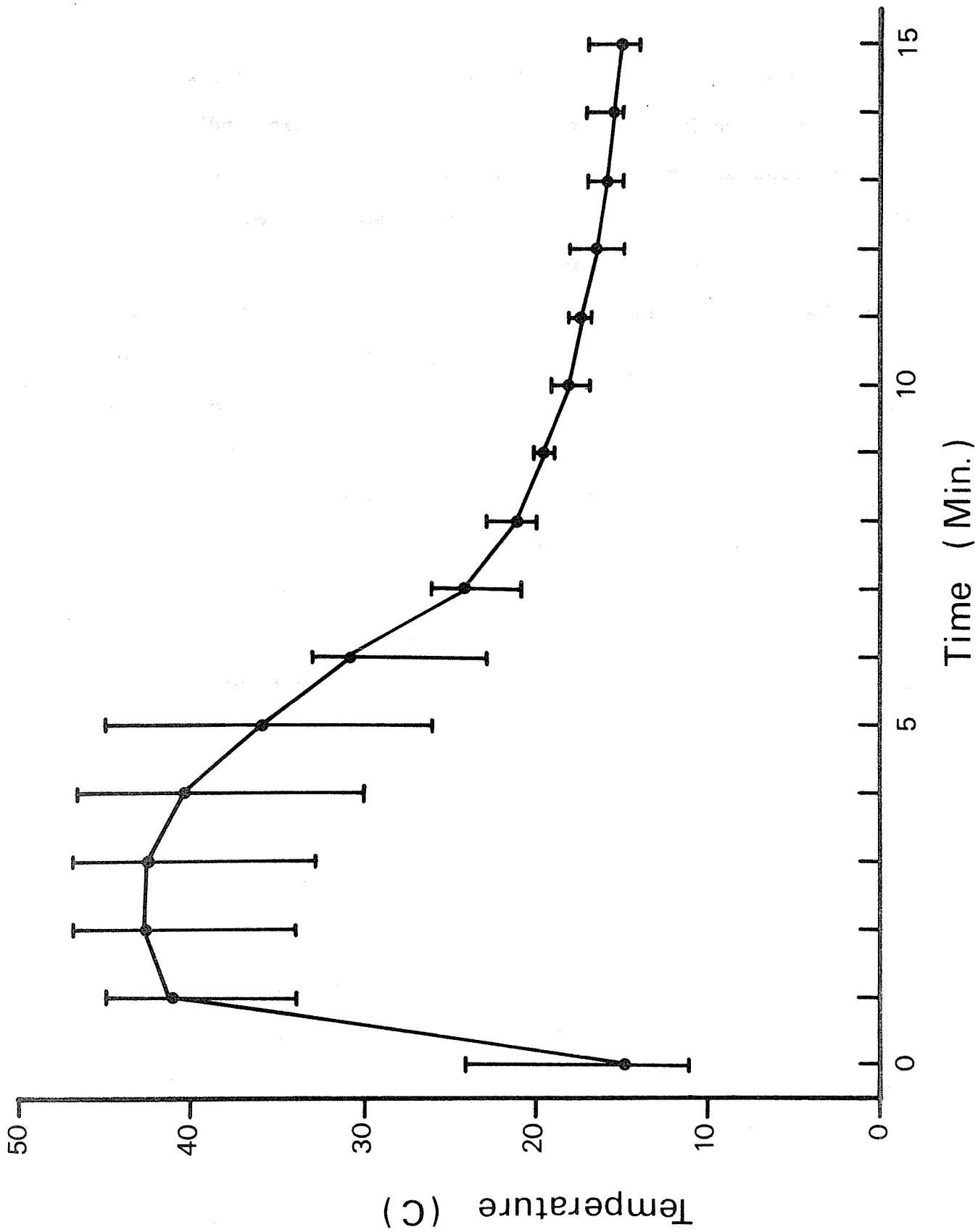


Figure 5-5. Average, minimum and maximum backwash temperatures applied to the heat-treated filter tube.

anthracite and the smallest size gravel (anthracite 42.9%, #4 gravel 57.1%) exclusively. No additional barnacles successfully settled within the filter tube.

The mean basal diameter of the *Balanus crenatus* population in the heated water treatment was 2.11 mm (Table 5-5). This is substantially less than the mean basal diameters of the populations in the filter tube treated with ambient sea water ($\bar{x} = 3.31$ mm) and the main filter ($\bar{x} = 4.86$ mm). Mean basal diameter and abundance were observed to be the lowest in this method of the control methods tested. No barnacles successfully set on the plexiglass tube.

5.3.4 Ambient Water With Cl₂

The average chlorine concentration in the filter tube backwashed with ambient sea water and chlorine was 0.89 mg/l for all backwashes combined. This method proved to be effective in limiting the concentration of algae and diatoms as compared to backwashing with ambient sea water. In the entire filter tube media 49 barnacles were present (Table 5-4). Distribution was concentrated in the anthracite (26.5%), the #3 gravel (36.7%), and the large #1 gravel (26.5%) and very sparse in the #4 and #2 gravels, 8.2 and 2.0%, respectively.

Although the distribution of barnacles was not uniform among the media, the size distribution was consistent among them (Table 5-5). The mean basal diameter for the entire filter population was 2.55 mm. The slope of the regression line for the relative growth rate curve for individuals on the filter tube walls was +0.0674, whereas that for the control population was +0.3127 (Fig. 5-4). The difference was determined to be significant (.01 level); indicating that backwash treatment with ambient sea water and chlorine was effective in reducing the growth rate of *Balanus crenatus*.

5.3.5 Hot Water with Cl₂

The average chlorine concentration in the filter tube backwashed with heated sea water and chlorine was 0.95 mg/l for all backwashes combined. Backwash temperatures were analyzed in the manner previously presented for the filter tube treated with heated sea water only. The average application of heat as well as the maximum and minimum range of the backwash water with chlorine are illustrated in Fig. 5-6.

Observations at the conclusion of the filter test run, showed a total of 75 barnacles present in the filter media (Table 5-4). Of these barnacles, 63 per cent (46 individuals) were associated with the anthracite, 13.7 per cent with the #4 gravel, and 2.7, 13.7, and 9.6 per cent, respectively, with #3, #2, and #1 gravel.

The size distribution of barnacles among the filter media is presented in Table 5-5. The population in the filter tube had a mean basal diameter of 2.58 mm. The population in the anthracite layer had a mean basal diameter of 2.34 mm. Those barnacles associated with the #3 gravel had the smallest mean basal diameter (1.65 mm). Conversely, those associated with the #2 gravel had the largest mean basal diameter (3.53 mm). The populations of the #4 and #1 gravel had mean basal diameters of 2.94 mm and 2.31 mm, respectively.

5.3.6 Daily Chlorination

High frequency low residual chlorination may be applied to discourage the setting of fouling organisms, in contrast to periodic high level doses designed to kill existing organisms. One filter tube was chlorinated at an average residual level of 0.21 mg/l (Fig. 5-7) for 2 hr daily during the period of filter operation.

Using a polynomial least-squares estimate a composite curve representing the chlorine concentration over the 84-day test period was obtained (Fig. 5-7).

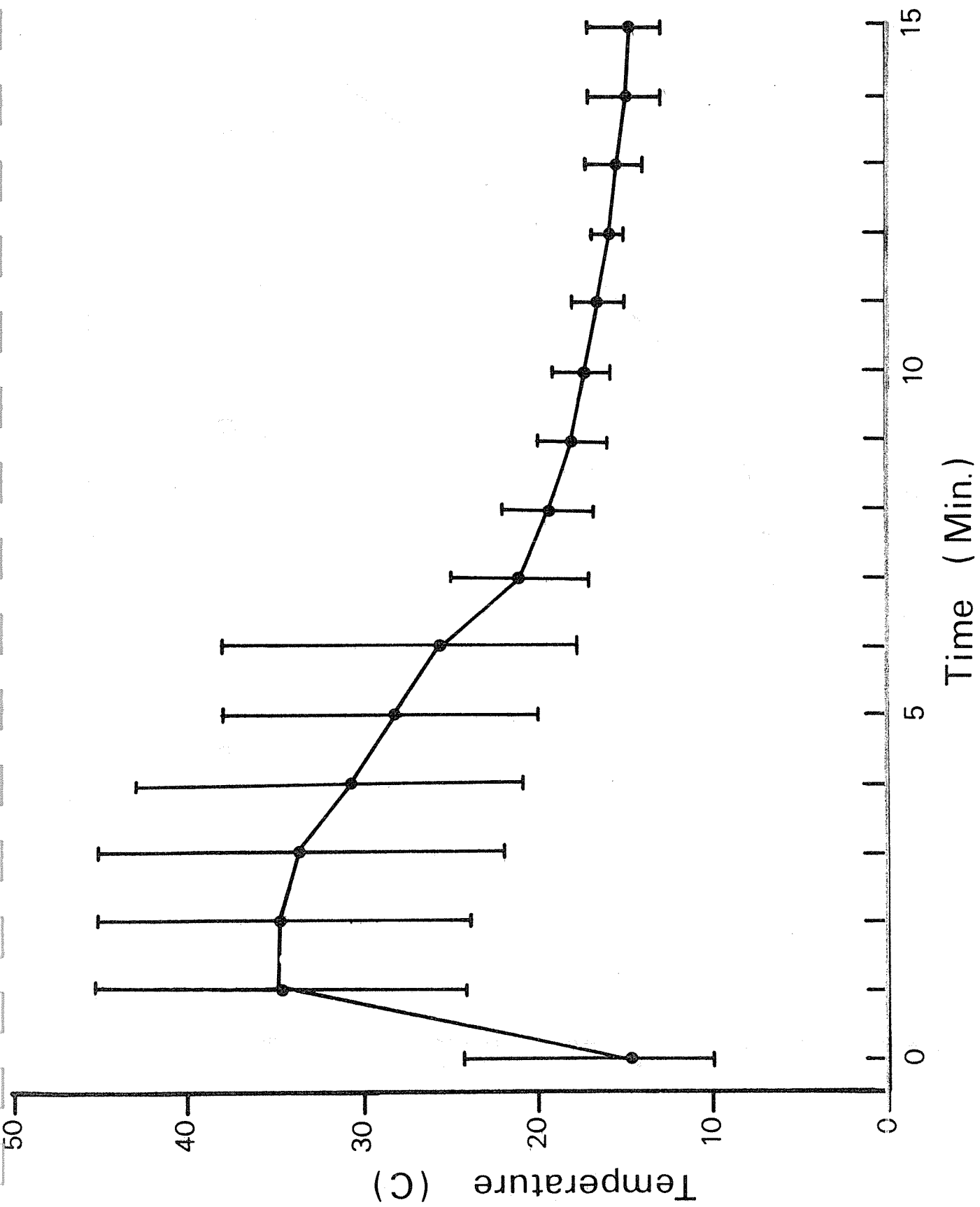


Figure 5-6. Average, minimum and maximum backwash temperatures applied to the heated water-chlorine filter tube.

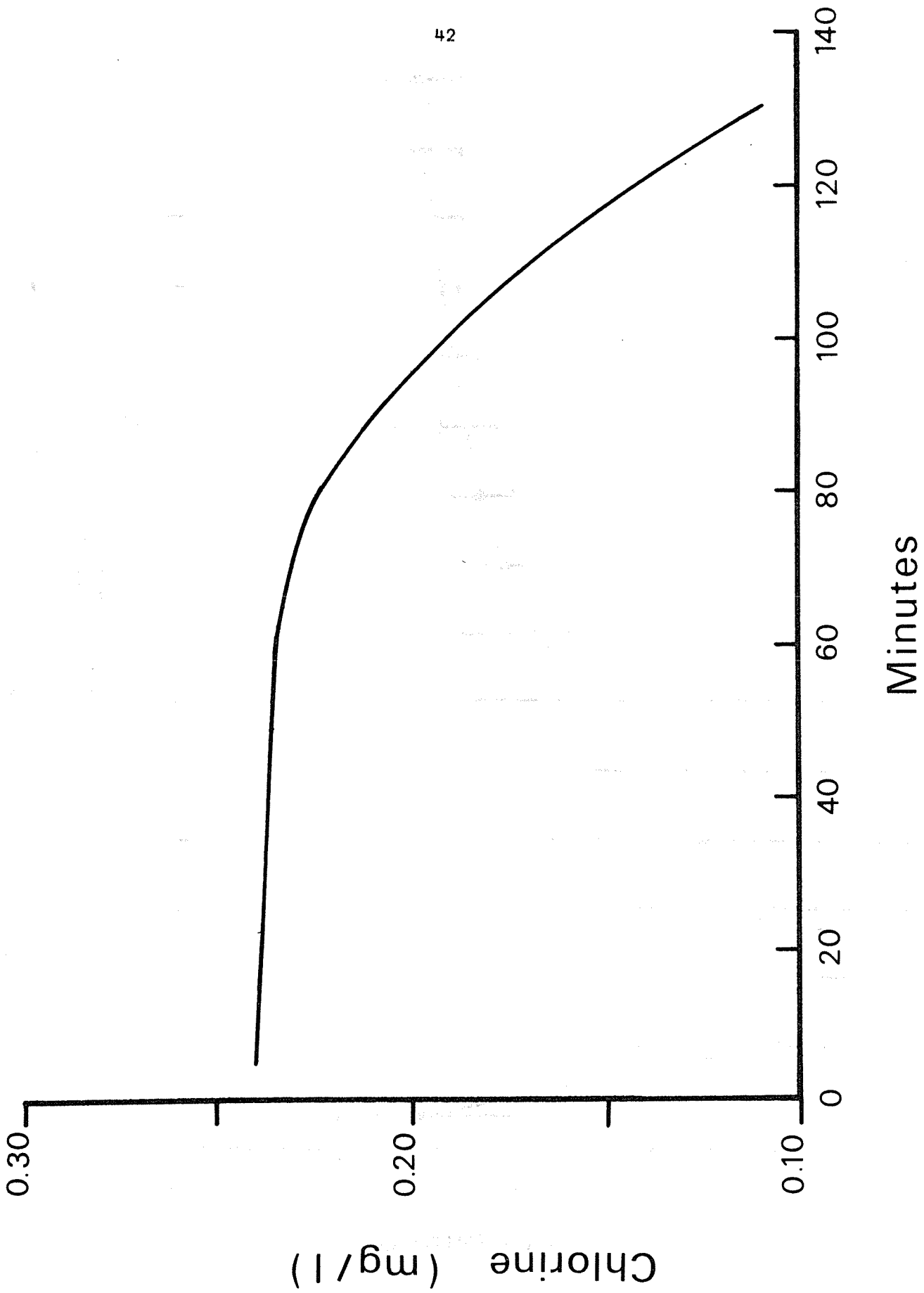


Figure 5-7. Polynomial least-square estimate of the chlorine concentration in the filter tube dosed 2 hr daily.

A mean chlorine concentration was calculated based on the least-square estimate at 5 min intervals for the 2 hr injection period on 420 observations.

A total of 16 barnacles was found associated with the filter media (Table 5-4). Distribution within the filter media was unique in that the anthracite and #1 gravel had few barnacles associated with them, 0 and 18.8 per cent, respectively. The #3 and #4 gravel had 25 per cent of the barnacles each, and the #2 gravel held 31.3 per cent.

The mean basal diameter of the barnacle population in the filter tube exposed to daily chlorination was 2.38 mm (Table 5-5). A progression in size within the filter media from least in the small gravel (1.94 mm) to maximum in the large supportive gravel (3.49 mm) was observed. This trend may be important since chlorine entered the filter tube at the anthracite layer and moved down from the smallest size gravel through the largest. No barnacles successfully settled on the plexiglass walls of the tube.

5.3.7 Continuous-flow Chlorine Bioassays

Continuous-flow bioassays were conducted during a 2 hr period each day for determination of the minimum effective concentration of chlorine. Chlorine exposures at residual levels of 0.046, 0.096, 0.120, 0.149 mg/l in tanks A, B, C, and D, respectively, and in two control tanks were tested. Average chlorine concentrations were calculated from the curves in Fig. 5-8.

The results of the accumulation of fouling organisms after 67 operational days (April 25 through July 1, 1972) indicated that barnacles were present in each chlorinated aquarium and only one barnacle occurred in the control (Table 5-6). The mean basal diameter of *Balanus crenatus* in the chlorinated aquaria was found to be as much as 7.3 mm greater than that in the controls. Unique to the control aquaria, however, was a slime buildup on the walls

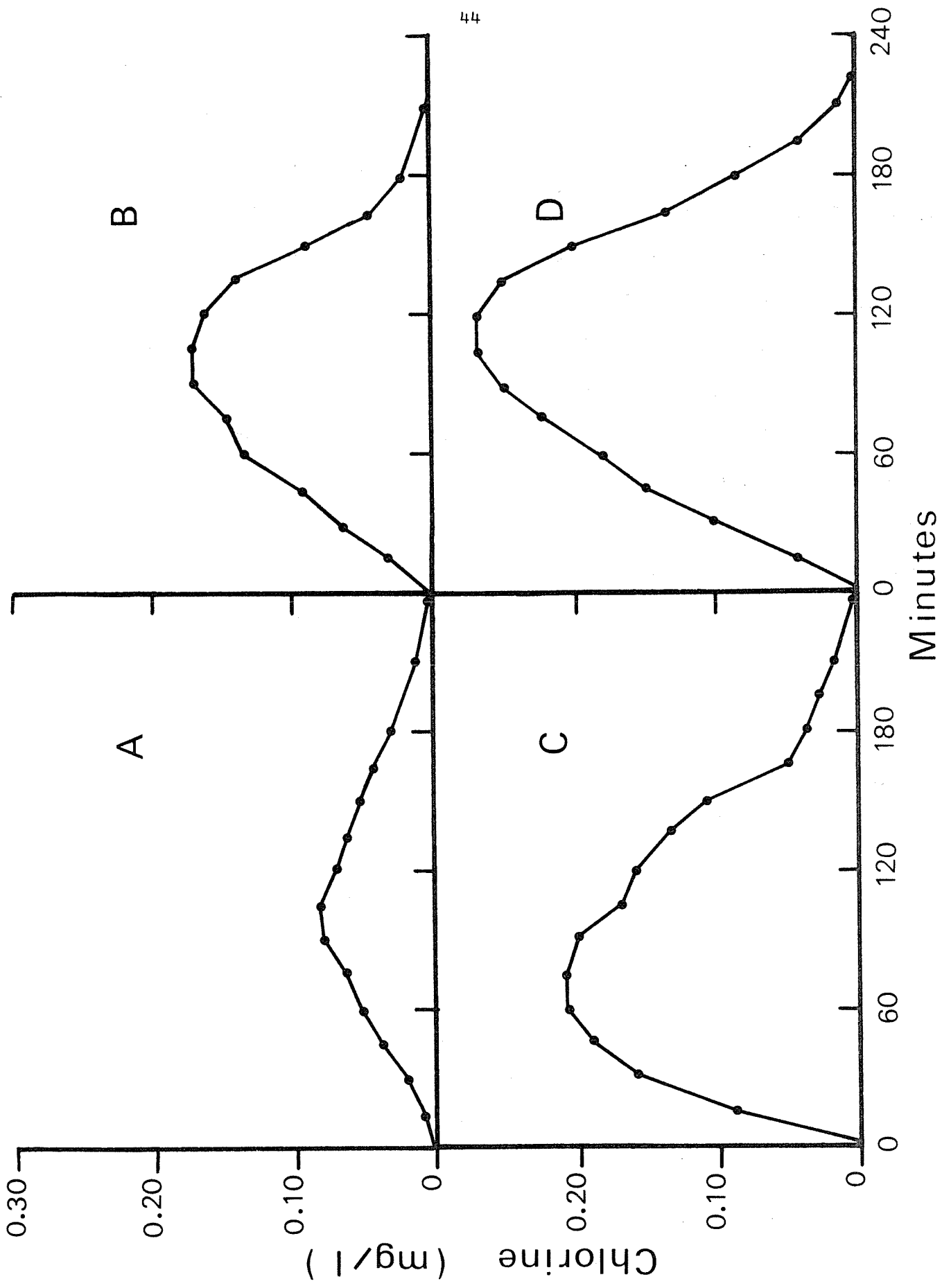


Figure 5-8. Polynomial least-square estimate of the chlorine concentration (Aquaria A-D) in each continuous-flow bioassay.

Table 5-6. Summary of the absolute abundance and size distribution of *Balanus crenatus* present in the experimental aquaria; chlorinated daily and control

	Cl ₂ concentration (mg/l)	Number of sessile fouling organisms	\bar{X} , basal diameter (mm)	Range from (mm)	to (mm)
Tank A	0.046	3	6.5	3.1	10.1
Tank B	0.096	2	3.5	3.1	4.0
Tank C	0.120	3	3.8	3.0	7.0
Tank D	0.149	1	2.9	2.9	2.9
Control 1	0	1	2.8	2.8	2.8
Control 2	0	0	0	0	0

and plexiglass fouling substrate and an accumulation and decomposition of organic detritus, which generated hydrogen sulfide and generally putrid conditions. No such deposits were observed in the aquaria which were chlorinated daily.

6.0 DISCUSSION

Some hydraulic aspects of sea water filtration were established during the 1971 and 1972 tests. The optimal size for the anthracite filtration media lies between 3/32 and 5/16 inches. The coarse filter media allows a higher rate of filtration and longer runs, however, the quantity and velocity of backwash water required to achieve adequate bed expansion is the limiting parameter. The proportion of each type of media and the combined depths can best be optimized with the modeling process (Appendix A). The exclusion of plankton including the larval stages of marine fouling organisms was impractical due to the extremely fine filter media required and the resultant short run times and low filtration rates. The low approach velocities (0.01 to 0.02 ft/sec) that fall within the range of acceptable filter rates (5 to 10 gpm/ft²) will not result in sink flow rates affecting the mobility of juvenile fishes and larger invertebrates (*Neomysis awatschensis*, Stober et al., 1971) in the water column above the filter surface. Provided the filter is placed so that tidal velocities across the filter face are in excess of the sink flow rates, the accumulation of pelagic organisms and debris in the vicinity of the filter will be minimal.

The seasonal changes in water quality (turbidity, temperature, and salinity) at the proposed filter location must be known. The increase in turbidity associated with the winter and spring floods from the Skagit River directly affect filter performance. The 1972 test was conducted during the time that maximum discharge occurred from the Skagit River so that the

ambient turbidities observed were of the magnitude which must be considered in filter design. Turbidity is subject to seasonal variation due primarily to planktonic organisms during most of the year and silt during flood periods. Silt appears to have the greatest effect in reducing filter performance.

Marine fouling is expected to pose the most serious operational difficulty in a rapid sand filtration system. Although the limited test period did not permit complete development of the fouling community, fouling did occur to a sufficient degree which allowed evaluation of the control methods. During the test period, barnacle succession progressed (*Balanus crenatus* and *B. cariosus*) but mussel (*Mytilus edulis*) setting did not occur. Mussels are the principle fouling organisms in marine cooling systems (Holmes, 1970); however, their potential for fouling the filter media is unknown in this investigation.

Settlement of barnacles and mussels may occur throughout the year with greatest numbers occurring from April through October. It is during these months of concentrated fouling that control techniques must be applied. Less emphasis can be given to fouling control from November through March. It must be remembered that the time of maximum fouling occurrence may vary with location and between years.

Ambient sea water backwash was considered representative of the control afforded by mechanical abrasion between particles. This abrasion disrupted environmental stability and was moderately effective in reducing algae attached to media particles. However, it was ineffective where interparticle impact force was insufficient to dislodge sessile organisms and was limited to that portion of the filter bed which was expanded.

A comparison between the two filters backwashed with ambient sea water was made. Relative abundance of *Balanus crenatus* was significantly less

in the main filter than in the corresponding filter tube. However, the mean basal diameter of barnacles present in the main filter was substantially greater than those in the ambient filter tube. It was established that the bed expansion of the main filter was inadequate which allowed a residual film of silt and bacteria to collect on the media particles. The larger barnacles in the main filter had probably set prior to the silt accumulation while subsequent spat settlement was discouraged (Moore, 1958), thus, limiting the population in the main filter. The absence of mechanical abrasion within the main filter may have created a more favorable environment for growth than the disrupted conditions which occurred in the ambient treated filter tube.

The high abundance of barnacles in the anthracite media and relatively large size, indicate the ineffectiveness of backwashing with ambient sea water as a fouling control technique. Mechanical abrasion did, however, reduce bacterial slime and algal accumulation on the anthracite media. In addition, the mean basal diameter of barnacles present in the anthracite was substantially less than those in the media not exposed to abrasive action, indicating partial effectiveness.

Anoxia appears to be an effective technique in discouraging aerobic fouling organisms; however, its effectiveness depends on the amount of BOD accumulated on the filter prior to complete loss of head. This technique requires a system shut down for a period of hours or days again depending on the amount of accumulated BOD and dictates a multiple filter arrangement requiring an area of sufficient size so that the required amount of cooling water will remain available. This technique has the advantage of no requirement for biocides and has been used successfully at the Marine Laboratory of California State University at Humboldt (E. O. Salo, personal communication) and in California power plants (Zeller and Rulifson, 1970). Complete anoxia was

not achieved during these tests due to the low biological oxygen demand and it is difficult to evaluate effectiveness objectively. However, control of fouling was indicated due either to dissolved oxygen depression or to the periodic termination of water flow through the filter which may have interrupted the supply of food or available nutrients. Barnacle abundance in the anoxic filter tube was 80 per cent less than occurred in the ambient filter tube.

The use of intermittent chlorination as a fouling control agent had been noted by Holmes (1970), Draley (1972), and Morris (1971). Intermittent chlorination was effective in controlling bacterial slime accumulation, but had only a limited effectiveness on macro-fouling organisms.

Principle objections to the use of chemical toxins as anti-fouling agents include the cost of application and the detrimental effects on non-target organisms (Waugh, 1964; Hamilton et al., 1970). This effect is particularly true when the treated effluent is discharged to the environment.

Comparison between the filter tubes treated by intermittent chlorination was made. Backwashing with chlorinated ambient sea water appears to be more effective than the hot water-chlorine combination. Barnacle abundance was greater in the filter tube treated with chlorinated hot sea water but mean barnacle size was essentially equal, indicating chlorine was equally efficient in reducing the growth rate of barnacles in both treatments.

The distribution pattern within the filter media is important. An extremely high relative abundance of barnacles occurred in the anthracite of the filter tube treated with hot water-chlorine. Distribution within the filter media treated with chlorinated ambient sea water does not show a similar trend. The distribution pattern may be a reflection of heat and not chlorine, as the same trend was observed in the filter tube treated only with heated sea water.

Comparison of the abundance of barnacles within the filters treated with hot water and hot water-chlorine showed that barnacle abundance was ten times greater in the filter treated with hot water-chlorine than in the heated non-chlorinated sea water treatment. This difference indicates that the addition of chlorine decreased the effect of heat through possible avoidance reaction, or the backwash temperature was low enough to permit survival.

Heated sea water was effective in reducing algal and bacterial accumulations on the filter media. Compared to other fouling control methods tested, mean basal diameter and barnacle abundance were observed to be lowest in the filter tube media treated with hot water during the backwash.

Distribution results indicate a decrease in the effectiveness of heated backwash in the anthracite and #4 gravel portion of the filter bed. Dynamic heat absorption, as the backwash water passed through the filter bed, may sufficiently reduce the backwash temperature to account for a decreased effectiveness of the method toward the filter surface. A second consideration, based on the small standard deviation in organism size, is that the population developed as the result of a single ineffective backwashing.

In general, most investigators feel that the larvae of various marine organisms are more sensitive to chronic low level concentrations of chlorine than are the adults (Dobson, 1946; Turner et al., 1948). Thus, greatest effectiveness results by repeated low level chlorination which either kills the larvae directly or creates an unfavorable environment for settlement.

The effectiveness of daily chlorination was evident in the absence of algae and slime accumulation on the media. This was the only technique tested which completely prevented such accumulations. Barnacles successfully settled within the filter tube. However, abundance and size were low compared

to most other control techniques tested. Comparisons between the filter treated daily with chlorine and the ambient treated filter tube showed a decrease in barnacle abundance of 79 per cent and barnacle size was significantly less.

Distribution is an important index parameter when evaluating the dynamics and effectiveness of daily chlorination. Chlorine was introduced into the filter tube directly above the anthracite surface, therefore, a higher local concentration may have been present in the anthracite due to incomplete mixing and dilution. Since samples were taken after complete passage through the media, this possible effect was not observed in the chemical analysis. The chlorine demand of the water and material within the filter also contributed to the difference in concentrations present in the anthracite and those quantitated from the underdrainage sampling port. The influence of these factors on the dynamics of chlorine appeared to have an effect on organism distribution within the filter.

The continuous flow chlorine bioassays illustrate the effectiveness of chlorine in reducing bacterial slime and resultant hydrogen sulfide accumulation. Presence of these conditions creates an unfavorable environment for settlement and were observed in the control aquaria. Chlorination, at a residual level which does not inhibit or destroy larval fouling organisms, may limit bacterial slime and hydrogen sulfide, enhancing settlement. The size and abundance of barnacles were comparable in the control and the maximum chlorine concentration tested. At lower chlorine levels, barnacle abundance and size increased with respect to the control.

The treatment with hot water appeared to be the most effective control technique tested followed by continuous chlorination and anoxia. It is certain that the heat and chlorine treatments would be effective if the filter bed could be "soaked" at high temperature or chlorine concentrations.

This may be possible by designing the filter in sections which could be dewatered and then flooded with a biocide. Provided that the BOD accumulations on the filter were consistently high enough to achieve anoxia this technique would also be reliable. It would be desirable to operate a scale model filter on-site throughout one annual cycle to provide experience in the control of a complete community of fouling organisms including the mussel (*M. edulis*) which was not possible in this study.

The backwash of settleable solids and turbid water from the filter may pose some concern to management agencies. The transient nature of the backwash is not expected to create a problem more severe than turbidity which occurs during minor beach erosion. The backwash of heat or biocidal chemicals from the filter will be controlled so that the threat to non-target organisms is minimized. The data developed in these tests are sufficient to determine feasibility and the probable requirements for construction, operation, maintenance, and fouling control in the initial engineering design by Strandberg (1972).

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Appendix A1.0 Mathematical Evaluation of Filter Performance

A mathematical model would be useful in designing the most efficient filter that would provide the quantity of water desired at the lowest cost. This model was proposed by Ives (1965). An effort has been made to simplify his model and to test it with data taken between day 17 and day 32 of Test Run A conducted at Kiket Island. No recordings were made of data during the first 17 days. The data from the initial filtration were used in the tests because of the increasing complexity of subsequent filter runs due to partial clogging, growth of fouling organisms, insufficient backwashing, etc. For the initial filter runs the initial deposit, flow, suspended matter in the inflow, and the condition of the filtering medium were known.

According to Ives, a plot of head loss vs time should present a linear relationship. A general linear relationship was evident in the plot of Run A during the period of filtration from day 17 to day 32 (Appendix Fig. A-1). The model was limited to this time period because beyond it the rate of head loss became exponential.

The slope of this line was calculated by the regression formula

$$b = \frac{\sum x_i y_i - (\sum x_i)(\sum y_i)/n}{\sum x_i^2 - (\sum x_i)^2/n}$$

where b = slope,

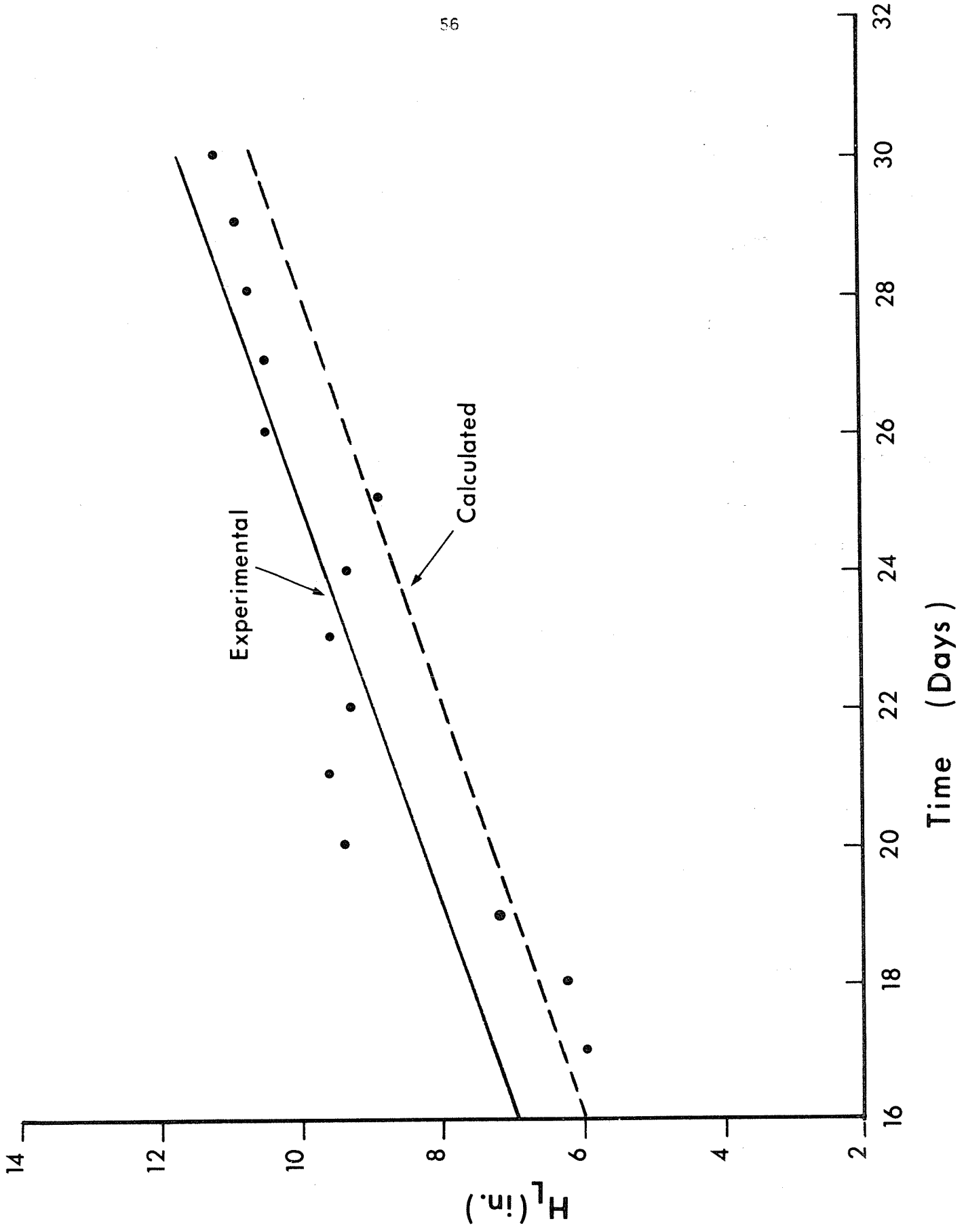
x = time,

y = head loss, and

n = number of observations.

Slope (b) = 0.0141 inches/hr.

The slope was calculated for those values of head loss less than a total of 12 inches observed in filtration Run A.



Appendix Figure A-1. Plot of experimental and calculated head loss (H_L) for Run A, showing linear relationship.

The average approach velocity of filtration, \bar{V} , over the same time period was calculated according to the formula:

$$\bar{V} = (\overline{\text{gpm}})(.1337)(12)(60),$$

where $\overline{\text{gpm}}$ is the mean flow rate in gpm/ft^2 , which was equal to 6.0,

.1337 is a conversion factor from $\overline{\text{gpm}}$ to ft^3/min ,

12 converts feet to inches,

60 converts minutes to hours,

so that \bar{V} is expressed in inches/hr.

Therefore, $\bar{V} = 618.36$ inches/hr.

The initial concentration of suspended matter, C_o , in the flow at the filter surface was determined to be 13.1 parts per million at the time the filtration was carried out. Total suspended matter was determined from a 5-gal sample according to Standard Methods, 1971, p. 537:

$$C_o = 13.1 \times 10^{-6}.$$

Ives then defined an approximate head loss constant, k as

$$k = \frac{b}{\bar{V}C_o},$$

where $\bar{V} = 618.36$ inches/hr,

$C_o = 13.1 \times 10^{-6}$, and

b (slope) = 0.0141.

Therefore, $k = 1.74$.

The volume of deposit/unit filter volume is the material that a filter medium accumulates during filtration. This material is composed of a wide range of types of matter and sizes and is very difficult to define. Therefore, Ives expressed the deposition rate as the specific

deposit, σ , which allows calculation of the rate of head loss without definition of the actual material responsible.

$$\sigma = h - h_0/k,$$

where h = head loss and

h_0 = initial head loss.

It was assumed that the filtration was carried out essentially in the anthracite layer of greatest depth (1 ft) and therefore greatest initial head loss.

Therefore, utilizing the equation for specific deposit we get varying values of σ with time. A plot of the specific deposit (σ) vs time is presented in Appendix Fig. A-2. A mathematical approximation of this curve is calculated from the equation:

$$\sigma = m(\log x) + \hat{b},$$

where σ = specific deposit,

x = time, and

\hat{b} = zero;

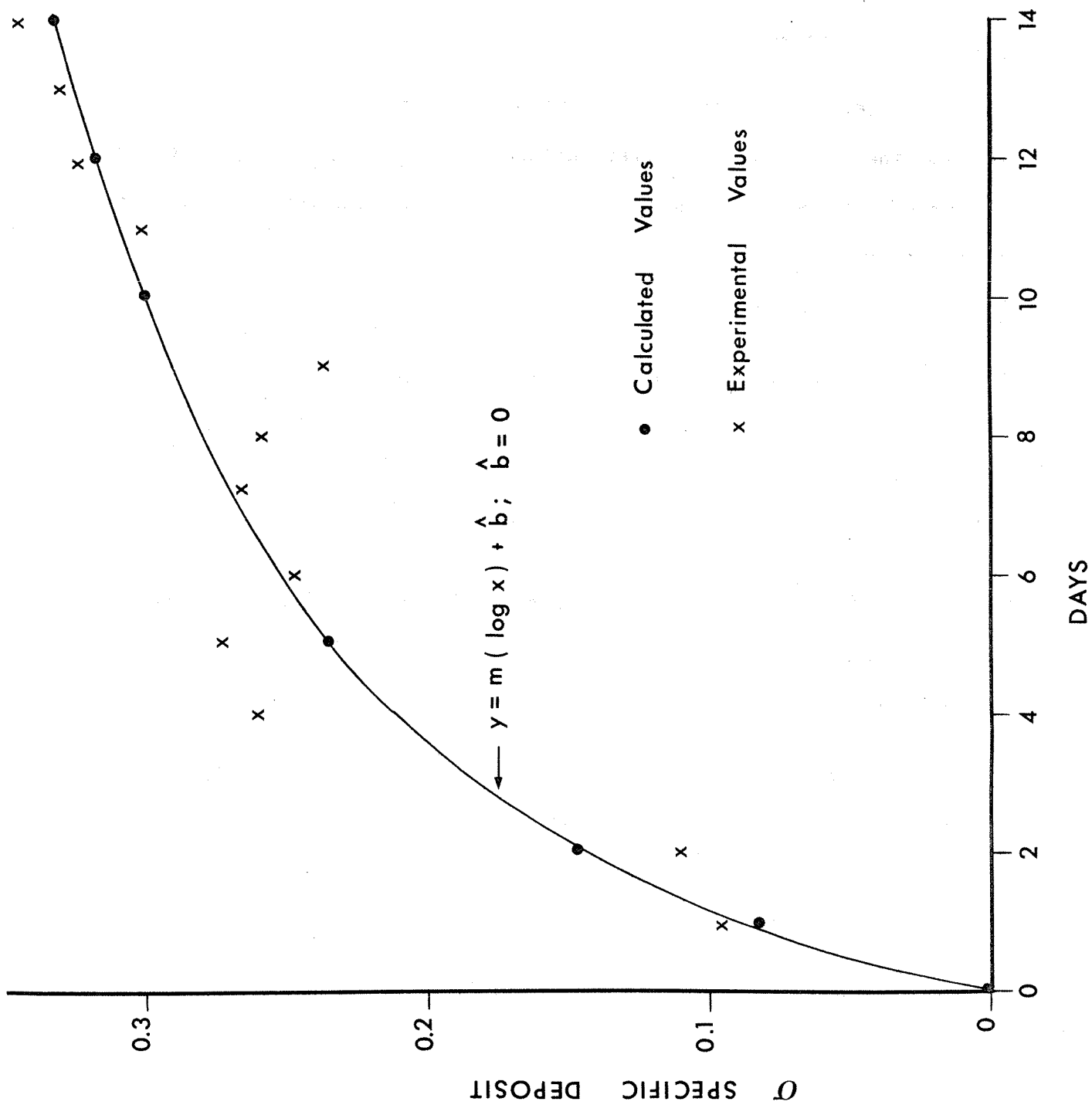
and solved for m by the regression formula:

$$m = \frac{\sum(\log x_i)(\Sigma\sigma_i) - (\Sigma\log x_i)(\Sigma\sigma_i)/h}{\sum(\log x_i)^2 - (\Sigma\log x_i)^2/h}$$

and thus we are able to plot the mathematical approximation

$$\sigma = m(\log x) + \hat{b} \text{ (Appendix Fig. A-2).}$$

This curve is used to approximate the experimental values. Ives calculated a filter coefficient (λ), which allows expression of the change in efficiency and performance of a filter related to the specific deposit.



Appendix Figure A-2. Plot of experimental and calculated values of specific deposit versus time.

$$\lambda = \frac{d\sigma/dt}{\bar{v}C},$$

where λ = filter coefficient of dimension units L^{-1} .

For the filter surface layer (anthracite), $C = C_o$, or the concentration of suspended material at the filter surface equaled the concentration in the water pumped to the filter.

As the curve changes slope, λ therefore changes value.

$$\lambda_1 = \frac{(d\sigma/dt)}{\bar{v}C_o}, \text{ gives the initial coefficient.}$$

Let the value of σ at slope $(d\sigma/dt)_1$ be σ_1 .

Similarly

$$\lambda_2 = \frac{(d\sigma/dt)}{\bar{v}C_o}, \text{ with the corresponding value } \sigma_2, \text{ gives the final coefficient.}$$

From Ives

$\lambda = A - B\sigma^2$, where A = approximate initial filter coefficient; L^{-1} ;

B = approximate filter coefficient constant; L^{-1} .

Then $\lambda_1 - \lambda_2 = B(\sigma_2^2 - \sigma_1^2)$

$$B = \frac{\lambda_1 - \lambda_2}{\sigma_2^2 - \sigma_1^2}, \text{ and } A = \left[\lambda + \frac{\lambda_1 - \lambda_2}{\sigma_2^2 - \sigma_1^2} \right] \sigma^2.$$

From these formulae,

$A = 0.397 \text{ inches}^{-1}$ and

$B = 3.396 \text{ inches}^{-1}$.

We can now plot σ vs λ according to the formula:

$$\lambda = A - B\sigma^2 \text{ (Appendix Fig. A-3).}$$

Utilizing these values thus derived, we have a representative mathematical model and can calculate:

C/C_o , σ , and head loss (H_L),

$$\text{where } T = 2 C_o t \sqrt{AB},$$

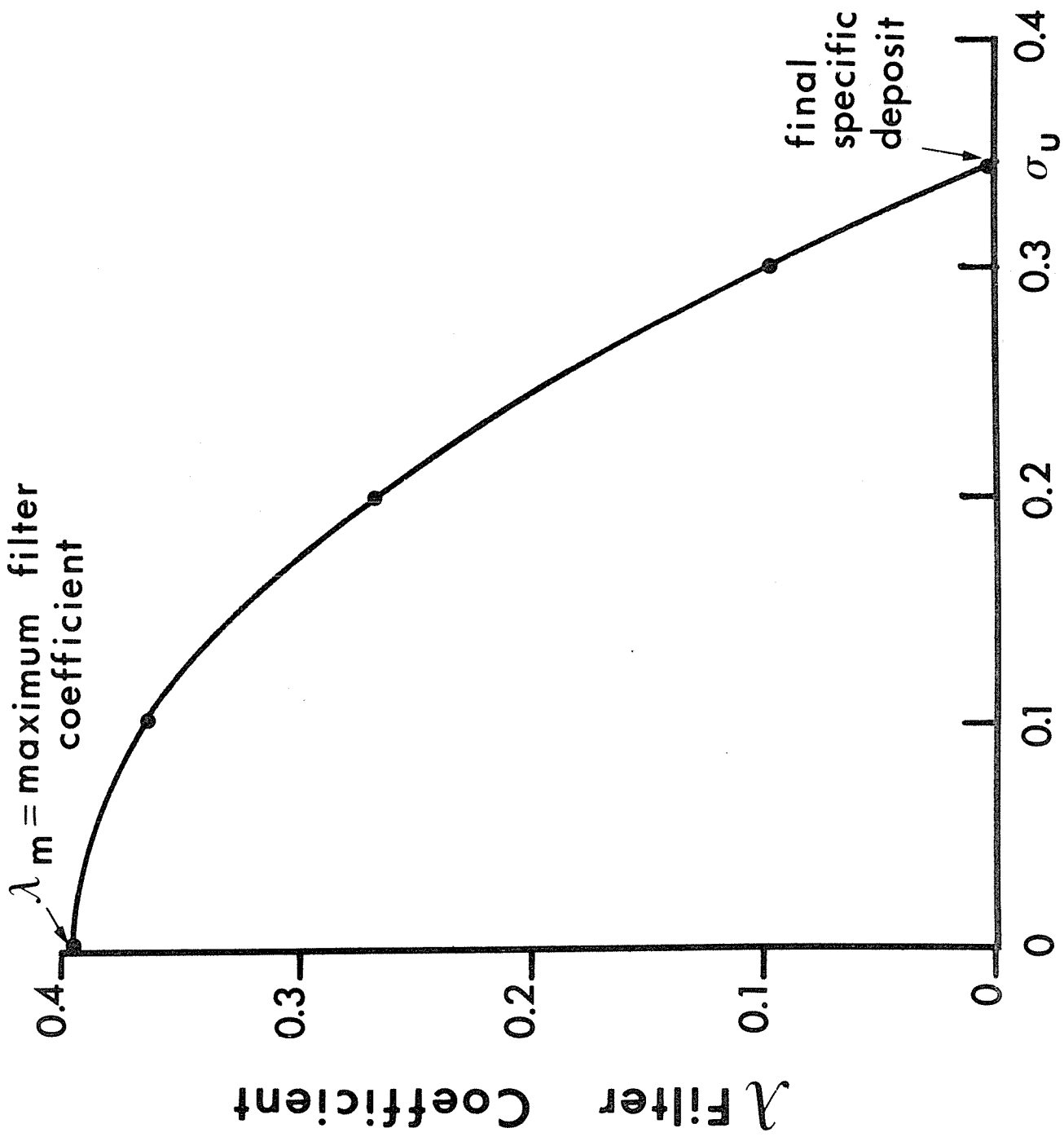
L = depth of filter medium measured from surface = 1 ft, and

t = time from commencement of filtration.

$$H_L = h_o L + \frac{k}{2 \sqrt{AB}} \ln \left[\left\{ \frac{[1 + e^{2AL}] \left\{ \left[\frac{(e^T + 1)}{(e^T - 1)} \right]^2 - 1 \right\}^{\frac{1}{2}} - 1}{[1 + e^{2AL}] \left\{ \left[\frac{(e^T + 1)}{(e^T - 1)} \right]^2 - 1 \right\}^{\frac{1}{2}} + 1} \right\} e^T \right]$$

Head loss (H_L) calculated from this formula is plotted in comparison with the actual data points (Appendix Fig. A-1). The agreement is not complete, but this model may be helpful in predicting filter performance prior to field tests as well as in providing aid in the evaluation of actual data.

While considering media for the filter, one can determine through laboratory testing $d\sigma/dt$ for different depths of material and at different times from the commencement of filtration. The coefficient A and constant B can be determined and from the results head loss can be calculated mathematically; thus the filter behavior at different depths of media under various operating times and environmental conditions can be predicted.



σ_u Specific Deposit

Appendix Figure A-3. Plot of specific deposit versus filter coefficient.