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THE UNIVERSITY OF ALBERTA

DISTRIBUTION OF TRIHALOMETHANES AND TOTAL ORGANIC CARBON IN PILOT SCALE GAC COLUMNS

by

© ROBERT C. ANDREWS

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled DISTRIBUTION OF TRIHALOMETHANES AND TOTAL ORGANIC CARBON IN PILOT SCALE GAC COLUMNS submitted by ROBERT C. ANDREWS in partial fulfilment of the requirements for the degree of Master of Science in Environmental Engineering.

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ABSTRACT

This thesis examined the loading distribution of trihalomethanes and total organic carbon within pilot scale granular activated carbon (GAC) contactors receiving finished drinking water and operating in the downflow mode. Three carbons originating from different sources were used for this comparison. Observed column loadings were compared to isotherms, and results predicted using the Polanyi-Manes adsorption potential theory. As well, loadings were evaluated as a function of carbon particle size.

Significantly higher loadings of trihalomethanes and total organic carbon were found in the upper 20% of the GAC beds. Isotherms successfully predicted full bed depth trihalomethane loadings for two of the carbons but underestimated loadings in the top 20%. Total organic carbon breakthrough curves exhibited the expected three distinct phases of adsorption, namely immediate low level leakage, a regular orderly breakthrough, and a pseudo steady-state plateau. For all carbons loadings were highest in the top one-third of the bed. Slow adsorption as opposed to biological activity appeared to be the governing removal mechanism. A replacement of the top 20% of the carbon in one of the beds resulted in enhanced adsorption of both trihalomethanes and total organic carbon.

A direct relationship was found to exist between particle size and adsorption capacity for trihalomethanes

and total organic carbon in stratified beds. Based upon mass transfer zone evaluations, shallow beds (<50 cm) with a predominantly small grain size (0.60-1.18 mm) should be optimal for removing trihalomethanes using the carbons tested. The Polanyi-Manes adsorption potential theory, which presents data in the form of isotherms, was useful in explaining the dependence of adsorption capacity on influent concentration, but was unable to predict preferential adsorption among trihalomethanes when compared to actual column loading results.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS USED IN TEXT

BAC	biological activated carbon
BV	bed volume
COD	chemical oxygen demand
DAI	direct aqueous injection
DOC	dissolved organic carbon
GAC	granular activated carbon
GC/FID	gas chromatography/flame ionization detector
GC-MS	gas chromatography - mass spectrometry
MPD	mean particle diameter
MTZ	mass transfer zone
MW	molecular weight
NPTOC	non-purgeable total organic carbon
OX	organic halogen
PAC	powdered activated carbon
THM	trihalomethanes
TOC	total organic carbon
TON	threshold odour number
TOX	total organic halogen
TTHM	total trihalomethanes
TTHMFP	total trihalomethane formation potential
UV	ultraviolet

1. INTRODUCTION

Potable water for the cities of Regina and Moose Jaw, Saskatchewan, Canada is drawn from Buffalo Pound Lake. This is a shallow prairie lake which often has high total organic carbon concentrations in the summer period, and blooms of blue-green algae. This condition has led to severe taste and odour problems in the finished water during most summers.

Present treatment at Buffalo Pound consists of addition of potassium permanganate (only during algae blooms), pre-chlorination past the breakpoint, coagulation with aluminum sulphate and an anionic polymer coagulatant aid, flocculation and sedimentation in upflow Graver-type clarifiers equipped with plastic tube settlers, pH adjustment with soda ash, and mixed media rapid gravity filtration. Capacity at the Buffalo Pound plant is 136 ML/day.

Under average summer conditions the plant normally produces a finished water with low turbidity (0.2 - 0.4 NTU) and colour (<5 Pt/Co units), but a high threshold odour number (5 - 15), fairly high total organic carbon levels (4 - 8 mg/L) and appreciable trihalomethanes (80 - 150 µg/L).

Attempts to find a method of treatment for trace organic substances and the desirability of a broad spectrum removal process for pesticides and algae toxins, led to extended in-house studies of granular activated carbon (GAC) in the late 1970's. Subsequently, a consultant's study in 1980 examined many different treatment alternatives and concluded that GAC contactors after full treatment were the best solution for the taste and odour problem (CH2M/Hill, 1980). However, the occurrence or removal of specific organic compounds in the water was not addressed.

During the summer and fall of 1982 research was conducted at the Buffalo Pound Water Treatment Plant to examine the removal of trihalomethanes from finished water using pilot scale GAC columns (Andrews et al., 1983). Focusing on the distribution of volatile organics in a single pilot column, this work served as background to more detailed research presented in this thesis. The latest study conducted during the spring and summer of 1984 specifically examined the loadings of trihalomethanes and total organic carbon in pilot scale GAC columns which differed in carbon type and depth.

2. LITERATURE REVIEW

2.1 USE OF GAC IN WATER TREATMENT

Activated carbon is finding increased use in drinking water treatment. While historically it has been used for taste and odour control, it has more recently been employed for removal of specific organic contaminants.

McCreary and Snoeyink (1977) discussed the major advantages of using powdered activated carbon (PAC) for controlling odour and colour derived organics. Granular activated carbon (GAC) was also considered as a treatment alternative since it was able to remove organic substances on a continuing basis. When used in a column or bed configuration GAC permitted higher adsorptive capacities to be achieved and easier process control than PAC.

Objectives of using carbon filtration at the Kralingen treatment plant in Rotterdam, The Netherlands included protection against occasional pollutants and toxic substances, removal of substances produced by chlorination, and removal of assimilable organic matter[1] produced by ozonation (Meijers et al., 1979). Schalekamp (1979) reported that the need for GAC filtration at the Lake waterworks in Switzerland was a result of phenol spills that contaiminated water

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[1] Assimilable organic matter is produced when ozonation partially oxidizes natural and anthropogenic compounds making them more susceptible to biological metabolism (Glaze, 1983).

supplies and adversely affected taste and odour. At the Davenport, Iowa water treatment facility algae blooms, upstream industrial pollution, agricultural runoff, and accidental spills caused chronic taste and odour problems. Conversion of 20 gravity sand filters to GAC resulted in significant taste and odour reductions (Blanck, 1980). Influent threshold odour numbers (TON) were reduced from 5.5 to <1. In addition, use of GAC helped reduce chlorine demand and allowed for easier maintenance of chlorine residuals.

Removal of purgeable halogenated orgnic compounds from groundwater using GAC was reported by Wood and DeMarco (1979). In this study it was discovered that the most economical use of GAC was on finished water. The installation of carbon at this point in the treatment system was not without problems however. All free chlorine added upstream was removed by the GAC which necessitated rechlorination prior to final discharge.

Recently there has been an increased awareness of the health significance of organic contamination. A report by DeMarco and Miller (1985) cites long term problems caused by carcinogens, mutagens and teratogens as primary focal points. Gas Chromatography using a flame ionization detector (GC/FID) capillary column profiles were found useful in interpreting the overall ability of GAC to remove a wide spectrum of organics. DeMarco and Miller (1985) noted that the use of this analytical method at a Cincinnati water treatment plant revealed the occurrence of at least two peaks in larger concentrations in the effluent than in the influent. This result indicated that despite the removal benefits of GAC, desorption of substances may occur during a decrease in the influent concentration. Organic halogen data (designated by the OX measurement collected in the same study) showed that GAC reduced OX concentrations but variations in effectiveness occurred during changing influent conditions.

van Puffelen (1983) stated that activated carbon is generally considered the best means for removing organic contaminants which cause toxicity and mutagenicity in drinking water. He stated that proving the effectiveness of activated carbon is difficult however, since there is no reasonably quick method for measuring the toxicity of the substance being treated. The Ames test, which measures the ability of a histidine-dependent strain of bacteria to revert to histidine-independence appeared to offer good possibilities in determining mutagenicity. Specific details concerning this have presented by Kruithof and Meijers (1983). They initiated investigations to attempt to develop operational guidelines for GAC based upon the toxicity of finished water. Activated carbon in granular form has proven to be more effective than powdered carbon for the removal of chronic toxicity and mutagenicity (van Puffelen, 1983). This author also stated that the removal of organic contaminants which cause chronic toxicity and mutagenicity are the primary objective of activated carbon in The Netherlands.

The American National Academy of Science (NAS) has published a review of the use of activated carbon for drinking water treatment (Suffet, 1980). The report outlined six major areas of importance concerning the use of GAC as follows:

- The adsorption efficiency of granular activated carbon
- The microbial activity on GAC
- The production of nonbiological substances by or within the GAC bed
- The regeneration of GAC
- The adsorption efficency of other adsorbents
- Analytical methods to monitor adsorbent unit processess in water treatment.

In sections that follow, several of these areas will be examined in detail to provide a background for research work conducted at the Buffalo Pound water treatment plant.

Suffet (1980) edited a compilation of information concerning chemicals of known health risks. His summary of known or suspected organic chemical carcinogens found in drinking water appears in Table 2.1.

2.2 EFFICIENCY OF GAC FOR VARIOUS TYPES OF ORGANICS

2.2.1 Biologically-Derived Odour

A review of information concerning GAC field installations suggests that odour breakthrough, probably of

Table 2.1 **Summation of Acute and Chronic Exposure Levels and Carcinogenic Risk Estimates of Organic and Inorganic Chemicals**

Chemical	Suggested No adverse Response Level (SNARL) - mg/L Exposure Period 24-Hour	 7-Day	 Chronic	Upper 95 Percent Confidence Estimate of Lifetime Cancer Risk Per µg/L*
Acrylonitrile				1.3×10^{-4}
Benzene		12.6		
Benzenehexachloride	3.5	0.5		
Cadmium		0.06	0.005	
Carbon tetrachloride	14	2.0		
Dichlorodifluoromethane	350	5.6		
1,2-Dichloroethane				7.0×10^{-7}
Epichlorhydrin	0.84	0.53		
Ethylene dibromide				9.1×10^{-6}
Methylene chloride	35	5.0		
Polychlorinated biphenyl	0.35	0.05		
Tetrachloroethylene	172	24.5		1.4×10^{-7}
1,1,1-Trichloroethylene	105	15		
Trichlorofluoromethane	88	8		
Toluene	420	35	0.34	
Uranium	3.5	0.21		
Xylenes	21	11.2		
Bromide	1400	224	2.3	
Catechol	2.2			
Chlorine dioxide			0.38	
Chlorite		0.21		
Chloroform	22	3.2		
Dibromochlormethane	18			
2,4-Dichlorophenol			0.7	
Hexachlorobenzene		0.03		2.9×10^{-5}
Iodide	115.5	16.5	1.19	
Resorcinol	11.7	0.5		

*Based upon human exposure and sublethal animal data

(source: Suffet 1980)

biological origin will follow breakthrough of general organic compounds (McCreary and Snoeyink 1977). Pilot scale studies by Forsyth et al. (1982) demonstrated similar results using three different types of GAC. McCreary and Snoeyink (1977) noted that the removal of odour can be successful for years whereas chloroform removal as indicated by chloroform extracted from the actual carbon may last only a few weeks.

Pilot plant evaluations conducted using GAC at the Amsterdam Municipal Waterworks in The Netherlands found that taste and odour causing compounds were removed effectively by all of the carbon brands tested (Kruithof et al. 1983). There was however, considerable difference in the removal of total organic matter among the carbons.

Ford (1973) evaluated the use of GAC for biologically derived taste and odour removal in a GAC pressure filter. Results were summarized chronologically as:

- A period of at least four months when even intense tastes are completely removed.
- A middle phase of about eighteen months when taste removal, although partial, is still effective in preventing consumer complaints.
- A final period when taste removal is still taking place, but where peaks of taste activity will produce breakthrough and consumer complaints.

Laboratory experiments to examine the adsorption of biological, causative agents of earthy-musty odours were reported by Herzing et al. (1969). Geosmin and 2-

methylisoborneol were found to be strongly adsorbed by GAC despite the presence of background natural organic matter.

2.2.2 Haloforms

In water treatment practise, small amounts of halogen-substituted single carbon compounds may be produced as a side reaction of disinfection of waters containing natural humic substances. The AWWA (1982) described a generalized reaction for the production of trihalomethanes:

Free Chlorine + Precursors (Humic Substances and Bromide) —> Trihalomethanes + Other Byproducts

Regulations governing trihalomethanes are usually concerned with the arithmetic sum of the individual compounds Thus "Total Trihalomethanes" (TTHM) include chloroform, bromodichloromethane, dibromochloromethane, and bromoform. Factors cited as influencing the generalized reaction include:

- Time
- Temperature
- Bromide and iodide concentration
- pH
- Concentration of precursors
- Chlorine dose and type (free or combined)

A complete discussion of the effect of each of these factors may be found elsewhere (AWWA 1982).

Rook (1976) investigated conditions for haloform formation and discussed the application of experimental data to practical water treatment. A mixture of CH_2Cl_2, CCl_4, $CHCl_3$, and $CHBr_3$ was continuously fed into identical 3 m deep GAC columns which varied only in contact time. Concentrations of individual compounds were in the range of 2-4 mg/L. When using a 12 minute contact time, breakthrough occurred after 22 days for $CHBr_3$; after fourteen days for CCl_4; after seven days for $CHCl_3$; and after two days for CH_2Cl_2.

In a report on pilot scale studies, Yohe et al. (1981) noted that chloroform comprised 79 to 94 percent of the instataneous TTHM measured at a Philadelphia water treatment plant. Sharp breakthrough of chloroform and chloroform precursors was noted immediately following startup in columns of 1 m GAC bed depth. Influent chloroform levels ranged from 71 to 176 µg/L, averaging 102 µg/L over the 14 week study period. Exhaustion was not observed to occur until approximately 9 weeks after startup. Cumulative mass loadings displayed a levelling trend as exhaustion was approached (Yohe et al., 1981; Cairo et al. 1979). In similar studies by Wood and DeMarco (1979) a continuous low level passage of chloroform was noted prior to major breakthrough at 28 days. This study utilized 1.5 m carbon bed depths and a contact time of 12.5 minutes.

Bromodichloromethane has been found to be more strongly adsorbed than chloroform in pilot scale studies (USEPA, 1980). In this study breakthrough and exhaustion occurred after 15 and 45 days respectively. Similar points for chloroform were reached after 8 and 23 days.

Cairo et al. (1979) evaluated the performance of carbon on the basis of mass loadings. Comparing different modes of operation, chloroform removal was 20% higher in a contactor than in a filter adsorber (where existing sand filters were modified to accept GAC media). The carbon in both columns was Filtrasorb® 300. In the same study, a carbon with smaller grain size (Filtrasorb® 400) was found to be more effective in removing the mass loading of chloroform than a larger carbon (Filtrasorb® 300) when both were operated in a similar contactor mode. Forsyth et al. (1982) reviewed chloroform cumulative mass loadings and found that loadings in the range of 0.42 to 1.6 mg/g of GAC would be expected at column exhaustion.

An examination of mass loading with respect to depth was presented by the USEPA (1980). Expressed on a per gram of GAC basis chloroform loadings increased with depth, whereas bromodichloromethane loadings did not appear to change significantly. Average chloroform and bromodichloromethane influent concentrations were 67 µg/L and 47 µg/L respectively.

2.2.3 Removal of Precursors

Removal of precursors of THM were examined by sampling humic substances from three geographically different areas of Massachusetts (Joyce et al. 1984). Various molecular weight fractions of fulvic acid from soil and water were analyzed for carbon and chlorinated to produce THM. The study results indicated that the molecular weight (MW) distribution of fulvic acids can be an important factor in precursor removal.

McCreary and Snoeyink (1977) stated that activated carbon can reduce the level of total organic matter in water. Removal of organic matter is particularily important in applications where the purpose of the carbon is to reduce the level of haloform precursors. Yee and Snoeyink (1980) stated that the performance of a carbon bed for adsorbing humic substances in water depended primarily on three factors:

- The type of humic substance
- The characteristics of the carbon
- Pretreatment processes

Activated carbon adsorption of commercial humic and fulvic acid extracted from peat was evaluated in work presented by Lee and Snoeyink (1980). In this study, mass transfer coefficients obtained from batch kinetic tests were used in mathematical models to predict the performance of activated carbon in columns. Carbon characteristics evaluated included: the type of raw material, surface area, total pore volume, and pore size distribution. Pretreatment was limited to studying the effect of coagulation with alum prior to adsorption.

Edzwald (1984) demonstrated the use of surrogate parameters and indirect measures of THM precursors. UV adsorbance measured at 245 nm was found useful in estimating non-purgeable TOC (NPTOC) and TTHMFP (TTHM formation potential an indication of precursors) concentrations of raw waters and in monitoring both pilot and full scale plant performance. This method offers potential as a rapid, easy, and inexpensive measurement tool.

2.3 FACTORS AFFECTING ORGANICS REMOVAL BY ACTIVATED CARBON

Lee et al. (1981) examined factors which limited the effectiveness of carbon adsorption processes in removing humic substances and other types of organic matter fr natural waters. GAC pore size distribution was found to be a key factor affecting the adsorption process. Pore volumes in pores with a radius less than 7 x 10^{-9} m were found to be well correlated to the adsorption capacity for humic and peat fulvic acids having a MW less than 1000. A similar relationship existed between pore volumes with a radius less than 40 x 10^{-9} m and fulvic acids having a MW more than 50 000.

The rate of uptake of a given type of fulvic acid was examined by Lee and Snoeyink (1980). Lower MW fractions achieved higher rates than the higher MW fraction. The presence of small amounts of higher MW fractions controlled the uptake rate of unfractionated peat fulvic acid. Weber et al. (1983) reported the dependence of adsorption on pH, initial concentration of humic material, carbon dosage and particle size, and levels of various inorganic ions in solution. The findings from their study are presented in Table 2.2.

Zogorski and Faust (1978) investigated the influence of various operating parameters on the removal of phenols from water by fixed GAC beds. Results indicated that the height of the mass transfer zone varied directly with:

- An increase in the linear velocity of the fluid
- An increase in the size of the adsorbent, especially for particle sizes greater than 0.65 mm
- pH when the value exceeded the pK_a value of the adsorbate

The rate of movement of the mass transfer zone was independent of the particle size and depth of the adsorbent within the contactor. The type of adsorbent, initial adsorbate concentration, linear velocity, and pH values above the pK_a for the adsorbate were found to influence significantly the rate of adsorbent utilization.

2.4 PRETREATMENT EFFECTS ON ADSORPTION PROCESSES

Summaries regarding the effects of various pretreatment methods are presented elsewhere (Suffet 1980; McCreary and Snoeyink (1977). In general, treatment prior to carbon adsorption is directed to the reduction of adsorbable organic

Table 2.2 **Factors Affecting the Adsorption of Humic Substances by Activated Carbon**

Factor	Nature of Effect	Extent of Effect
Activated carbon type	Increased adsorption for larger-pore-size carbons	Significant
Carbon particle size	Increased adsorption by smaller particles	Substantial
pH	Increased adsorption at lower pH	Significant in neutral range; substantial at lower pH
Ca^{2+}	Increased adsorption with increasing Ca^{2+} concentration	Substantial
Mg^{2+}	Same as Ca^{2+}	Slightly less than Ca^{2+}
K^+	Increased adsorption with increasing K^+ concentration	Significant but far less than Ca^{2+} and Mg^{2+}
Na^+	Same as K^+	Slightly less than K^+
Al(III)	Decreased adsorption with increasing Al(III) concentration	Slight to none
Fe(III)	Same as Al(III)	Significant to none

(Source: Weber et al., 1983)

matter. Lowering the organic concentration reduces the rate of column exhaustion and corresponding GAC regeneration frequency, decreases competitive adsorption, and lowers demand for disinfectant that could form undesirable end products (Suffet, 1980). Characteristics of organic compounds may also be altered thus making them more amenable to removal by biological activity in carbon beds (McCreary and Snoeyink, 1977).

2.4.1 Chemical Coagulation

Water treatment plants employing activated carbon usually pretreat the water by chemical coagulation with metal salts for turbidity or by lime-soda softening for the removal of hardness. Randtke and Jepson (1981) carried out coagulation experiments to explore the removal mechanisms for various organics. These results aided in the selection of chemical dosages and coagulation conditions for subsequent experiments designed to investigate changes in the adsorptive capacity of activated carbon for TOC. A pH of 6.0 was selected for the majority of experiments based upon previous investigations. Lower values of pH did not significantly increase removal. Organic substances including humic and fulvic acids from five sources were found to be effectively removed by coagulation using alum or ferric sulfate. The predominant removal mechanism was the precipitation of insoluble organic - aluminum complexes. Significant increases in the adsorptive capacity of remaining TOC were evident following this type of pretreatment. The removal of either strongly or weakly adsorbing organic molecules was not preferentially influenced by either coagulation or softening.

Semmens and Field (1980) stated that the most important variables influencing organics removal by alum were alum dose and pH. The study concluded that optimum conditions for organics removal differed from optimum conditions for turbidity removal. Organics removals increased when alum dosages exceeded those normally used for turbidity removal. Similar findings were reported by Kavanaugh (1978) during investigations of modified coagulation techniques.

Kavanaugh (1977) presented data concerning the effect of iron pretreatment on carbon adsorption. Results indicated that coagulation with iron may reduce the adsorption capacity of carbon for tannic acid. Pore blockage was the main reason stated for this behavior.

Research conducted by Yee and Snoeyink (1980) demonstrated that the service time of a carbon bed could be extended significantly when humic substances were partially removed by alum coagulation before carbon adsorption. Findings of isotherm studies using Filtrasorb® 400 matched results of column studies and indicated that adsorption of fulvic acid could be increased three times using alum coagulation over that obtainable without pretreatment. Application of a computer model developed by Crittenden and Weber (1978) provided evidence that the model could accurately describe the adsorption of peat fulvic acid remaining after coagulation in column experiments. The Buffalo Pound water treatment plant employs the use of coagulation with alum and an anionic polymer. This treatment step could provide benefits to subsequent carbon adsorption by reducing influent concentrations of humic substances and thereby increasing bed service time.

2.4.2 Chlorine and Chlorine Dioxide

McCreary and Snoeyink (1977) suggested that prechlorination may enhance adsorption of particular substances by rendering them more insoluble. However, a review of the literature by Suffet (1980) indicated that removal of organics via biodegradation due to microbial growth on GAC may be hampered by prechlorination. Also identified was the need for further research to identify the end products of reactions between activated carbon and chlorine or chlorine dioxide. Using a computer model Suidan et al. (1977) investigated the effect of pH and temperature on the reaction between free chlorine and activated carbon in batch and packed bed reactors. The model was based upon both surface reaction and pore diffusion as rate limiting steps and accounted for the reduction in reaction rate owing to the buildup of reaction products on the carbon surface. The effect of the presence of organic compounds on the rate of uptake of free chlorine was not determined since the research evaluated only pure solutions. The rate of uptake of free chlorine was considered difficult to evaluate because of the wide variety of organic compounds and the possibility of free chlorine reacting with adsorbed and nonadsorbed organics.

A system using pre- and post-chlorination was compared to one using pre-chlorine dioxide and post-chlorine disinfection in a study by Lykins and DeMarco (1983). Chlorine dioxide was found to be an effective disinfectant as well as allowing a 30-40% reduction in THM precursors as indicated by a measure of TTHM formation after 3 days of storage. Up to 80% of the remaining precursors were removed by subsequent GAC treatment. This removal value was sightly higher than for prechlorinated water, but bed exhaustion times were found to be similar.

McCreary and Snoeyink (1981) applied a solution containing chlorine and humic substances partially reacted with chlorine to a GAC column. No additional chloroform or TOX[1] species were found to be formed from unreacted humic acid which suggested that the chlorine residual had been chemically reacted by the GAC. A TOX mass balance confirmed this observation since no additional mass of organochlorine compounds was produced. Results of this type are significant since these compounds are usually considered a potential health risk and are often resistant to biological degradation.

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[1] Total Organic Halogen (TOX) is a measure of organically bound halogen.

2.4.3 Ozone

Rice et al. (1978) presented an excellent review on the status of ozonation prior to GAC. The review focused on current European trends involving the use of ozone in water treatment plants. Use of ozonation before GAC treatment eliminated the need for breakpoint chlorination and allowed ammonia to be removed biologically. A pilot scale evaluation of ozone-GAC combinations for THM precursor removal has been described by Glaze et al (1983). Low doses of ozone alone were found to be ineffective for reducing THM precursor (5-15% reduction of THMFP). However, for ozonated water followed by GAC treatment, removals of TOC continued long after times obtained using GAC only. Data indicated that bacteria plate counts increased upon passing ozonated water through the GAC columns. This suggested that biomass accumulations could not be attributed only to filtration effects but rather to a proliferation of several species of bacteria since effluent total plate counts fluctuated instead of consistently increasing with time. Glaze (1983) noted in summary that ozonation partially oxidizes natural and anthropogenic compounds which makes them more susceptible to biological metabolism on GAC filters. DiGiano (1983) cites possible disadvantages of using preozonation including the reduced adsorbability of organic matter when measured by TOC or UV absorbance. A reasonable explanation is the production of more polar byproducts which tend to be less adsorbable.

Snoeyink (1983) suggested that the use of ozonation prior to GAC adsorption results in biological oxidation on the carbon thus minimizing problems with biological slimes in distribution systems.

2.5 BIOLOGICAL ACTIVITY IN GAC BEDS

A comprehensive discussion of biological processes in GAC filters was presented by van der Kooij (1983). The following process parameters were determined as having some influence on the colony counts observed in GAC filtrates:

- Running time
- Empty-bed-contact time and apparent linear velocity
- Backwashing
- Water composition (as determined by type of raw water and extent of pretreatment) and temperature
- Filter material (including carbon type and depth)

van der Kooij states that heterotrophic microorganisms adsorb organic compounds and utilize them partly for synthesizing new cell material (assimilation) and partly to meet the energy needs of the cell (dissimilation). A measure of oxygen consumption in relation to removal of dissolved organic carbon (DOC) and chemical oxygen demand can serve as a measure of the biological activity in GAC filters.

Biological activated carbon (BAC), is sustained by the deliberate introduction of dissolved oxygen to maintain aerobicity of bacteria just before water enters GAC beds

(Rice et al., 1978). The source of the oxygen may be from the direct addition of oxygen or ozonation. The following advantages of using preozonation followed by GAC adsorption were presented by Rice, et al., (1978):

- More effective removal (up to 200%) of dissolved organics from solution by the BAC;
- Increased capacity of the carbon to remove organics (by a factor of about 10);
- Increased operating life of the carbon columns before having to be regenerated (up to 3 years), especially if the GAC can be kept free of halogenated organics;
- Biological conversion of ammonia in the GAC columns;
- Use of less ozone for removing a given amount of organics than using ozonation alone (BAC is cost-effective over ozonation in removing dissolved organic carbon); and
- Filtrates from BAC columns in drinking water plants can be treated with small quantities (0.1-0.5 mg/l) of chlorine or chlorine dioxide, which produces drinking water of acceptable bacterial quality (zero fecal coliforms) and provides a residual disinfectant for distribution systems.

The preceeding are maximum advantages and are not always achieved. Neukrug et al. (1984) evaluated the effectiveness of ozone-GAC in a Philadelphia conventional water treatment process. Long ozone-water contact times and high gas-to-liquid ratios were required to achieve desired oxidation and disinfection. TOC removal following preozonation displayed an increase in GAC performance only after long service times (exceeding 100 days). Breakthrough of volatile halogenated organics occurred earlier for ozone-GAC systems than for GAC alone possibly because of low molecular weight organics produced by ozonation competing more strongly for available adsorption sites.

DiGiano (1983) stated that biodegradation increases in importance as the adsorptive capacity of the GAC becomes exhausted. At this time substrate concentrations begin to build in the fluid phase adjacent to the biofilm in the carbon particles. The movement of biodegradation in a downflow bed is shown in Figure 2.1. Typical breakthrough curves with and without biodegradation appear in Figure 2.2.

In treatment studies of the Delaware River, four parameters were used to determine the microbiological quality of a GAC system (Cairo et al., 1979). These included the membrane filter total coliform test, standard plate count test, biochemical identification of bacteria, and scanning electron microscopy. The major purpose was to determine the levels of coliforms and bacteria in the adsorber effluents and changes in these levels over time. Bacterial levels in the effluents were found to decrease and level off only after the population in the adsorber had become established and reached a pseudo steady-state situation. The most predominant bacteria were identified as belonging to the genus *Pseudomonas*.

FIGURE REMOVED DUE TO UNAVAILABILITY
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Figure 2.1 Depiction of Three Zones of Activity in Activated Carbon Adsorbers When Microbial Activity is Significant

At Time 1, microbial activity has not developed because the substrate concentration external to the carbon particles is still low. At Time 2, biodegradation is increased in the upper region where substrate is available. The exhausted zone below will soon become bio-active; the adsorption zone has been forced lower in the bed as exhaustion occurs. At Time 3, breakthrough of organic compounds, due to exhaustion of adsorption capacity, begins. Breakthrough will not be complete because the biodegradation zone will increase and account for a final steady-state removal condition.

(Source: DiGiano, 1983)

FIGURE REMOVED DUE TO UNAVAILABILITY
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Figure ~~2.2~~ Predicted Effluent [illegible]centration as a Function of Service Time Using a GAC Bed

(Source: DiGiano, 1983)

A report by the AWWA (1981) suggested that more research under controlled conditions must accompany laboratory, pilot, and full scale tests to provide a deeper understanding of microbial activity before design recommendations can be made.

2.6 MONITORING GAC BEDS

Appropriate monitoring techniques must be applied to ensure good organic removals and to indicate the quality of water produced. The need for regeneration or replacement of a GAC bed may also be determined by monitoring for a particular compound or group of compounds (McCreary and Snoeyink 1977). Threshold odour commonly used as a monitoring parameter may prove inadequate in describ[illegible] total organic removal. For instance, breakthrough of TOC has been found to occur much earlier than threshold odour in pilot plant studies (Forsyth et al., 1982). McCreary and Snoeyink (1977) suggested that the parameters of COD, TOC, UV intensity in the range of 240-255 nm and fluorescence intensity could be used as indicators of total organic content. The easiest measurements to make, absorbance and fluorescence, however were observed to have drawbacks since the processes used to remove organics will selectively remove certain fractions of organics changing the UV absorbance or the fluorescence to TOC ratio. Edzwald et al. (1984) in a discussion of the use of surrogate parameters suggested that

UV absorbance was excellent for estimating full scale water treatment plant concentrations of non-purgeable TOC (NPTOC) and THM precursors. Despite the varying treatment conditions of pilot plant studies, UV (254 nm) absorbance was found to be useful for predicting NPTOC and TTHMFP.

A study by Kruithof et al. (1983) used UV (254 nm) absorption to evaluate pilot plant studies in Amsterdam. To reduce displacement of substances already adsorbed and guarantee adsorption of toxic substances it was suggested that a certain residual capacity (e.g. 20% UV extinction) be maintained on the carbon filters.

A review of analytical methods used to monitor adsorbent unit processes emphasized the need to monitor the variability of influent organic compounds (Suffet, 1980). Monitoring of influent species type and concentration would assist in the assessment of competitive and re-equilibration effects noted in effluents. Chromatographic profiles of influents and effluents could be used to evaluate treatment performance following GC-MS confirmation analyses. GC analysis may then be used alone where defined concentration limits for pollutants have been established.

Suffet (1980) noted the need for acquiring information regarding the mutual reduction in adsorption capacity for competing organics in multicomponent mixtures encountered in drinking water treatment. He suggested that pilot studies would be necessary to confirm the relative order of breakthrough of each contaminant, and to assess the importance of displacement effects caused by a variable influent concentration and competitive adsorption. In recent studies, (Summers and Roberts, 1983) chloroform has been used as a conservative indicator of the behavior of organic contaminants in GAC beds containing Filtrasorb® 300. Chloroform breakthrough and saturation was found to occur earlier than specific organic or collective parameters. Monitoring the removal of chloroform may therefore provide reasonable assurance that other hazardous compounds have been removed as well.

Alben and Shpirt (1983) examined distribution profiles for various volatile organics and organic acids on GAC using four pilot columns operated in series. From the profiles it was possible to construct a case history for GAC saturation and evaluate chromatographic displacement within the pilot scale bed. Although localized depletion of chloroform was noted at the inlet of the system after 26 weeks of operation, other compounds less volatile than chloroform were noted to be concentrated in this same region. Results presented in Figure 2.3 show cumulative adsorption profiles of TTHM which were found to closely resemble chloroform trends. Using this profile it was possible to verify the actual occurrence of chloroform displacement.

Monitoring ports spaced at intervals of 120 cm along the bed depth provided evidence for TTHM displacement but the effluent's response to fluctuations in influent THM levels was obscured. Sampling ports spaced 20 cm apart were

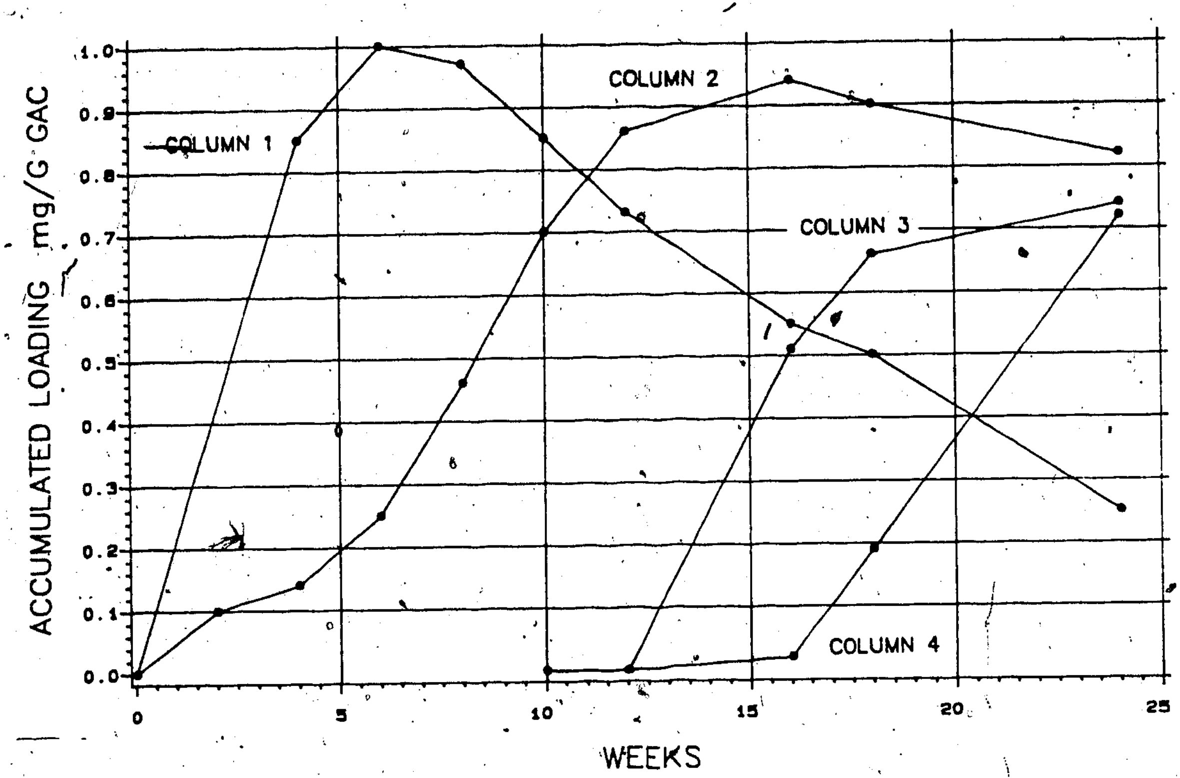

Figure 2.3 Cumulative Adsorption of TTHM on Series Pilot Columns 1-4

(Source: Alben and Shpirt, 1983)

recommended for detailed dynamic THM adsorption studies. To establish breakthrough curves, corresponding distribution profiles and subsequent evidence for displacement, weekly sampling was suggested as a minimum.

The pilot study at the Buffalo Pound water treatment plant incorporated these suggestions in the original design. Monitoring ports were installed at 10 cm intervals along GAC bed depths and most analyses were conducted bi-weekly.

3. RESEARCH OBJECTIVES

As is evident from the literature review, granular activated carbon is well known as an effective means of reducing the concentrations of volatile organics and total organic carbon in drinking water. A deeper understanding of loading characteristics of these compounds in pilot scale GAC columns and an examination of predictive theories would aid in the development and operation of a full scale system.

The study conducted at Buffalo Pound had five main objectives:

1. To determine the loading distribution of trihalomethanes and TOC in pilot-scale GAC columns of varying depths and carbon type. This was accomplished by monitoring liquid phase concentrations of sampling ports spaced at 10 cm intervals of bed depth.
2. To assess the effectiveness of a partial bed replacement on specific compound removal efficiency and loading characteristics.
3. To evaluate the effect of carbon grain size in GAC beds on trihalomethane and TOC adsorption.
4. To determine the usefulness of adsorption isotherms in predicting column loading behavior.
5. To examine competitive adsorption effects qualitatively by applying the Polanyi-Manes adsorption theory to compare actual adsorption occurring in isotherm and column tests to that predicted for single compounds in pure water.

3.1 EXPERIMENTAL PLAN

The 88 day study conducted during the summer of 1984 was divided into three main phases (Table 3.1). In all three phases samples of plant finished water (column influent) and monitoring port effluents were routinely collected. These samples formed the basis for evaluation of all pilot scale GAC experimentation.

Phase 1 (61 days)

Phase 1 examined column influent and monitoring port effluent characteristics of Columns A, B, CA, CA+CB, and S. This portion of the study allowed the performance of 3 carbon types and varying bed depths to be directly compared under identical operating conditions. Initially Ports 1 and 3 were monitored more frequently than Ports 5, 10, and 15 to enable collection of detailed breakthrough data in the upper column segments.

Phase 2 (27 days)

In Phase 2 the top 31 cm of carbon was replaced with virgin carbon in Column CA. This replacement occurred after TTHM removal efficiencies had decreased to 30% when measured as column effluent (Port 15). The entire 30 cm bed of Column S was replaced to provide a parallel comparison. No changes were made to Columns A or B which continued to provide comparative data.

Phase 3 (88 days)

Phase 3 involved conducting isotherm tests where time permitted. Additional isotherm analyses were conducted following the completion of Phases 1 and 2.

Table 3.1 Experimental Design Phases

	Duration	Activity	Objectives
PHASE 1	61 days	- Parallel operation at Columns A, B, CA+CB, and Column S - Collection and analysis of influent and intermediate port effluent samples	(1)
PHASE 2	27 days	- Carbon replacement in Columns CA and S - Continued parallel operation of Columns A and B - Collection and analysis of influent and intermediate port effluent samples	(2), (3)
PHASE 3	88 days	- Isotherm experiments - Grain size distribution analyses	(3), (4), (5)

4. EXPERIMENTAL METHODS AND PROCEDURES

4.1 ADSORPTION ISOTHERMS

The carbon used in isotherms was from the identical lot used in the pilot scale columns. A general consensus points to the use of pulverized or powdered carbon for batch isotherm experiments using GAC (Arbuckle, 1980; Fochtam and Dobbs, 1980; Singer et al., 1980; USEPA, 1979). The use of pulverized material minimizes variations in results due to particle size and allows equilibrium to be achieved faster. For isotherm tests the carbon was pulverized using an Oster blender at maximum speed for a period of 120 seconds.

Varying carbon dosages from 0.01 g/L - 0.02 g/L and 0.05 g/L - 0.5 g/L were weighed into 500 mL and 150 mL bottles respectively. Following this, 2.0 mL and 6.7 mL of distilled water which had been passed through a Gelman I water purifier was added to the 150 mL and 500 mL bottles respectively. The carbon was then allowed to wet for a period of 42 - 66 hours. Upon filling each bottle with column influent, sufficient sodium thiosulfate was added to destroy up to 6 mg/L of free chlorine. After filling with sample such that no head space was remaining, the bottles were covered with an aluminum foil seal, plastic screw cap, and a further parafilm seal on the outside of the cap. Youssefi and Faust (1980) have suggested adding a phosphate buffer to maintain pH at a given value. This was not done in this study since previous studies (Andrews et al., 1983) had shown that initial pH values of 7.0 had varied only slightly in test samples, typically 0.1 pH unit. Immediately after filling the bottles a sample of column influent was analyzed for THM and pH. All bottles were agitated for a period of 24 hours using a Labconco roller apparatus. The 24 hour equilibration time was based upon equipment limitations and previous kinetic investigations by Andrews et al. (1983) which had shown that equilibrium for the major THMs was reached after 6 hours when using 30 x 40 mesh size GAC. Results obtained by Yosse[illegible] and Faust (1980) were in close agreement. When using pulverized GAC, stated equilibration times range from 2 hour[illegible]tman and Dobbs, 1980) to 4 to 7 days (Crittenden and Hand, 1983). The combination of a minimum 42 hour wetting period followed by 24 of equilibration was felt to address these requirements satisfactorily.

Following the agitation period, GC analyses were conducted on the control, followed by the bottle containing the highest carbon dosage. The analyses continued in order of decreasing carbon dosage, to minimize any effects of extending the contact period past 24 hours.

4.1.1 Freundlich Adsorption Isotherm

The Freundlich equation is generally used in water and waste water. This equation has been applied successfully by others (e.g. Youseffi, 1980) where GAC was the adsorbent under similar influent concentrations. The general form of the equation is:

$$\frac{X}{M} = KC_f^{1/n}$$

where: C_o = amount of organic compound in untreated solution

C_f = amount of organic compound in treated solution

$X = C_o - C_f$

M = weight of adsorbent

K = empirical constant

n = empirical constant

Estimates of K and n were obtained by plotting Log $\frac{X}{M}$ vs Log C_f and applying least squares to the following form of the equation:

$$\text{Log } \frac{X}{M} = \text{Log } K + 1/n \text{ Log } C_f$$

The structure of the Freundlich model ensures a high correlation between estimates of K and n - i.e. one parameter can be varied to compensate for a change in the other and give the same predicted value. For this reason, K values should not be compared without considering the corresponding n values. Although experimental designs for obtaining precise individual parameter estimates (e.g. Huck, 1984) can be readily applied to isotherm parameter estimation, this was outside the scope of the study.

Results from batch isotherm tests cannot be used to assess the affects of dynamic operating conditions upon adsorption. However, as suggested by Perrich (1981) properly designed isotherm experiments may provide estimates of:

- Carbon capacities and associated exhaustion rates
- Degrees of removal based on desired effluent objectives
- Preferential adsorption of component groups
- Comparisons of alternative carbons

When the Freundlich isotherm is applied to a set of data, the constants K representing the X/M intercept, and slope (1/n) may be used to describe adsorption characteristics. The K value represents the maximum capacity of the carbon (expressed as the weight of compound adsorbed per unit weight of carbon) for a compound at a given initial concentration C_o. A high K value indicates a large capacity. The slope of the isotherm (1/n) indicates the effect of concentration on adsorption capacity. A low slope reflects a high adsorbability where a small increase in the carbon dosage will cause a large decrease in the residual concentration. A high slope represents the converse. In general an isotherm which appears convex to the ordinate is favourable whereas a concave isotherm is unfavourable. The extremes of these cases are horizontal and vertical lines representing infinite and zero adsorbability respectfully.

4.2 PILOT SCALE GAC COLUMNS

The pilot columns used in this study were 2.4 m long by 15 cm inside diameter (Figure 4.1). The columns were of PVC material chosen for ease of handling and availability.

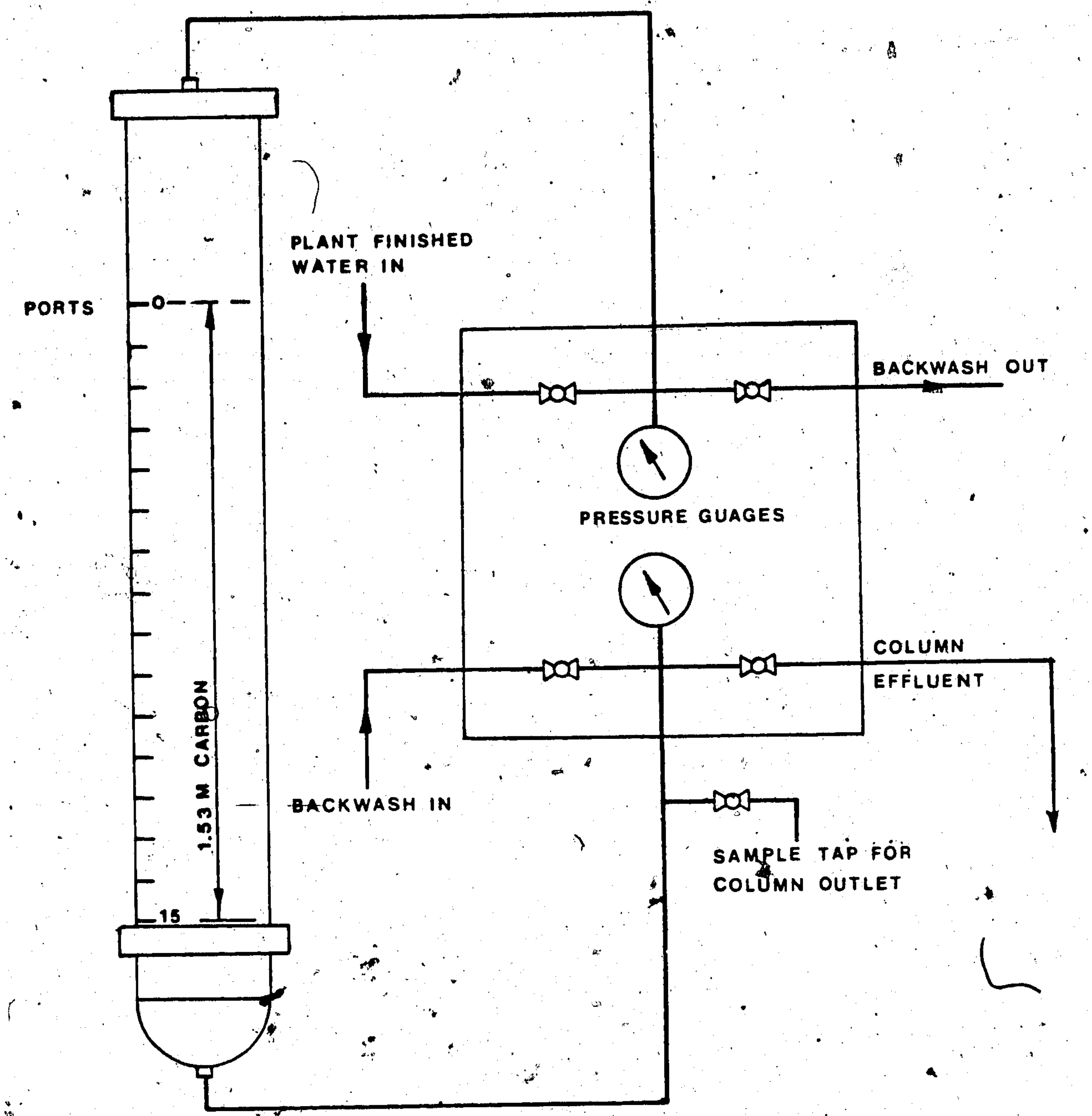

Figure 4.1 Typical Pilot Scale Column

Studies by Kreff et al. (1981) suggest that pilot scale columns constructed of PVC have an insignificant effect on levels of purgeable volatile organic compounds. Each of three identical columns (A, B, and CA) were filled to a depth of 153 cm with fresh carbon (Table 4-1). A fourth column designated "CB" was connected in series to receive the effluent of Column CA. This column was filled to the same depth as the others with the same carbon as in Column CA. A fifth column which was considerably shorter than the others (bed depth 31 cm) was designated "S". This column served as an isolated shallow bed allowing direct adsorption comparisons to be made to the top portion of a deeper bed (Column CA). After allowing the carbon to wet for a period of 24 hours, the columns were backwashed, levelled at approximately 153 cm and placed into service.

The flowrate of finished plant chlorinated water to each column was maintained at 3.5 mm/s which approximated normal sand filter throughput in summer months and was the design flow rate of the full scale GAC contactors. This flow provided an empty bed contact time of 7.3 minutes for Columns A, B, CA, CB, and 1.5 minutes for Column S. Stainless steel sampling ports, 7.5 mm ID projecting 5 cm into the column were provided at 10 cm intervals down the side of the column; stainless steel screens were incorporated into the ports. Ports designated as #1 and #3 represent bed depths of 10 cm and 31 cm respectively. Effluent samples for Columns A, B, CA and CB were collected near the bottom

Table 4:1 Granular Activated Carbons Used in Study

Carbon Name	Norit® Row 0.8 (Column A)	Witco® 950 (Column B)	Filtrasorb® 300 Columns (CA, CB & S)
Manufacturer	Norit	Witco	Calgon
Mesh Size	NA	8 x 30	8 x 30
Wetted Density kg/m^3	355	425	420
Surface Area m^2/g	NA	1000-1100	1000
Iodine No.	900	1050	900
Abrasion No. (Ro-Tap)	NA	NA	70-80
Ash Content %	6	1%	8
Average Pore Size (m x 10^{-9})	NA	0.5-3.0	1.0-2.0
Source	Peat	Petroleum	Bituminous

NA - Not Available

of the bed from ports designated A15, B15, CA15 and CB13 respectively. Plant finished water from the same source as column influent served as backwash water. The backwash procedure lasted approximately 10 minutes with flowrates varying between 3.6 mm/s and 10.8 mm/s. Samples of backwash effluent were collected routinely for visual examination to determine the type of matter present. At day 61 of the study period the top 31 cm of carbon was removed from Columns CA and S and replaced with fresh GAC to observe the effects of a 20% bed replacement. It should be noted that this replacement represented the entire bed in Column S.

4.3 ANALYTICAL

4.3.1 Trihalomethanes (THM)

Chloroform, bromodichloromethane, and dibromochloromethane concentrations were determined by gas chromatography on a Hewlett-Packard 5840A unit equipped with an electron capture detector following a method described by Nicholson et al. (1977). Sample volumes of 5 microliters were introduced by direct aqueous injection (DAI) into a 1.8 m by 6 mm in.) glass column, packed with Chromosorb 101. A carrier gas mixture of 5% methane in argon was used at a flowrate of 32.2 mL/min. The design of this study required that a large number of samples be analyzed daily on a routine basis. This precluded use of the more time consuming purge-and-trap method and dictated use of the DAI method.

The DAI method may yield concentrations slightly higher than the purge-and-trap method because of its measurement of both actual and potential trihalomethanes (Boyce and Hornig, 1983). However, in the context of this study, an increase of this type was not considered significant since most results were used for comparative purposes.

4.3.2 Total Organic Carbon

Total organic carbon concentrations were obtained from a correlation with UV absorbance, as described by Edzwald et al. (1984). Using a Beckman model 910 spectrophotometer UV absorbance was measured at 254 nm using a 10 cm path length on samples previously filtered through a 0.45 μm filter. TOC concentrations were then read from a calibration curve relating UV adsorbance to the theoretical TOC contained in a set of potassium hydrogen phthalate standards prepared with distilled water (Appendix A). It was recognized that the same set of standards would produce a TOC of approximately 1.2 mg/L higher when analyzed using a Beckman model 915B total carbon analyzer. This increase was attributable to TOC in the distilled water blank.

4.3.3 Standard Plate Count

Standard plate counts were conducted according to the Heterotrophic Plate Count method as outlined in Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WPCF, 1981).

4.3.4 Free and Combined Chlorine

Free chlorine residuals were measured on a Wallace and Tiernan Amperometric titrator at pH 7. A Fisher Model 397 chlorine titrator was used to measure combined chlorine residuals at pH 4.

4.4 DATA ANALYSIS

4.4.1 Computer Program GAC7

In order to simplify data analysis, all data points for monitored compounds were input to the computer program GAC7 (Appendix B). This program was written specifically for the Buffalo Pound GAC pilot study but may easily be adapted for use with any GAC study employing the use of column type contactors. Common design variables including column diameter, monitoring port spacing, carbon density, flowrate, and division of bed depth by segments may easily be adjusted as input variables. An Osborne I portable computer was used to facilitate both on-site data input in addition to office output and data analysis. The program was capable of performing the following manipulations for each pilot column:

- Tabulate input data.
- Calculate percent removal of a given compound at each monitoring port.
- Calculate accumulated segment loadings (mg) between designated monitoring ports based upon liquid phase concentrations.

- Calculate accumulated segment loadings (mg/g GAC) between designated monitoring ports.
- Tabulate test duration for each monitoring port.
- Calculate breakthrough times for each segment using linear extrapolation.
- Calculate total adsorbed (g) for each segment.
- Calculate percentage of total adsorbed by each segment.
- Calculate the average influent concentration (µg/L).
- Calculate the total amount of each compound entering the column during the test period.

All calculations could be updated on a day to day basis as new data were input to the program.

4.4.1.1 Breakthrough Calculations - Segment Basis

Each segment was considered as a distinct, separate area in the column. To calculate breakthrough in a particular segment the influent concentration (effluent concentration from the segment above) was compared to the effluent of the segment being evaluated. Since both levels were constantly rising, the breakthrough value (days) was defined as the time when 2% of the segment influent concentration appeared in the segment effluent. While this definition is somewhat arbitrary, the 2% value typically represented the detection limit for most compounds. In cases where the first data point was not obtained at day zero, an initial concentration of zero was assumed and projected to the first value. Breakthrough times calculated prior to the first data point were based on these linear extrapolations.

4.4.1.2 Breakthrough Calculations - Total Column Bed Depth

For purposes of examining the entire column, breakthrough was defined as the time when the effluent concentration monitored at the lowest port reached 2% of the column influent value. Thus, a column was viewed as one large segment (Ports 0-15).

4.4.1.3 Accumulated Segment Loading Calculations

Loadings at apparent exhaustion were calculated by dividing the net weight of a compound deposited in a segment by the weight of carbon in that segment. Loadings were calculated for each sampling interval and summed over the 88 day operating period. Thus a value of 1.39 mg/g for chloroform in segment 0-1 would represent the difference between the column influent concentration and the concentration at Port 1 multiplied by the flow to the column and divided by the weight of the carbon between the top of the column and Port 1. For segments which had not reached apparent exhaustion during the test, an extrapolated amount deposited after the end of the test was obtained by graphical integration. Methods used to determine both apparent exhaustion and extrapolated apparent exhaustion are discussed in section 4.4.2.

Loadings are thus based on differences in liquid phase concentrations and were not actually measured. Calculations assume no generation of THMs within the column.

4.4.2 Apparent Exhaustion and Extrapolated Loading Calculations

The time to reach exhaustion or "saturation" as defined by some workers is usually assumed to occur when the effluent concentration reaches some preselected fraction of the influent concentration. In cases where the influent concentration is fixed, a plot of effluent data usually resembles an S-shaped curve which asymptotically approaches the influent concentration. In a dynamic situation such as a water treatment plant, the influent concentration of a particular compound will usually vary constantly and may tend to follow seasonal trends. As a result, the classical S-shaped effluent concentration may not be obtained. Since adsorption is an equilibrium process an increase or decrease in adsorption capacity will result from a respective increase or decrease in influent concentration. The term "apparent exhaustion" is therefore used as an operational definition, representing a point where the effluent concentration has either reached or parallels the average influent concentration under varying influent conditions. Apparent exhaustion may therefore be used as an operational guide to define the active life of a GAC bed.

Apparent exhaustion times were determined by applying a linear least squares regression formula to the series of concentration data points extending upward from breakthrough to a point where they either intersected the average influent concentration or a plateau formed by a levelling of effluent concentration values. Successive data points were entered into the regression formula until a maximum correlation was achieved. The slope of the line was calculated and used to construct a line originating at breakthrough. Apparent exhaustion was denoted as the point where this line intersected an average concentration line. Extrapolated apparent exhaustion times are denoted in cases when actual exhaustion was not achieved during the test period. For these cases the average influent concentration obtained during the test period was assumed to continue until apparent exhaustion has been reached.

4.4.3 Graphical Data Presentation

In order to simplify data presentation, data points were plotted on a segment basis with respect to time for each column (unless otherwise stated). Plots have usually been divided in such a way that the upper portion of the bed may be reviewed in detail. To this end, segments 0-1 and 1-3 are plotted on a separate graph. Segments 0-5, 5-10, and 10-15 are plotted together to illustrate adsorptive behaviour of the three "main" column segments.

5. PRESENTATION AND DISCUSSION OF RESULTS

In the following section, Columns A and B will be compared in detail with respect to the removal and distribution of trihalomethanes and TOC. Specific results concerning bromodichloromethane and dibromochloromethane may be found in Appendicies C and D, respectfully. Comparisons will be drawn at both apparent exhaustion and at the end of the test period. As well, important observations will be presented as they occurred during the 88-day operating period. Results concerning Column CA will also be discussed but to a lesser degree. The purpose of this column was to evaluate the effect of a partial bed replacement on adsorption characteristics.

Concentration plots for individual compounds illustrate the breakthrough and apparent exhaustion characteristics when evaluated on both a cummulative and segment basis. Accumulated loadings expressed per gram of GAC allow comparisons among carbons of varying densities, and serve as a common base for comparison of all compounds. Appropriate tables have also been included to highlight distribution characteristics of individual compounds.

Results concerning headloss and chlorine removal will not be discussed in the text but are presented for reference purposes in Appendix K.

5.1 TRIHALOMETHANES

5.1.1 TOTAL TRIHALOMETHANES

5.1.1.1 Column A

Influent, effluent, and intermediate port adsorption data appear in Table 5.1 and Figures 5.1 and 5.2. The influent concentration during the 88-day study period averaged 92.2 µg/L showing an increasing trend. Breakthrough at Ports 1, 3, 5 and 10 occurred at days 0.1, 0.2, 0.4, and 1.1, respectively. At Port 15, breakthrough did not occur until day 13.5, corresponding to 2,654 bed volumes (B.V.). Apparent exhaustion in the lowest segment of the column (segment 10 - 15) occurred at day 77 (15,100 B.V.).

The adsorptive capacity expressed in mg/g GAC apparent at exhaustion was the highest in segment 0-1 at 2.97 mg/g GAC (Figure 5.3). Segment 1-3 immediately below displayed a much lower loading at 1.70 mg/g GAC. Considering the column as three equal segments (0-5, 5-10 and 10-15) the highest loading (2.23 mg/g GAC) at apparent exhaustion occurred in segment 5-10. Loadings obtained at the end of the test period increased in all segments as a direct result of the increasing influent concentration.

Extrapolations used to calculate apparent exhaustion assumed an averaged constant influent concentration. This allowed direct comparisons regarding loadings to be made among various bed segments. In actual water treatment plant

Table 5.1 TTHM Adsorption Data - Column A and Column B

Column A

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
		cm	Days	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.1	50.0	3338	5.0	1952	2.97
3	1-3	20.4	0.2	5[illegible].4	2432	1.85	2231	1.70
5	0-5	51.0	0.4	64.1	7413	2.26	5657	1.72
10	5-10	51.0	1.1	72.0	8325	2.53	7332	2.23
15	10-15	51.0	13.5	76.7	5125	1.56	4654	1.42

Average influent concentration: 92.2 µg/L
Total entering column during test: 44235 mg
Test duration: 88 days

Column B

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
		cm	Days	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.2	54.9	4500	5.72	3061	3.89
3	1-3	20.4	0.4	54.5	4022	2.55	3676	2.33
5	0-5	51.0	0.8	63.11	12406	3.16	10220	2.60
10	5-10	51.0	1.8	86.8	11055	2.81	10931	2.78
15	10-15	51.0	2.6	131.6*	8031	2.04	12074*	3.08*

Average influent concentration: 92.2 µg/L
Total entering column during test: 44234 mg
Test duration: 88 days
*Extrapolated value

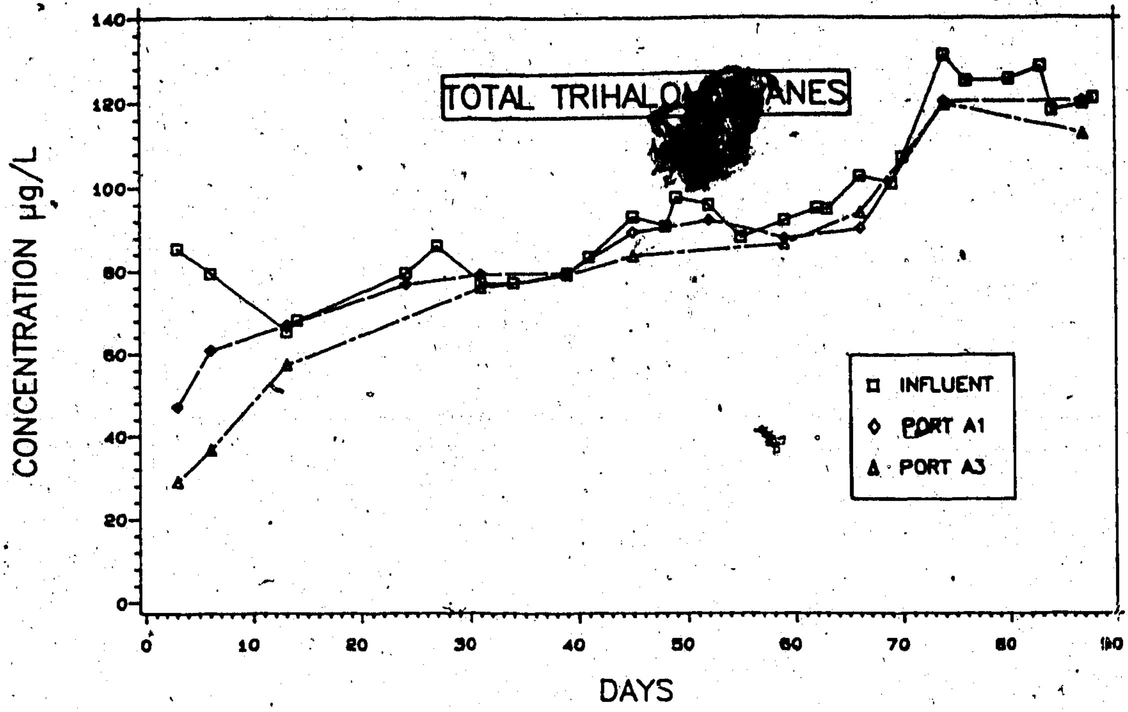

Figure 5.1 TTHM in Finished Water and Removal by 10 and 31 cm GAC (Column A)

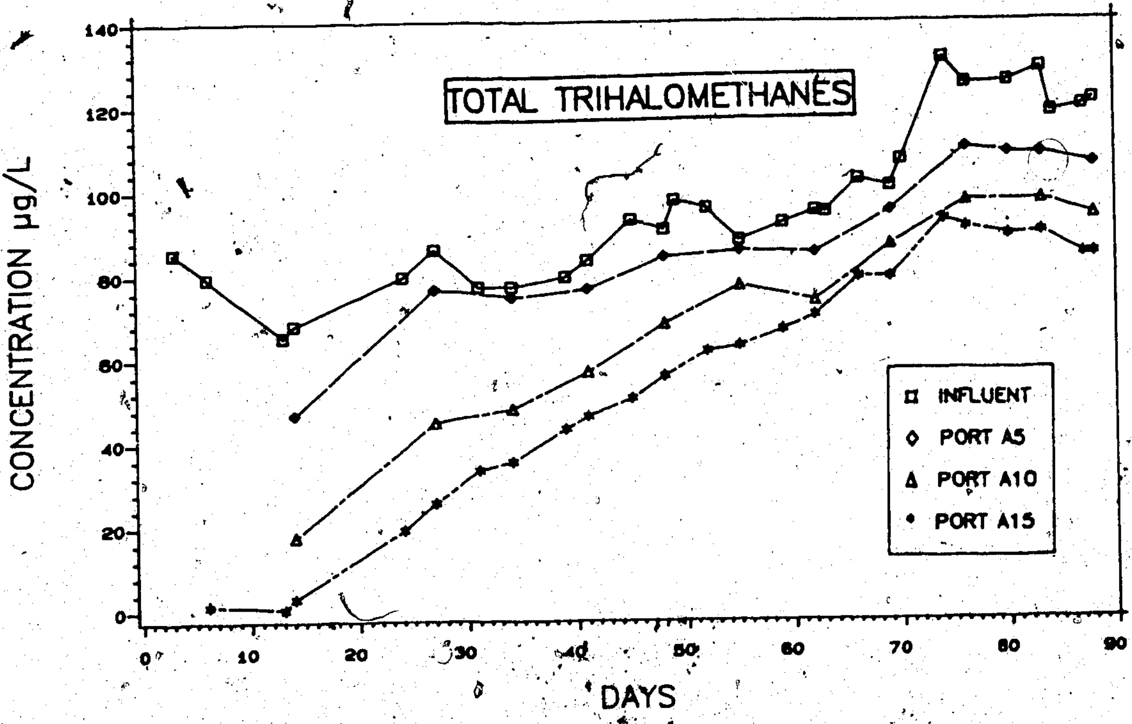

Figure 5.2 TTHM in Finished Water and Removal by 51, 102, and 153 cm GAC (Column A)

operation the influent concentration of a particular compound may follow seasonal trends. An example of this behavior is the increasing TTHM influent trend noted in Figures 5.1 and 5.2.

Immediately following startup, loading of the virgin carbon in the upper most segments appears very rapid (Figure 5.3. Once a levelling, albeit moderately increasing trend had been established (days 14 to 40, Figure 5.1) a similar leveling trend decreased rate of loading was noted in segment 0-1 loading presented in Figure 5.3. (Apparent exhaustion immediately follows this period for segments 0-1 and 1-3.) As the influent concentration increases dramatically from day 45 to the end of the study period, the loading in segment 0-1 increased. The loading in segment 1-3 displayed an increase followed by a decrease, while the loading in segment 0-5 showed a slow increase with time and appeared inhibited to respond directly. The slow loading trend of segment 0-5 is accompanied by the increase in adsorptive capacity of segment 5-10 following day 34 of the study period. The distance between the accumulated loading lines of segments 5-10 and 10-15 increased with an increasing influent concentration due to the high adsorptive ability of the middle segment.

On a more localized scale, once apparent exhaustion has been reached for Ports A1 and A3 (Figure 5.1), the TTHM levels at these depths roughly paralleled the fluctuations in the influent. At Ports A5, A10 and A15 plateaus are

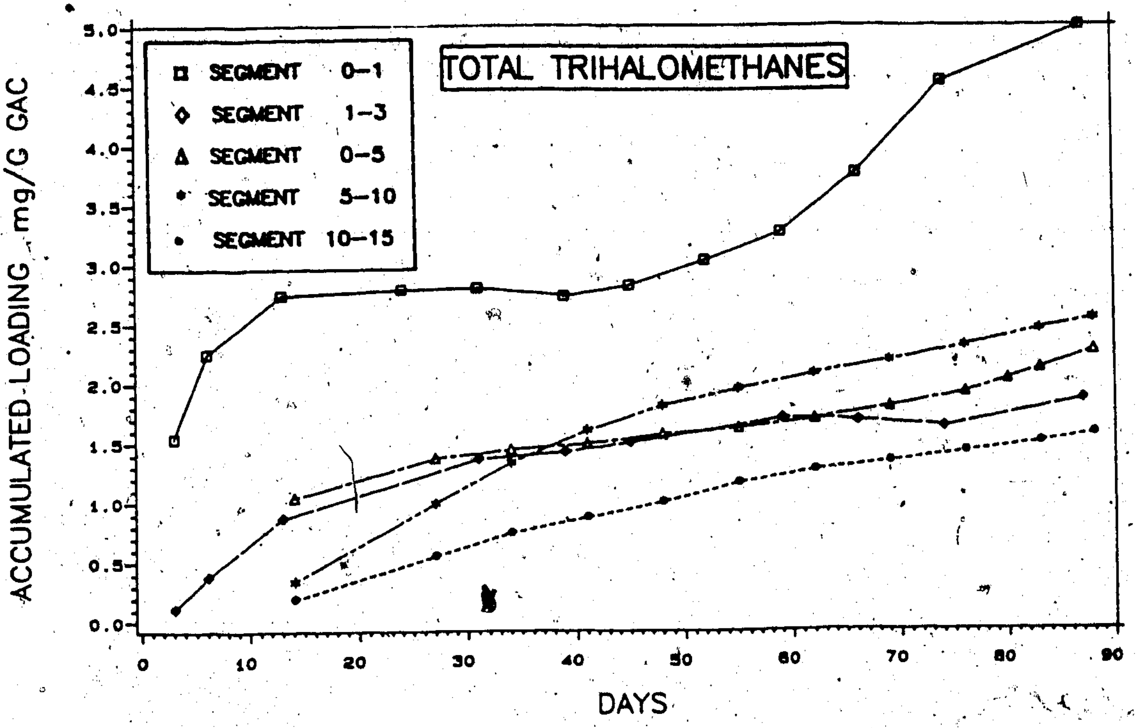

Figure 5.3 TTHM Accumulated in Column A

reached near the end of the study period as the influent concentration leveled off.

Of particular importance is the unusually high adsorptive capacity of segment 0-1. In this segment 7% of the total bed depth adsorbed 16% of the TTHM entering the column at the end of the test period.

5.1.1.2 Column B

The adsorptive capacity of Column B in general was higher than that of Column A as shown by data in Table 5.1. With the exception of segment 10-15 all breakthrough values were higher than for Column A. If sampling frequency had been increased in the early period of operation, this breakthrough value may have also been lower.

Concentration and accumulation profiles (Figures 5.4, 5.5, and 5.6) generally appear similar to those for Column A, but show higher removals. The predominantly high adsorptive capacity of segment 5-10 previously seen in Column A was not readily apparent in Column B (Figure 5.6). This may partly be attributed to the higher adsorptive capacity of the segment 0-5 above.

The effect of an increase in influent concentration on segment loading is shown in Figure 5.5 and 5.6. As influent concentration increased in the latter half of the study period, segment 0-1 adsorption increased whereas segment 1-3 showed an almost proportional decrease in loading rate. Since segments 5-10 and 10-15 did not reach apparent

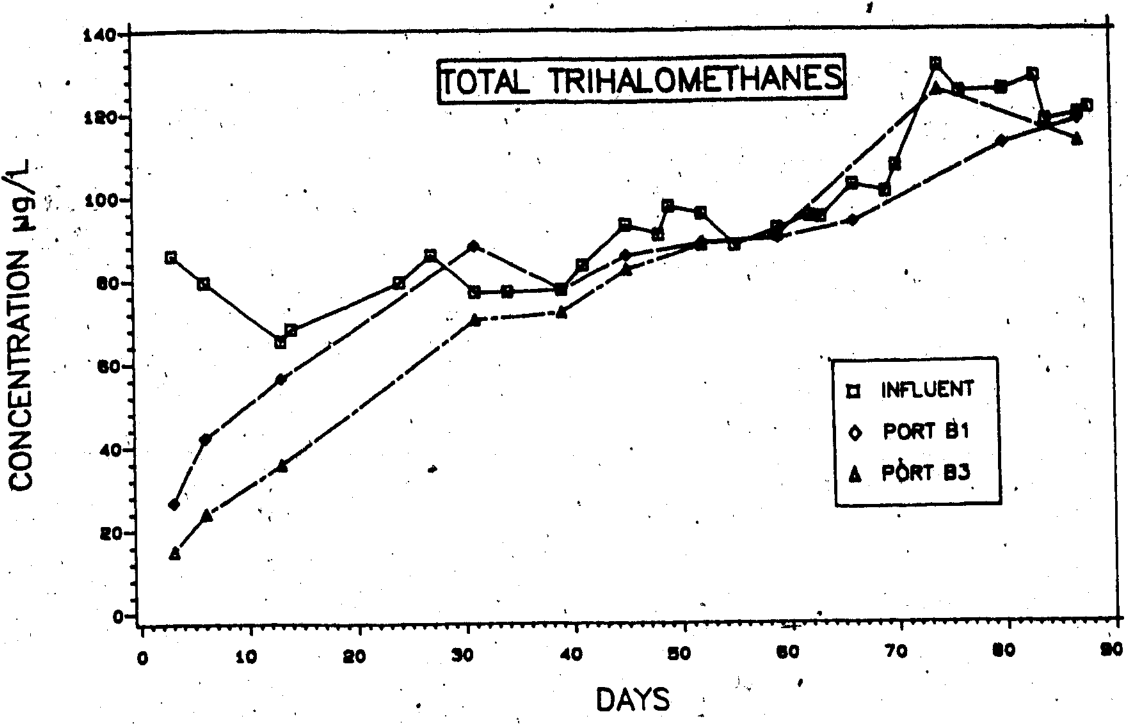

Figure 5.4 TTHM in Finished Water and Removal by 10 and 31 cm GAC (Column B)

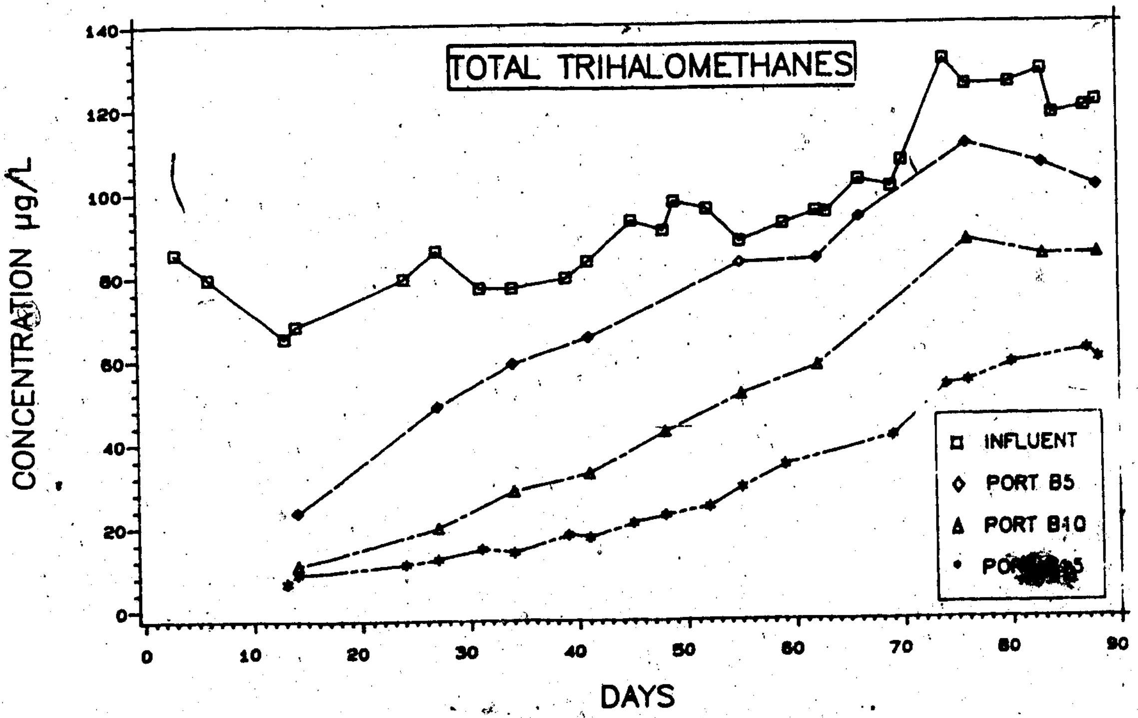

Figure 5.5 TTHM in Finished [illegible] and Removal by 51, 102, and 153 [illegible] (Column B)

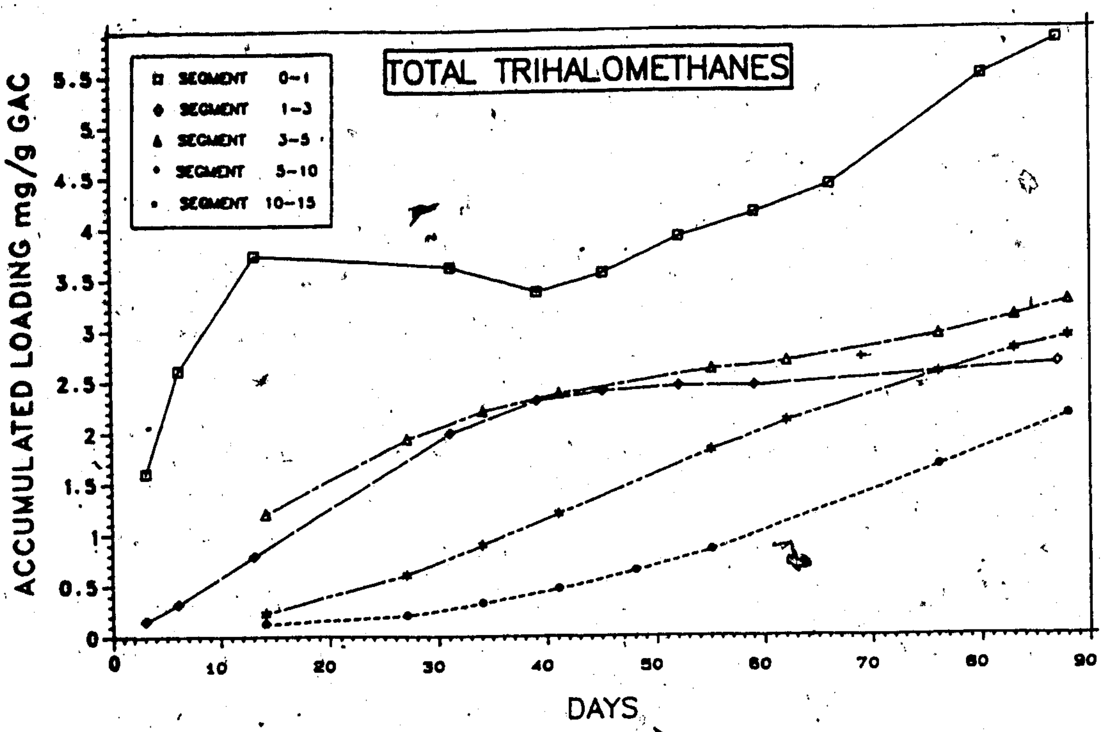

Figure 5.6 TTHM Accumulated in Column B

exhaustion until near or after the end of the study period there appears little if any influence of upper segments on lower segment adsorptive capacity.

At the end of the 88 day test period 39% of the adsorption taking place in the column occurred in the top 33% (segment 0-5).

5.1.2 CHLOROFORM

5.1.2.1 Column A

Results for the adsorption of chloroform appear in Table 5.2 and Figures 5.7, 5.8, and 5.9. The chloroform concentration during the 88 day study period averaged 54.1 µg/L and displayed a sharply increasing trend towards the latter half. This compound was the major contributor to TTHM, accounting for 59% of the total concentration. As a result, concentration and accumulation profiles were very similar to those for TTHM.

The effect of changing influent concentration on the adsorptive behavior of column segments is shown in Figure 5.9. Segment 5-10 displayed an increasing rate of accumulation immediately following an apparent exhaustive levelling trend in segment 0-5. This occurred during a period of low increase in the influent concentrations measured both as influent to the column, and influent to segment 5-10 (effluent of segment 0-5). A rapid increase ~~in~~ these concentrations following day 55 of the study period caused an increasing rate of accumulation in segment 0-5 and

Table 5.2 Chloroform Adsorption Data - Column A and Column B

Column A

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
			cm	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.1	Undefined	1731	2.64	-	-
3	1-3	20.4	0.2	47.0	1238	1.01	1024	0.78
5	0-5	51.0	0.3	50.6	3717	1.13	2360	0.72
10	5-10	51.0	0.8	53.4	3346	1.02	2782	0.85
15	10-15	51.0	3.6	56.2	2573	0.78	2189	0.67

Average influent concentration: 54.1 μg/L
Total entering column during test: 25922 mg
Test duration: 88 days

Column B

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
			cm	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.1	29.1	1852	2.35	1274	1.62
3	1-3	20.4	0.3	34.1	1062	0.68	1254	0.79
5	0-5	51.0	0.6	41.0	4619	1.18	3565	0.91
10	5-1[illegible]	51.0	1.1	69.2	5609	1.42	4701	1.20
15	10-1	51.0	1.3	97.1	900	1.25*	4573*	1.17*

Average influent concentration: 54.1 μg/L
Total entering column during test: 25922 mg
Test duration: 88 days
*Extrapolated value

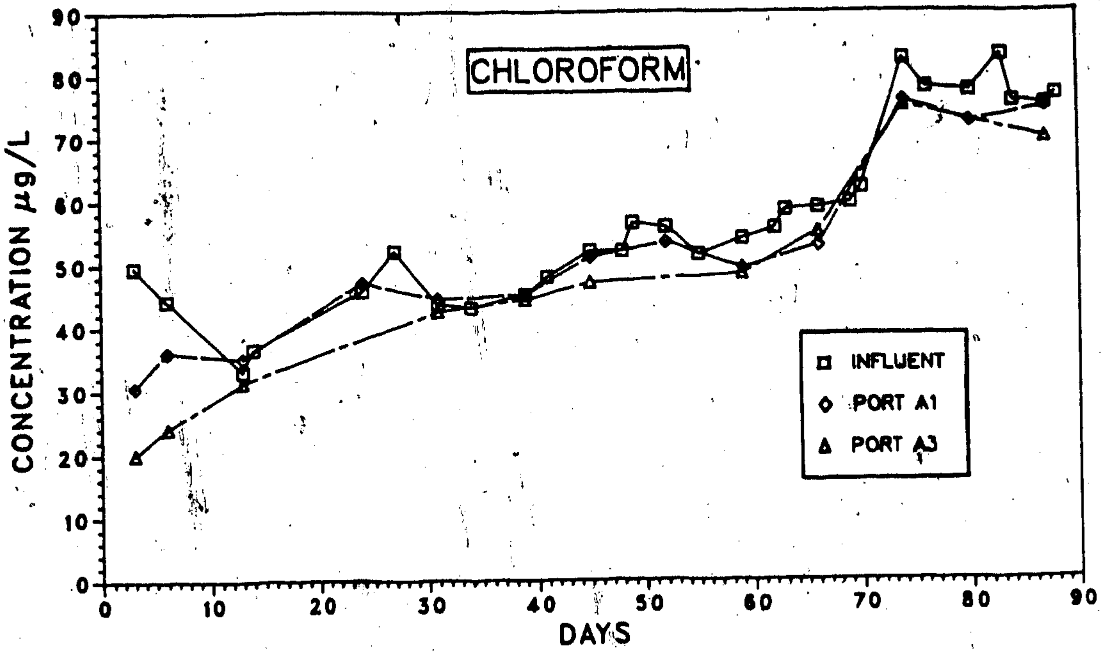

Figure 5.7 Chloroform in Finished Water and Removal by 10 and 31 cm GAC (Column A)

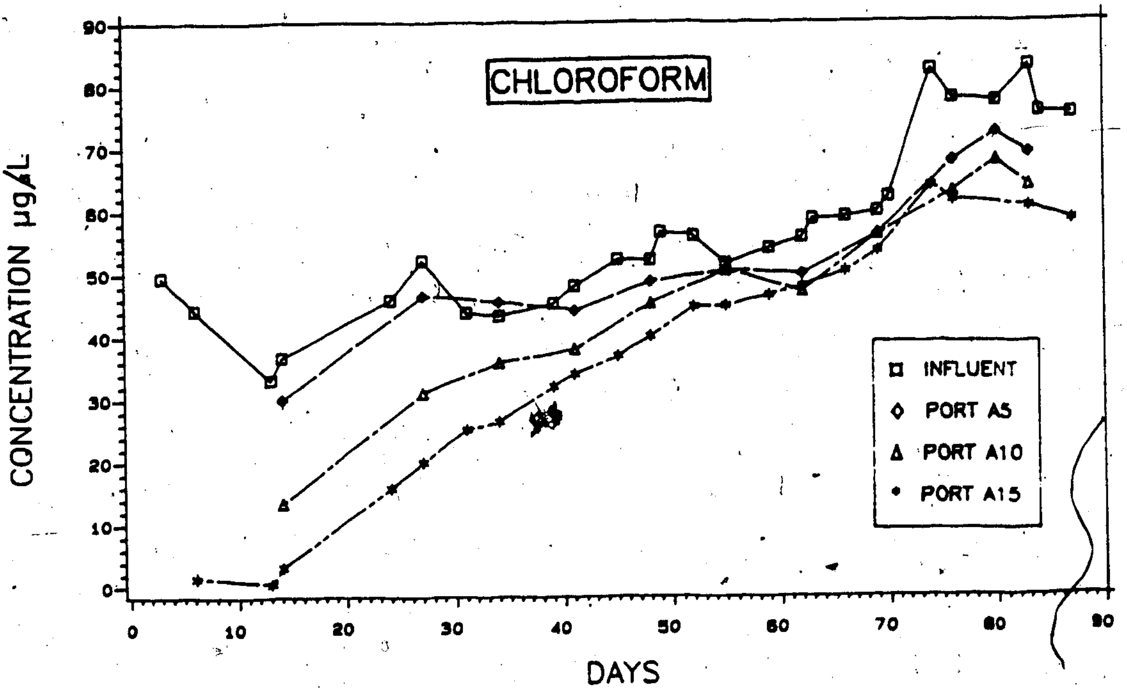

Figure 5.8 Chloroform in Finished Water and Removal by 51, 102, and 153 cm CAC (Column A)

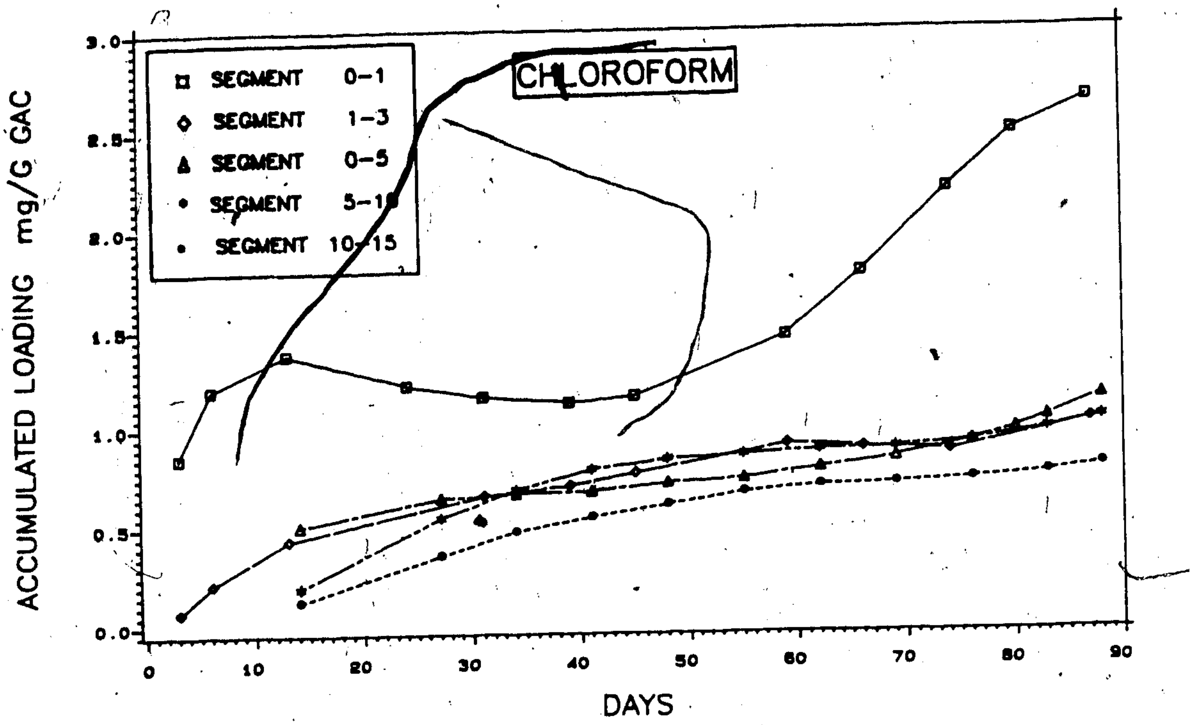

Figure 5.9 Chloroform Accumulated in Column A

corresponding decrease in the loading rate of segment 5-10. The constant loading pattern of bottom segment (10-15) indicated that as for TTHM, it was relatively immune to fluctuations in loading rates of upper segments and adsorbed at a rate proportional to the effluent concentration of the segment above.

Because of a lack of data initially following startup an apparent exhaustion value could not be obtained for segment 0-1. However, end of test loading data (Table 5.2) reveal that segment 0-1 was capable of adsorbing more than 2.5 times the amount adsorbed in any other segment when expressed on a per gram GAC basis.

The effect of an increasing column influent trend following day 45 is noted in the increased loading capacity of segment 0-5. At apparent exhaustion (day 51) 0.72 mg/g GAC had been accumulated in this segment in contrast to the 1.13 mg/g GAC adsorbed at the end of the 88 day test period.

5.1.2.2 Column B

All breakthrough values expressed as days were lower than for TTHM (Table 5.2), but generally slightly higher than the results of Column A. This indicates that chloroform was more readily adsorbed by Column B. Concentration and accumulation profiles appear in Figures 5.10, 5.11, and 5.12.

Segment 5-10 reached the highest loading of the three major segments at both apparent exhaustion and the end of the test period. Loading in segment 0-1 was approximately

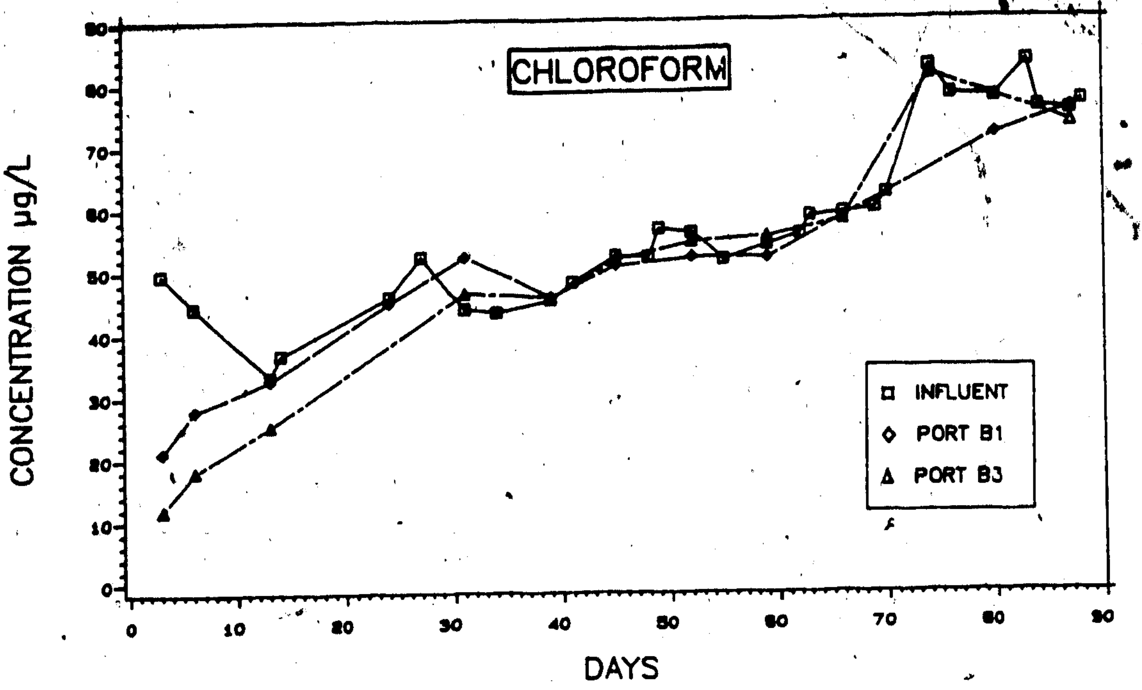

Figure 5.10 Chloroform in Finished Water and Removal by 10 and 31 cm GAC (Column B)

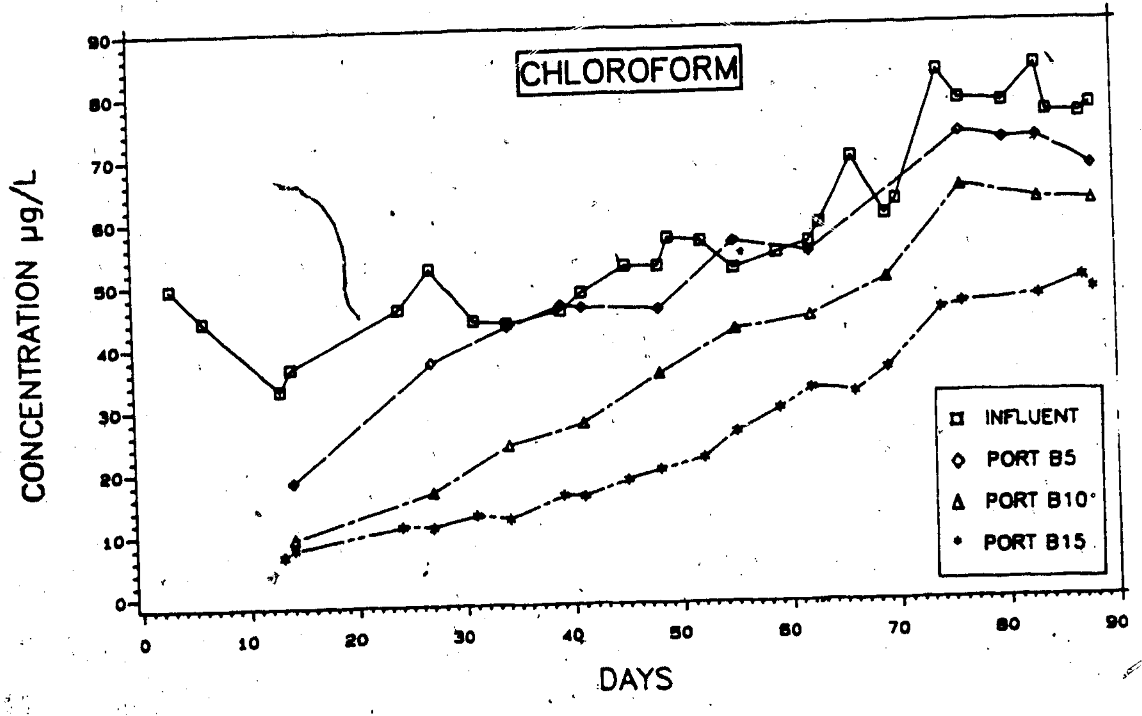

Figure 5.11 Chloroform in Finished Water and Removal by 51, 102, and 153 cm GAC (Column B)

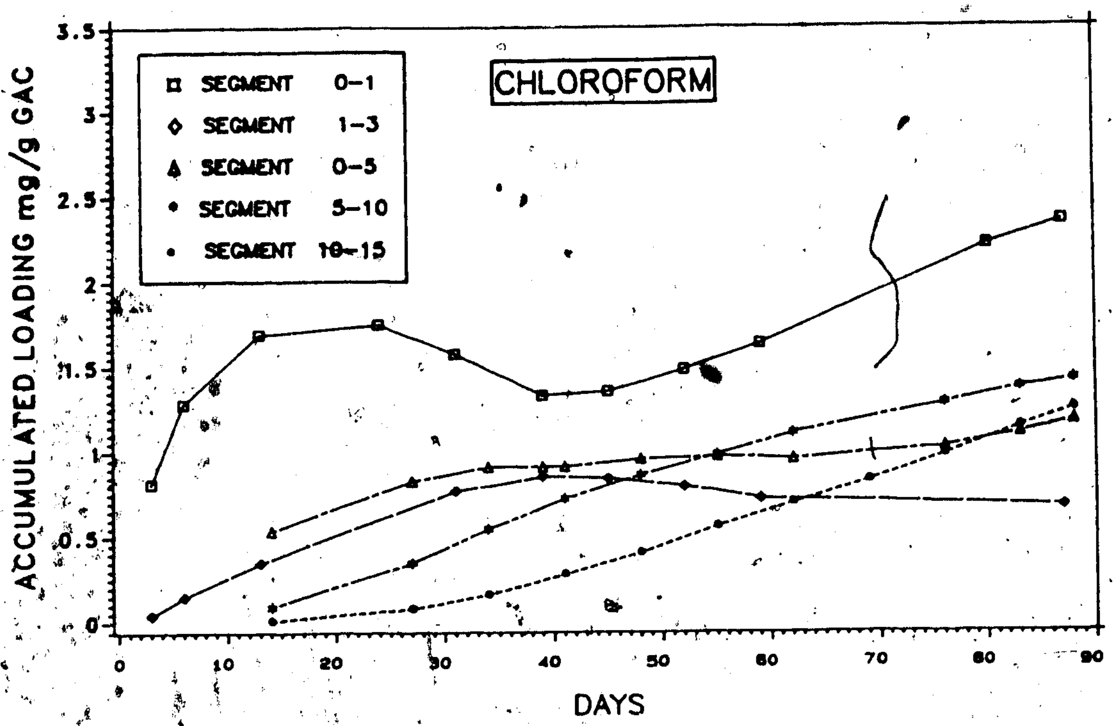

Figure 5.12 Chloroform Accumulated in Column B

2 times values found in any other segment when comparing end of test results. Segment 1-3 exhibited an uncharacteristically low accumulation value of 0.68 mg/g GAC and 0.79 mg/g GAC at the end of test and apparent exhaustion respectively. This indicated a decrease in the adsorptive capacity during the latter half of the study period.

Of the three major segments, a continued increase in adsorptive capacity was noted in segment 5-10 following apparent exhaustion in segment 0-5 at day 41. Segment 10-15 displayed a constant increasing trend as noted earlier in TTHM results for this column. Also, as for TTHM, apparent exhaustion was not reached until day 97 of operation. This extrapolated value exceeded the 88 day study period and suggests that approximately equal loadings may occur in both segments 5-10 and 10-15.

The decrease noted in adsorptive capacity of segment 1-3 following an increase in influent concentrations suggests that chloroform may be competitively displaced in upper segments of this GAC bed. Since chloroform appears less strongly adsorbed than TTHM in general, competition from one or more of the other constituent compounds would seem likely. This phenomona will be addressed in greater detail in discussions of the Polanyi-Manes adsorption theory.

5.1.3 COMPARISON OF TTHM REMOVAL BY COLUMNS A, B, AND CA

In total, three carbon post contactors of equal depth were operated in parallel during the 88 day study period. Results from Columns A and B were discussed in previous sections. Columns CA, CB, and S differed in either depth and/or operating conditions and therefore could not be directly compared for the full study period.

Special treatment of data pertaining to Column [illegible] and series Columns CA and CB was required. These columns were used to study both the effects of a partial carbon replacement after 61 days of operation, and the effect of an extended bed depth. As a prerequisite to this discussion, results from these columns will be briefly compared to Columns A and B. Results collected from columns prior to the replacement of carbon in Columns CA and S are presented in Figure 5.13 and Appendix E.

The TTHM loading in segment 0-1 of Column CA was similiarly proportioned but slightly higher than either Column A or B. In segment 0-5 the overall loading was highest in Column B. Loadings in segments 5-10 and 10-15 were similar but differed from the inverse relationships between depth and loading noted in Columns A and B.

Chloroform, the major component of TTHM, followed a similar loading pattern as expected. Results for bromodichloromethane and dibromochlormethane will not be discussed but are presented in Appendix E.

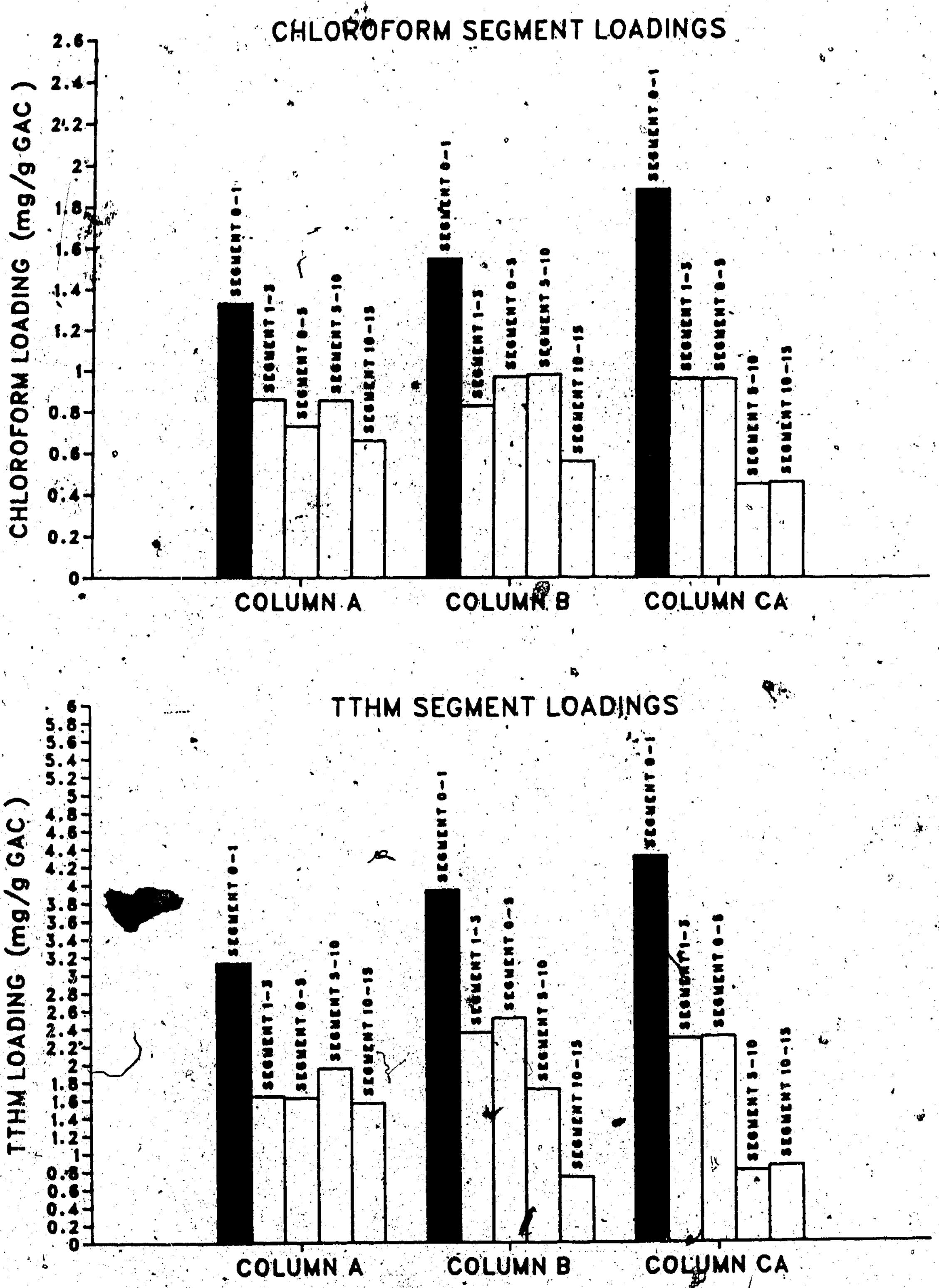

Figure 5.13 Segment Loadings of Columns A, B, and CA

In summary, TTHM were removed more effectively in upper segments and less effectively in lower segments of Column CA than either Columns A or B. It was for this reason and based on previous pilot studies (Forsyth et al., Andrews et al., 1983) that Filtrasorb 300® (Column CA) was chosen for detailed bed replacement studies.

5.1.4 Partial GAC Bed Replacement Evaluation - TTHM

Columns CA and S were operated in parallel to assess the effects of a partial bed replacement and of backwashing lower segment unexhausted carbon into upper bed segments. At day 61 of the test period the top 31 cm of carbon (segment 0-3) was removed from Columns CA and S, and replaced with fresh GAC. This represented 20% and 100% of the carbon present in columns CA and S respectively and permitted exploring the possibility of increasing bed life with only a partial bed replacement.

Concentration profiles for Columns CA and S are shown in Figures 5.14 and 5.15 respectively. Large decreases in TTHM concentrations are noted immediately following the carbon replacement, as expected.

A comparison of accumulated TTHM at Ports CA1, CA3, S1, and S3 appears in Figure 5.16. After backwashing at day 66 accumulation profiles of segments CA 0-1 and S 0-1 appear roughly parallel (Figure 5.16). The similar loading capacity seen in Column CA suggests that carbon being displaced from lower bed segments to upper bed segments during backwashing

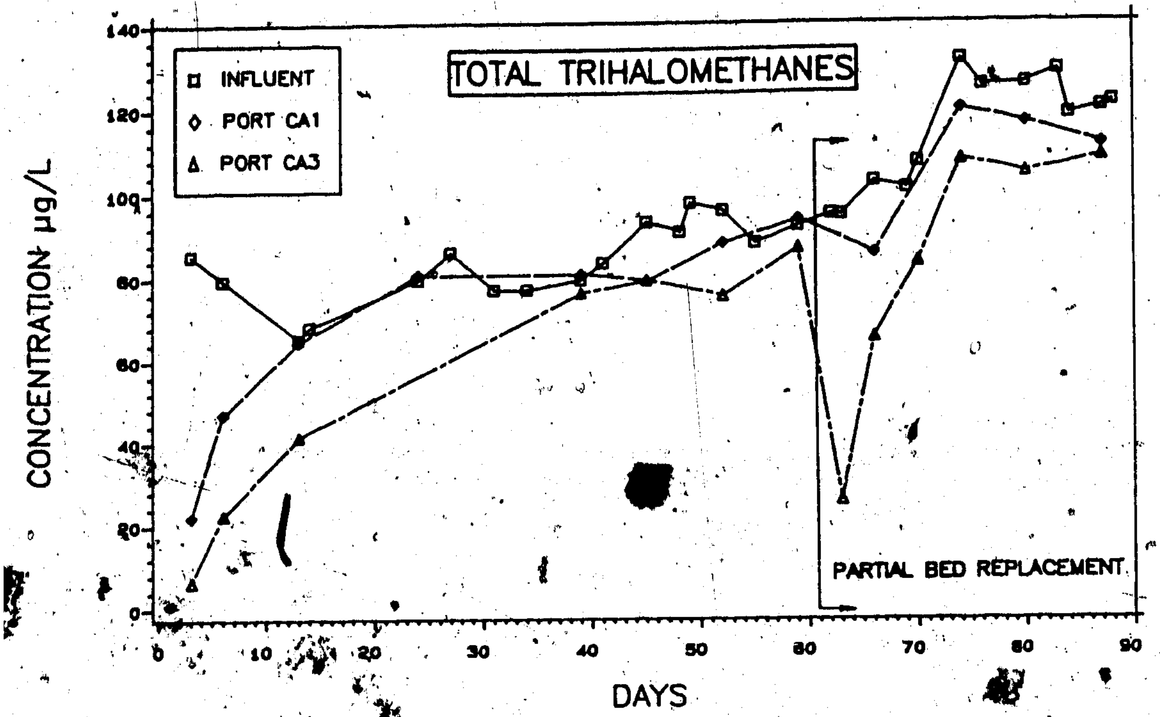

Figure 5.14 TTHM in Finished Water and Removal by 10 and 31 cm GAC (Column CA)

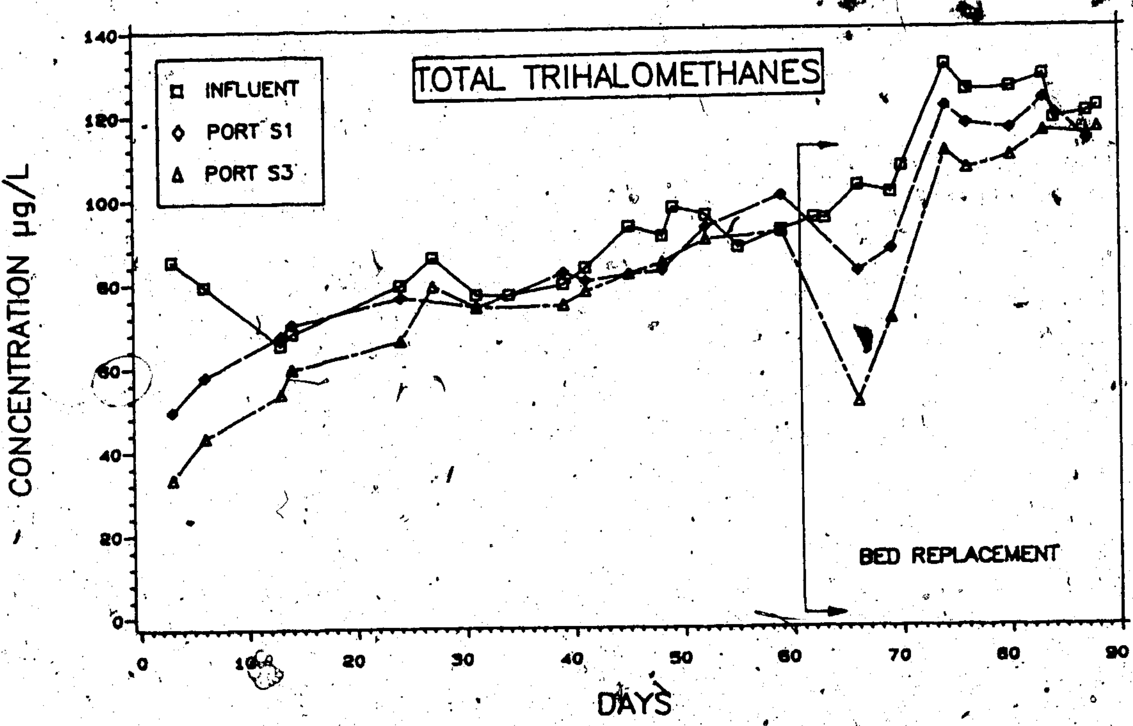

Figure 5.15 TTHM in Finished Water and Removal by 10 and 31 cm GAC (Column S)

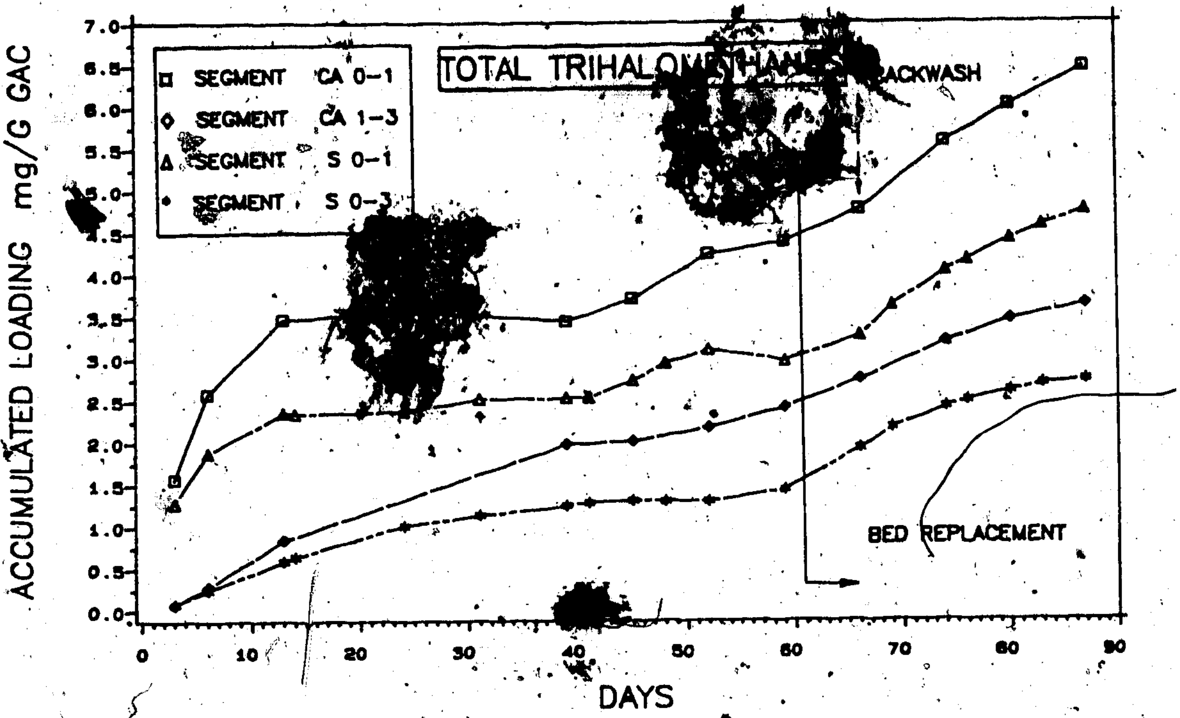

Figure 5.16 TTHM Accumulated in Columns CA and S

was not exhausted. Had this not been the case, capacity would be expected to decrease. Bed stratification was visibly noticeable and consistent with findings by Alben and Shpirt (1981). The existence of smaller diameter particles in the CA 0-1 segment would cause an increase in adsorptive capacity as suggested by Weber (1972).

Prior to the carbon replacement segment S 0-1 accumulated only 68% as much TTHM as the corresponding CA 0-1 segment. Segment S 1-3 accumulated 60% as much as segment CA 1-3. These values illustrate the enhanced adsorption effect in upper segments of backwashing attributable to bed stratification. Higher adsorptive capacity would be expected in the upper segments of the deeper bed CA, due to the increased availability of unexhausted small particles. An evaluation of loadings vs depth as a function of particle size distribution is presented in section 5.3.

Immediately following the carbon replacement a sudden increase in the rate of accumulation is evident by the increased adsorption profile slope in both Columns CA, and S with the exception of segment CA 0-1 (Figure 5.16). At the end of the test period (27 days later) segments S 0-1 and S 0-3 represented 86% and 106% respectively of the amount accumulated in segment CA 0-1 and CA 0-3 after the replacement. The increase in these percentage values suggests that the carbon displaced by backwashing into the upper segments of Column CA during later bed life is causing a reduction in capacity. This effect was probably a result of partially exhausted particles.

The potential of an increasing influent concentration to cause increased loadings was examined by comparing cummulative TTHM loadings (segment 1-15) for Columns A, B, and CA on the same graph (Figure 5.17). Adsorptive capacities in Columns A and B appear to be unaffected by the increasing influent TTHM trend following day 63 of operation. On a more localized scale, cummulative TTHM loadings for segments 0-1 and 1-3 in Columns A and B are presented in Figures 5.3 and 5.6. No concentration effect is noted for segment 1-3 in either column, however segment 0-1 does exhibit a slight loading rate increase in both columns following day 63. It may therefore be assumed that the linear increase in TTHM loading of column CA following carbon replacement was a direct result of the new unused capacity except possibly in segment 0-1 where concentration may induce a small capacity increase.

Total loadings in Columns A, B, and CA are shown in Table 5.3a at day 59 (immediately before the replacement) and at the end of the study period. Column CA bed loading increased 49% following the replacement compared to 30% and 49% increases in Columns A and B which did not receive new carbon. Prior to the replacement, Columns A and CA removed similar amounts of TTHMs. The 19% increase in loading capacity of Column CA in excess of Column A may therefore be attributed to the 20% bed replacement. Column B displayed no signs of reaching exhaustion and on a concentration basis removed more TTHM than either Column A or CA.

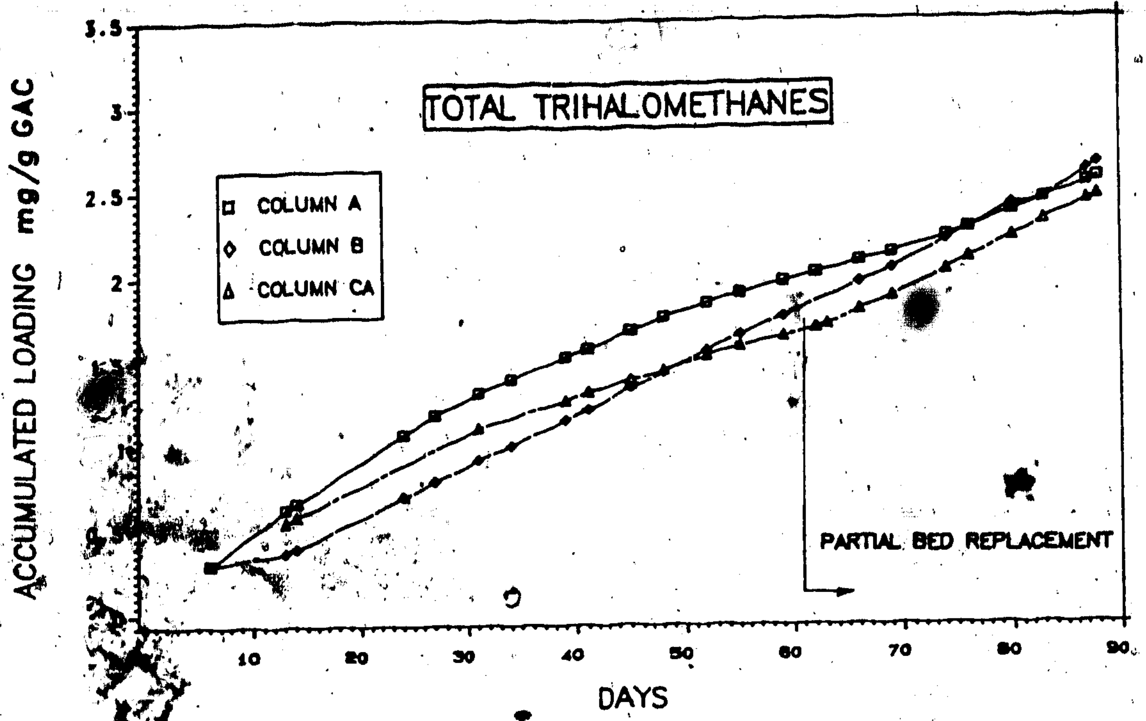

Figure 5.17 TTHM Accumulated in Columns A, B, and CA

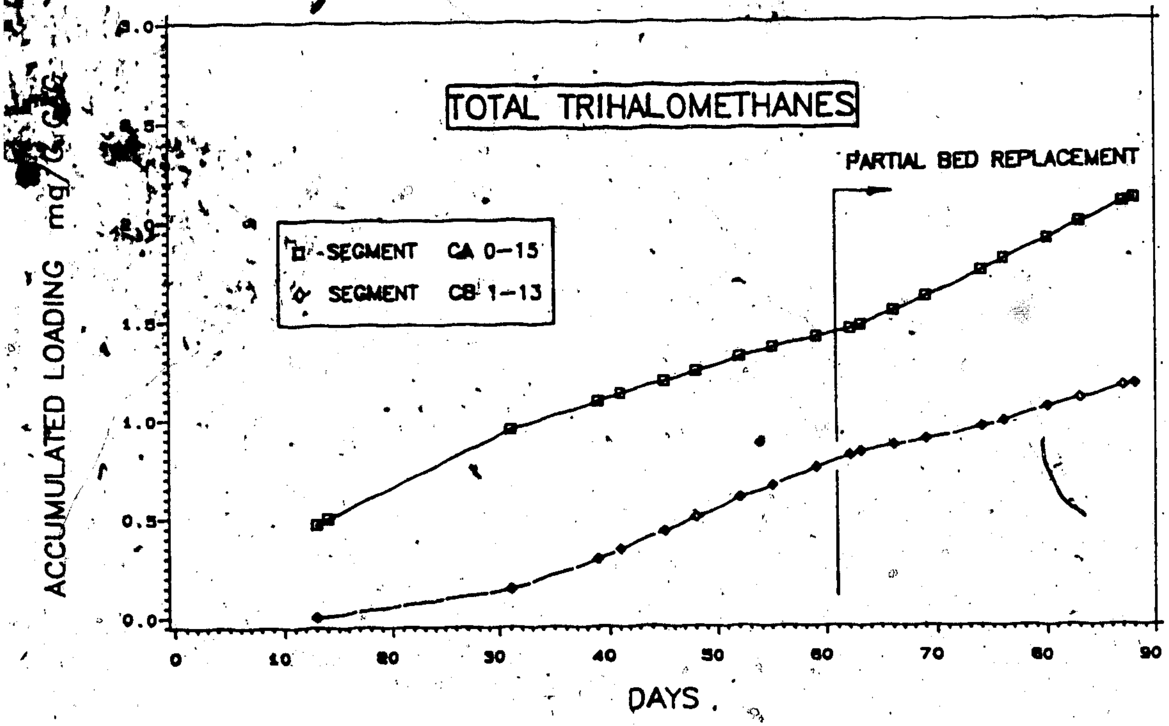

Figure 5.18 TTHM Accumulated in Columns CA and CB

Table 5.3 Trihalomethane Segment Loadings (mg/g GAC) Columns A, B, CA, and S (Before and After Bed Replacement)

(a) Column A, B, and CA

	Loading (mg/g) - Total Column		
	Column A	Column B	Column CA
Prior to Partial Bed Replacement (Column CA)	1.69	1.75	1.41
End of Study	2.19	2.63	2.10
% Increase	30%	50%	49%

(b) Column CA and S

	Loading (mg/g) - Segment 0-3	
	Column S	Column CA
Prior to Partial Bed Replacement (Column CA)	1.95	3.07
End of Study	3.40	4.57
% Increase	74%	49%

The total bed depth loading of Column S is compared to the Column CA segment 0-3, representing the same amount of carbon, in Table 5.3b. An absolute increase in Column S loading capacity of 25% was observed above that attained in Column CA. This increase illustrates the decrease in capacity resulting from backwashing partially exhausted carbon into upper segments in Column CA.

5.1.5 Removal of TTHM by Deep Beds - Columns CA+CB

The series combination of Columns CA+CB allowed adsorption of TTHM to be studied in a bed depth totalling 286 cm. Actual carbon depth in Column CB measured 153 cm from top to bottom (same as Column CA) but was monito[illegible] the lowest port (Port 13), representing a bed depth o[illegible] cm.

Results profiling TTHM accumulation in Columns CA and CB are shown in Figure 5.18. At the end of the test period loadings of 2.10 mg/g GAC and 1.16 mg/g GAC were present in Columns CA and CB, respectively. The effect of the 20% carbon replacement in Column CA at day 61 is noted as an increase in slope of the Column CA accumulation curve and decrease in slope of Column CB accumulation curve. These deviations suggest that upper bed capacity was increased, resulting in a lower influent concentration to Column CB and consequently a decreased loading rate. The assumption that this behavior occurred prior to complete apparent exhaustion of either Column CA or CB was confirmed by the positive slope noted in both accumulation profiles.

When Columns CA and CB are viewed as one single bed, depth 286 cm, the highest loadings prior to the end of the study period occurred in the upper half of the bed as expected. An observation of this type however must be viewed with some caution when making comparisons to a single deep bed as opposed to a series situation as in this case. For instance, if particle size distribution could be shown to directly influence adsorptive capacity then an actual one-piece bed may attain a deeper zone of given particle size as opposed to two series beds. The extent of stratification would of course be a function of backwash velocity. In series beds fines from the second bed cannot be backwashed to the top of the first bed where the highest influent concentration exists.

5.2 TOTAL ORGANIC CARBON

Total organic carbon (TOC) data did not exhibit the characteristic breakthrough curves noted for trihalomethanes. Instead, three well defined phases of adsorption existed. These phases, as identified by McGuire et al. (1983) are: (1) immediate low level leakage, (2) a regular orderly breakthrough, and (3) a pseudo steady-state plateau. Two common theories that may be used to describe the long term pseudo-steady-state removal include biological removal and slow adsorption kinetics (Maloney et al., 1983).

To assist in evaluating apparent exhaustion and breakthrough values, an average concentration was calculated for the plateau section of each individual breakthrough curve. This concentration represents the average steady-state influent concentration to the column segment immediately below. Apparent exhaustion was calculated as the time when a linear approximation to the breakthrough curve intersects the steady-state concentration. By projecting the linear extrapolation back to a point where concentration would equal zero, breakthrough was found in most cases to occur immediately following startup. Breakthrough values noted in Tables 5.4, 5.5 and 5.6 are those calculated by the computer program GAC7. These values always exceed zero since the program uses a straight line extrapolation assuming that concentration equals zero at time zero. Thus, loadings calculated by the program may be slightly higher than actual.

5.2.1 Column A

TOC adsorption data appear in Table 5.4 and Figures 5.19, 5.20, and 5.21. The average influent concentration was 3.6 mg/L showing a slight decreasing trend during the latter half of the study period. Distinct plateaus are seen for all the segments, including minor segments 0-1 and 1-3 at the top of the column. Breakthrough most likely occurs, very soon after startup. In absence of data a straight line extrapolation has been used which may overestimate in early stages (Figures 5.19 and 5.20).

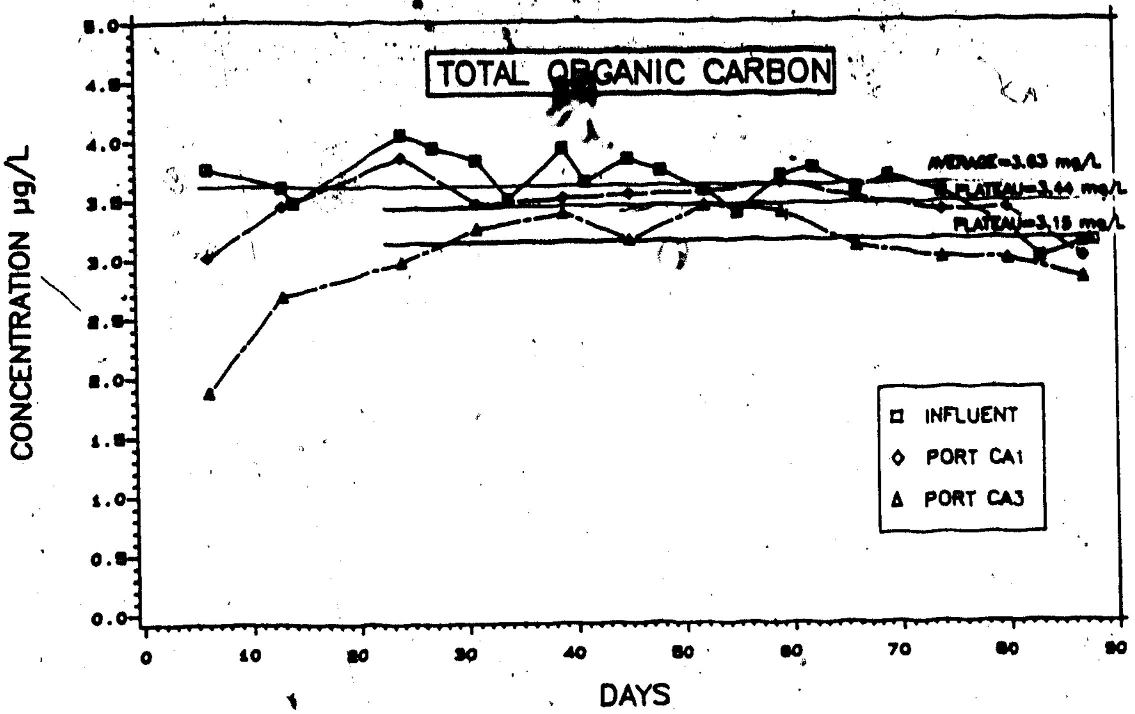

Figure 5.19 TOC in Finished Water and Removal by 10 and 31 cm GAC (Column A)

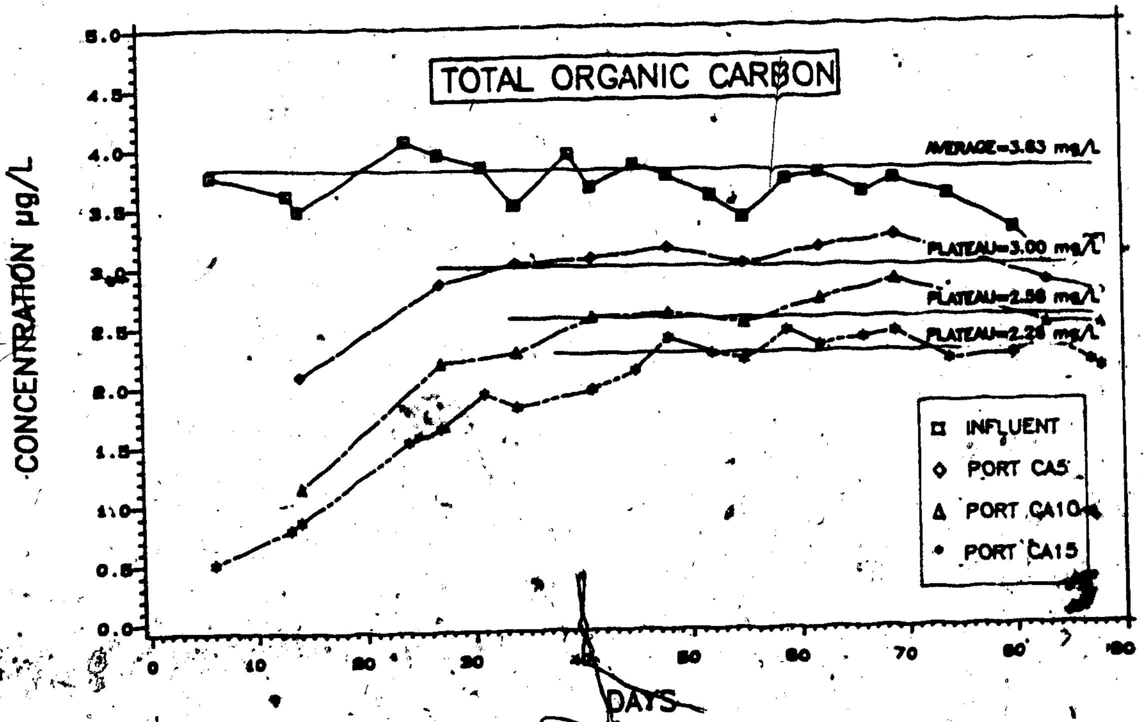

Figure 5.20 TOC in Finished Water and Removal by 51, 102, and 153 cm GAC (Column A)

Table 5.4 TOC Adsorption Data - Column A

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
		cm	Days	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.2	14.4	155	236	92	140
3	1-3	20.4	0.2	27.6	214	163	116	88
5	0-5	51.0	0.5	32.3	440	134	295	90
10	5-10	51.0	0.9	37.2	233	77	131	40
15	10-15	51.0	0.9	45.0	164	50	89	27

Average influent concentration: 3.6 mg/L
Total entering column during test: 1742 g
Test duration: 88 days

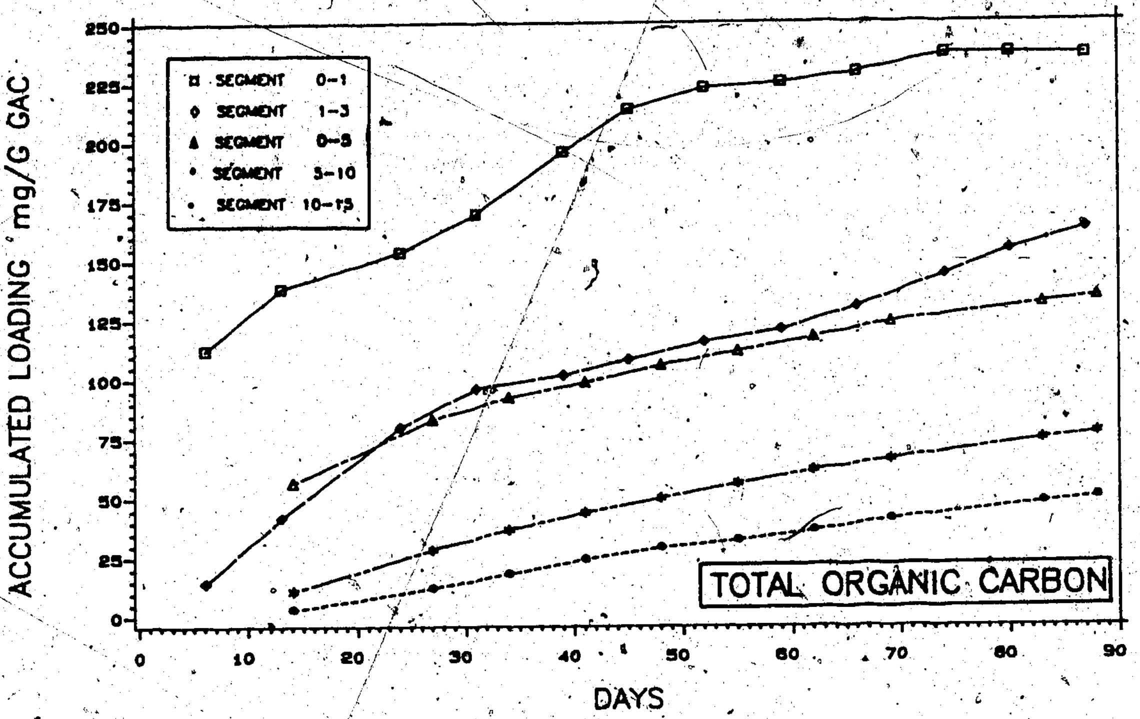

Figure 5.21 TOC Accumulated in Column A

In general, effluent concentrations at each of the segments paralleled the influent concentration. At apparent exhaustion the highest loading of 140 mg/g GAC was obtained in segment 0-1. Plots of accumulated TOC (Figure 5.21) suggest that segment 0-5 has a much higher capacity to remove TOC than either segments 5-10 or 10-15.

When the mass of TOC adsorbed at apparent exhaustion is compared to the mass at the end of the test (Table 5.4) over one-half of the amount removed at the end of the test may be attributed to either biological activity or slow adsorption.

In an attempt to define the actual mechanism governing TOC reduction, 100 mL of 4N NaOH was added to the column at day 61 of the study period. This solution was slowly drawn through the column over a 10-15 minute period and produced a pH of 11-12 in the effluent. Samples collected 1 week later showed a reduction in standard plate counts from 480,000 units/mL to 98,000 units/mL. This reduction in bacteria concentration had only a minor effect on the removal efficiency of TOC (Figures 5.19 and 5.20). The decrease in slope in some segments of Figure 5.21 following day 61 appears to result from a combination of bacterial reduction and a decreasing TOC influent concentration. The proposed TOC reduction for this carbon following apparent exhaustion appears to be slow adsorption as opposed to biological activity.

5.2.2 Column B

Column B TOC adsorption data appear in Table 5.5 and Figures 5.22, 5.23, and 5.24. Distinct plateaus following apparent exhaustion are noted in Figure 5.23 but are spaced much closer together vertically than those for Column A. This indicates that less TOC removal occurred following apparent exhaustion than noted in Column A. Loading results shown in Table 5.5 and Figure 5.24 confirm this observation. Effluent concentration trends for segments 0-1 and 1-3 were erratic (Figure 5.22) and did not reflect trends in the influent concentration until very near the end of the study period. Apparent exhaustion could not be defined for segment 0-1 since no trend was defined by the concentration data profile.

Examination of the three major segments at apparent exhaustion shows that both the highest accumulated amount and loading occurred in segment 0-5. The magnitude of the loading in this segment becomes readily apparent from Figure 5.24. Segments 5-10 and 10-15 contributed very little to the removal of TOC. In fact segment 10-15 was found to have accumulated no TOC during the first 69 days of operation. At both apparent exhaustion and at the end of the test period the mass of TOC adsorbed was found to vary inversely with column depth as previously noted for Column A.

Treatment with NaOH at day 61 did not appear to affect bacteria concentration or TOC removal. The proposed TOC

Table 5.5 TOC Adsorption Data - Column B

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
			cm	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.1	Undefined	150	191	Undefined	Undefined
3	1-3	20.4	0.2	26.5	120	77	65	41
5	0-5	51.0	0.3	29.6	322	82	215	55
10	5-10	51.0	0.4[2]	28.2	44	12	14	4
15	10-15	51.0	0.2	120.7	14	3	0[1]	0[1]

Average influent concentration: 3.6 mg/L
Total entering column during test: 1742 mg
Test duration: 88 days

[1] Effluent value from segment exceeds influent

[2] Estimate appears high due to lack of data immediately following startup

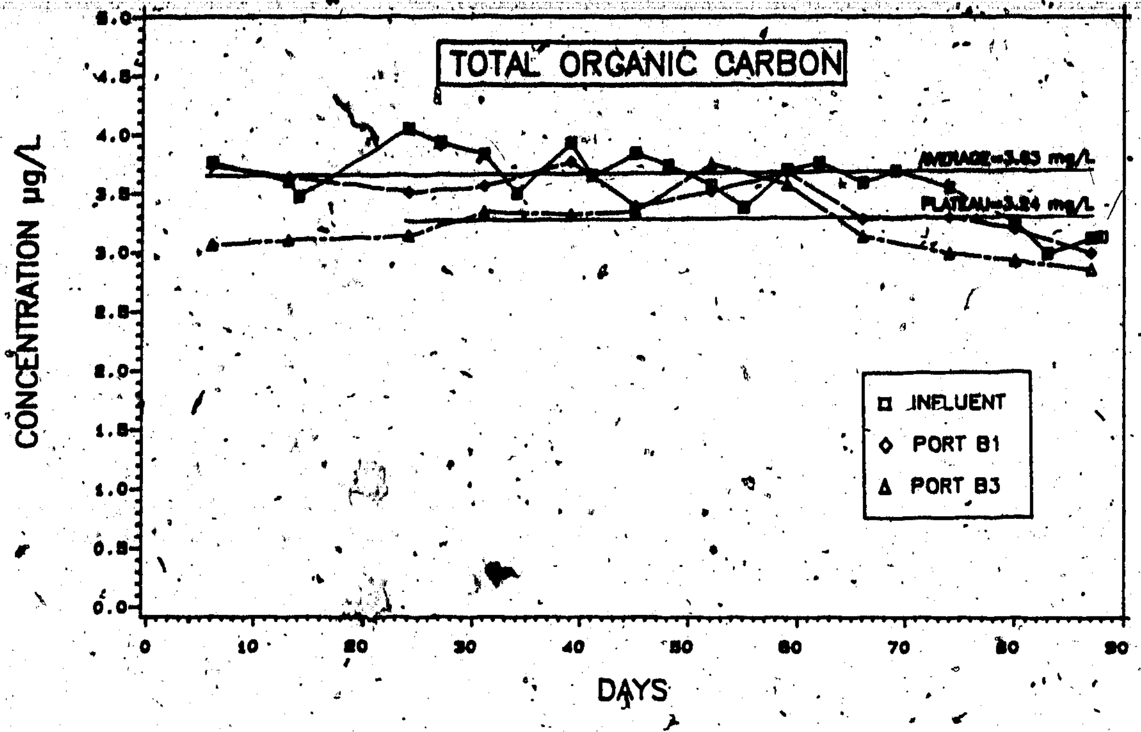

Figure 5.22 TOC in Finished Water and Removal by 10 and 31 cm GAC (Column B)

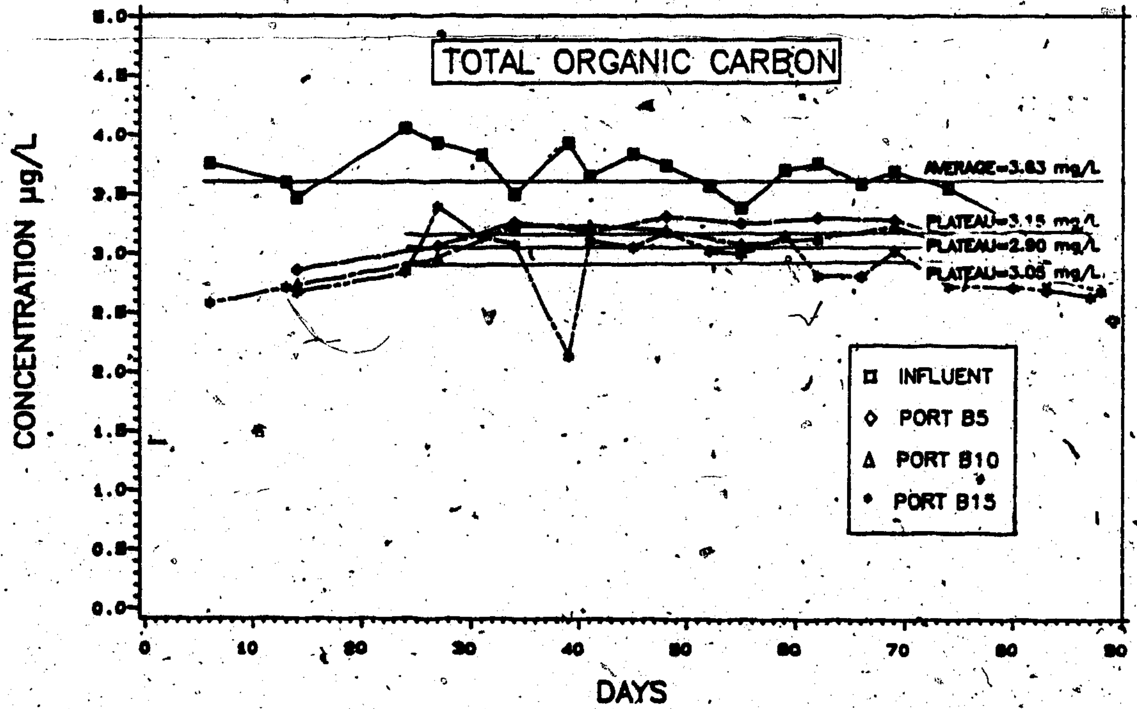

Figure 5.23 TOC in Finished Water and Removal by 51, 102, and 153 cm GAC (Column B)

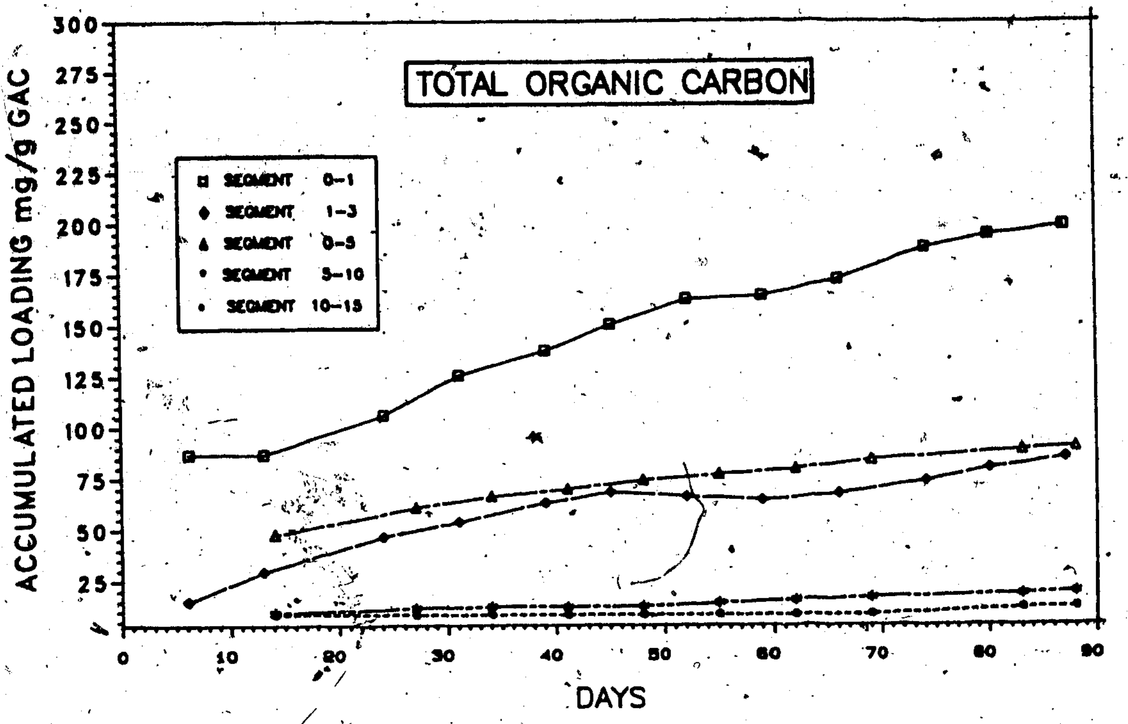

Figure 5.24 TOC Accumulated in Column B

removal mechanism following apparent exhaustion would be slow adsorption as noted for Column A but occuring at a much lower rate.

5.2.3 Column CA

Column CA adsorption profiles may be compared to Columns A and B at apparent exhaustion since in all cases [illegible]ent exhaustion occurred prior to the carbon replacement (Column CA) at day 61. Adsorption data appear in Table 5.6 and Figures 5.25 and 5.26. Very distinct plateaus are seen for the period extending from apparent exhaustion until the carbon replacement at day 61.

Accumulated TOC plots (Figure 5.27) show that segment 0-1 accumulated the highest amount of TOC both before and after the replacement. At apparent exhaustion (day 23) the loading for segment 0-1 (177 mg/g GAC) was more than two times that achieved by the next highest segment (0-5). Loading behavior with respect to depth in the three major segments paralleled the inverse trend noted previously in both Columns A and B but with a much higher loadings in segment 0-1. A comparison of Column A, B, and CA segment loadings is shown in Figure 5.28. End-of-test loadings for Column CA should not be directly comparied due to a partial bed replacement at day 61. At apparent exhaustion Column A achieved the highest loadings in the three major segments, followed by Columns CA and B respectively.

Table 5.6 TOC Adsorption Data - Column CA

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at Apparent Exhaustion	
		cm	Days	Days	g	mg/g GAC
1	0-1	10.2	0.2	23.5	138	177
3	1-3	20.4	0.3	34.8	99	64
5	0-5	51.0	0.5	34.6	327	84
10	5-10	51.0	0.8	35.9	109	28
15	10-15	51.0	1.2	38.0	70	18

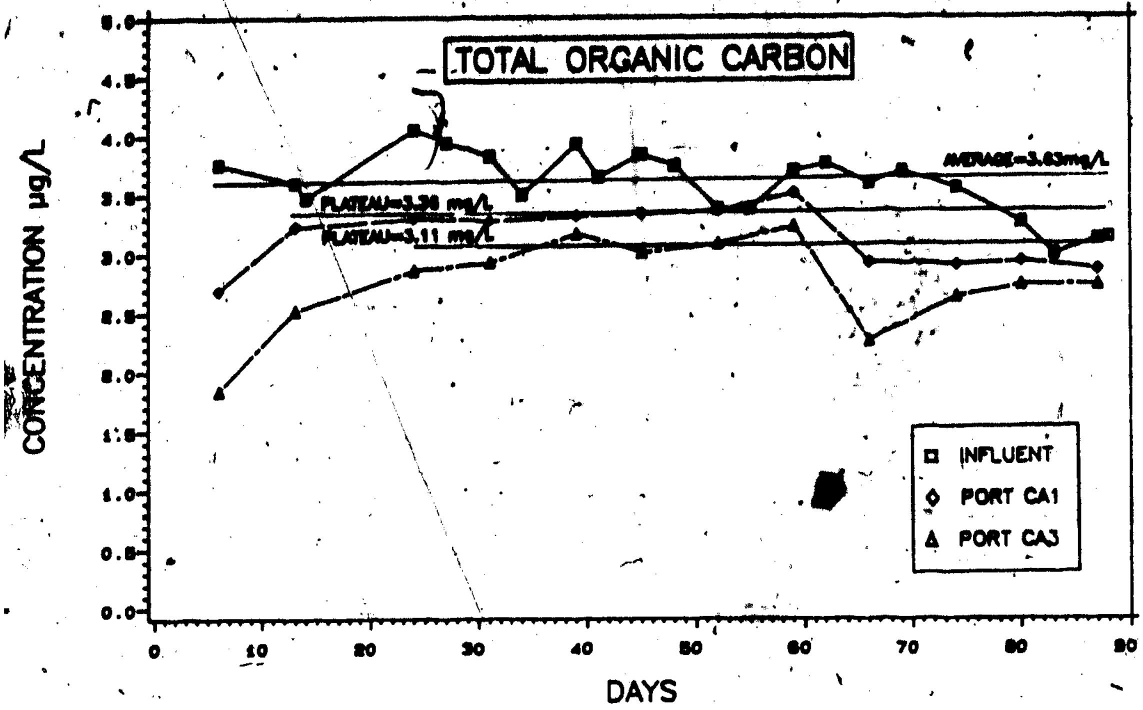

Figure 5.25 TOC in Finished Water and Removal by 10 and 31 cm GAC (Column CA)

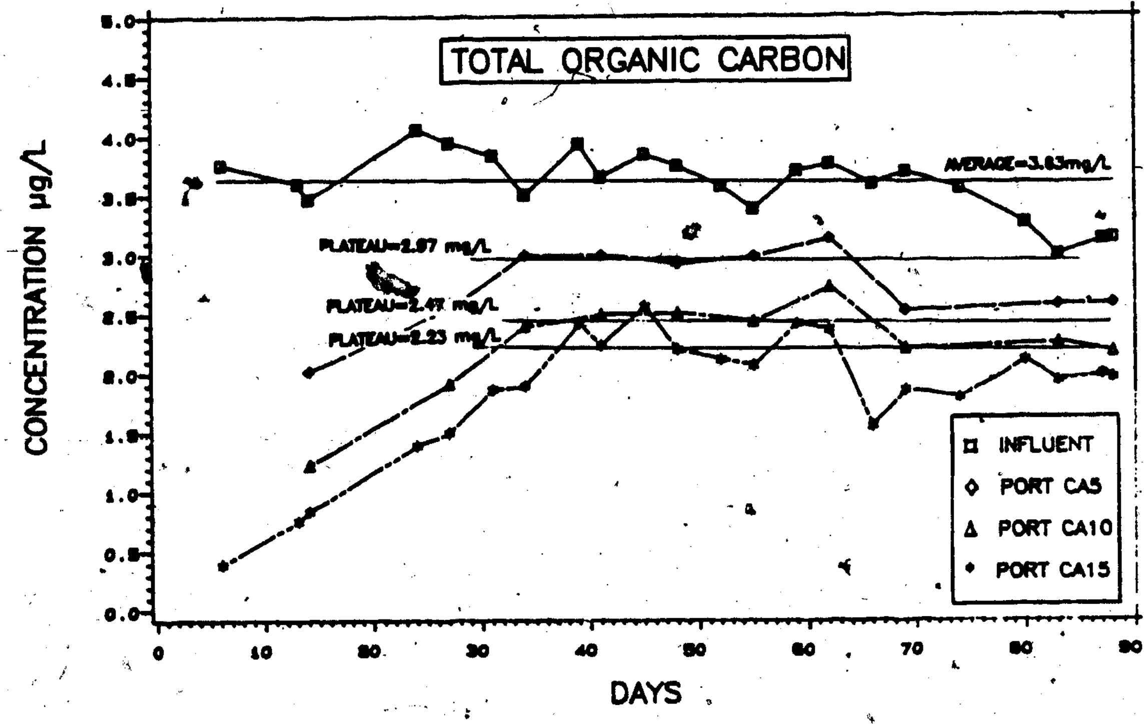

Figure 5.26 TOC in Finished Water and Removal by 51, 102, and 153 cm GAC (Column CA)

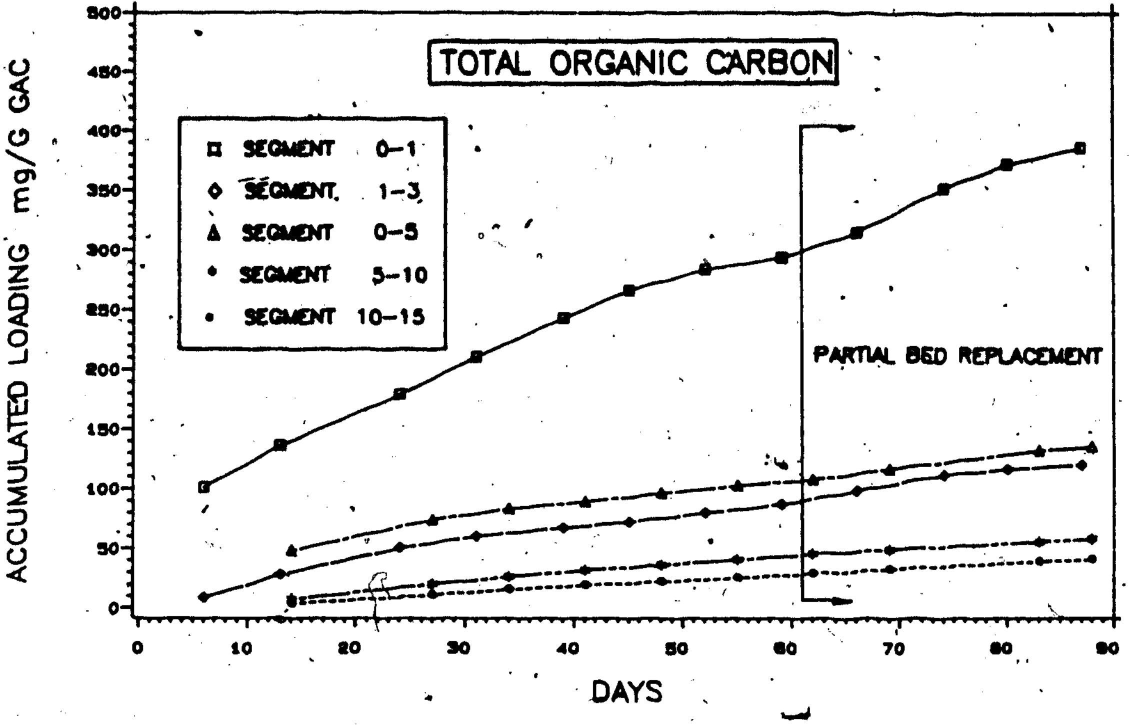

Figure 5.27 TOC Accumulated in Column CA --

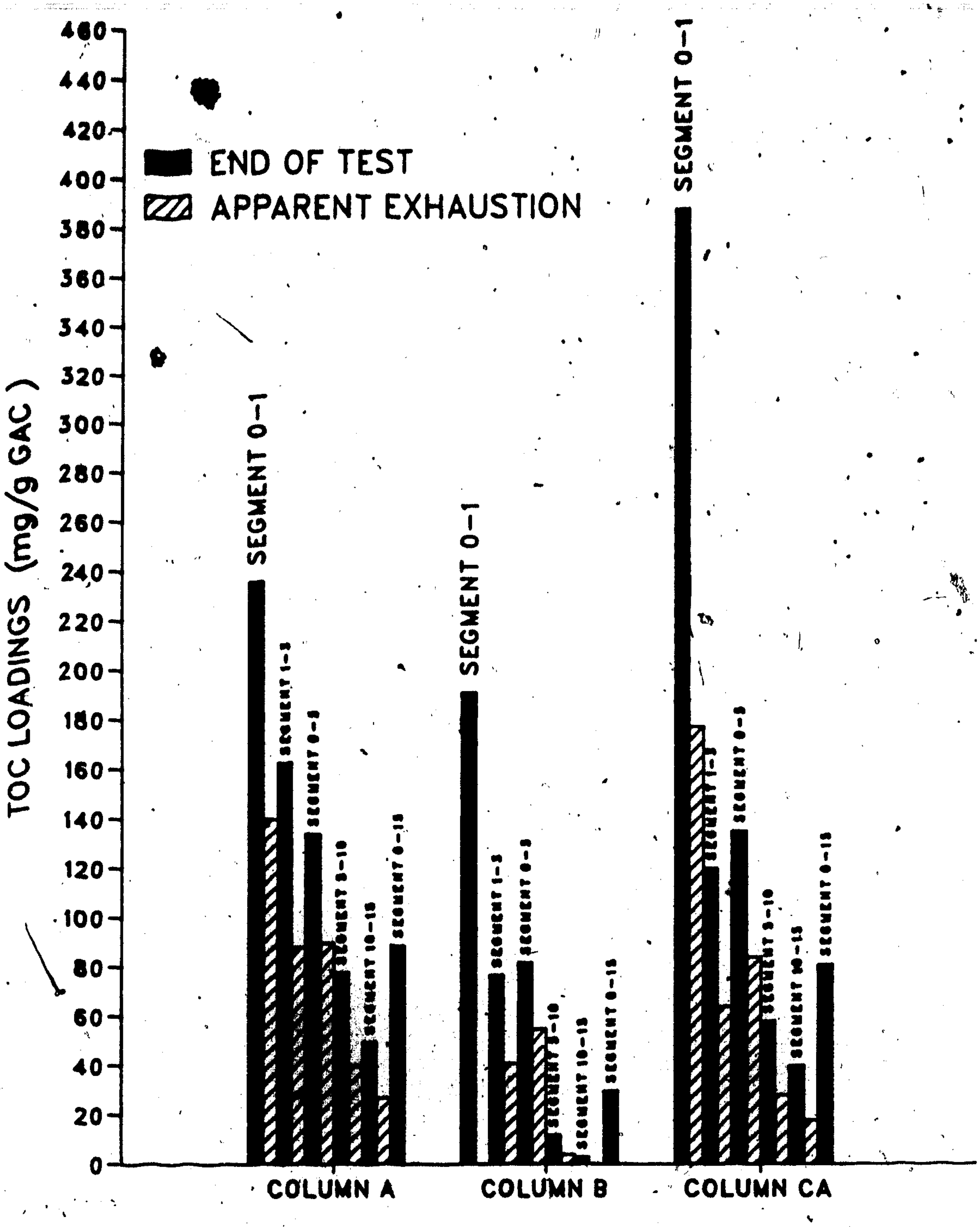

Figure 5.28 TOC Segment Loadings (mg/g GAC) – Columns A, B, And CA

Detailed bacterial analyses conducted at day 82 are presented in Table 5.7.

For the three major segments (0-5, 5-10, 10-15) TOC loadings were compared to bacteria counts (Table 5.7) to determine if a relationship existed. Major segment loadings at apparent exhaustion were subtracted from accumulated loadings at day 83 to eliminate the fraction of TOC readily adsorbed by the carbon and plotted vs bacteria counts obtained at day 82. The linear result suggested that TOC removal following apparent exhaustion was a result of biological activity. However, it should be noted that the period under consideration did include a 20% bed replacement. This may cause loadings to be higher than in a bed without the addition of virgin carbon but should not drastically alter the relationship. Comparison to Columns A and B was not possible since detailed bacterial analyses had not been conducted on these columns.

5.2.4 Partial GAC Bed Replacement Evaluation - TOC

As discussed earlier in section 5.1.4 a replacement of segment 0-3 carbon in Columns CA and S was performed to assess effects on removal efficiencies. Concentration profiles for Column CA were shown in Figures 5.25, 5.26, and 5.27. As noted for TTHM, large decreases in TOC effluent concentration followed the carbon replacement at day 61. Concentration profiles for Column S are shown in Figure 5.29.

Table 5.7 **Bacterial Analysis - Column CA**

Monitoring Port	Bacterial Concentration[2] (units/100 mL)	Accum. Loading[1] (mg/g GAC)
1 (segment 0-1)	49,000	-
3 (segment 1-3)	70,000	-
5 (segment 0-5)	140,000	48.1
10 (segment 5-10)	39,000	27.1
15 (segment 10-15)	11,000	21.3

[1] (Day 83 loading minus apparent exhaustion loading)
[2] Monitored at day 82

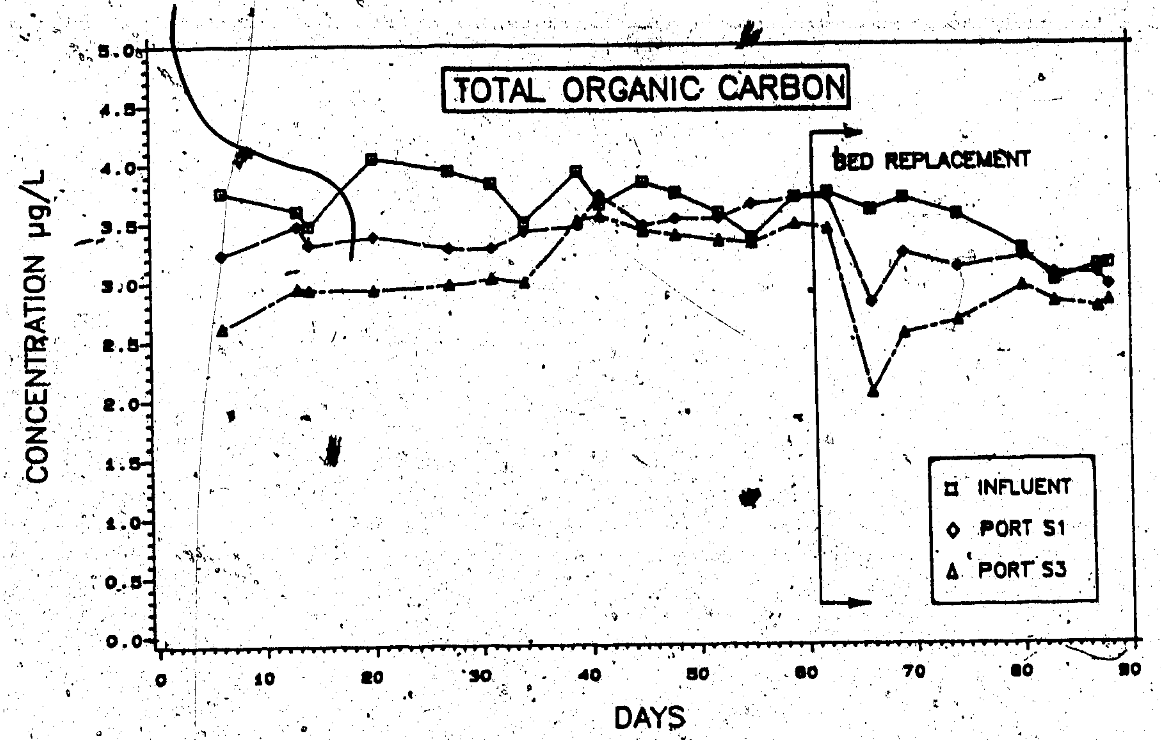

Figure 5.29 TOC in Finished Water and Removal by 10 and 31 cm GAC (Column S)

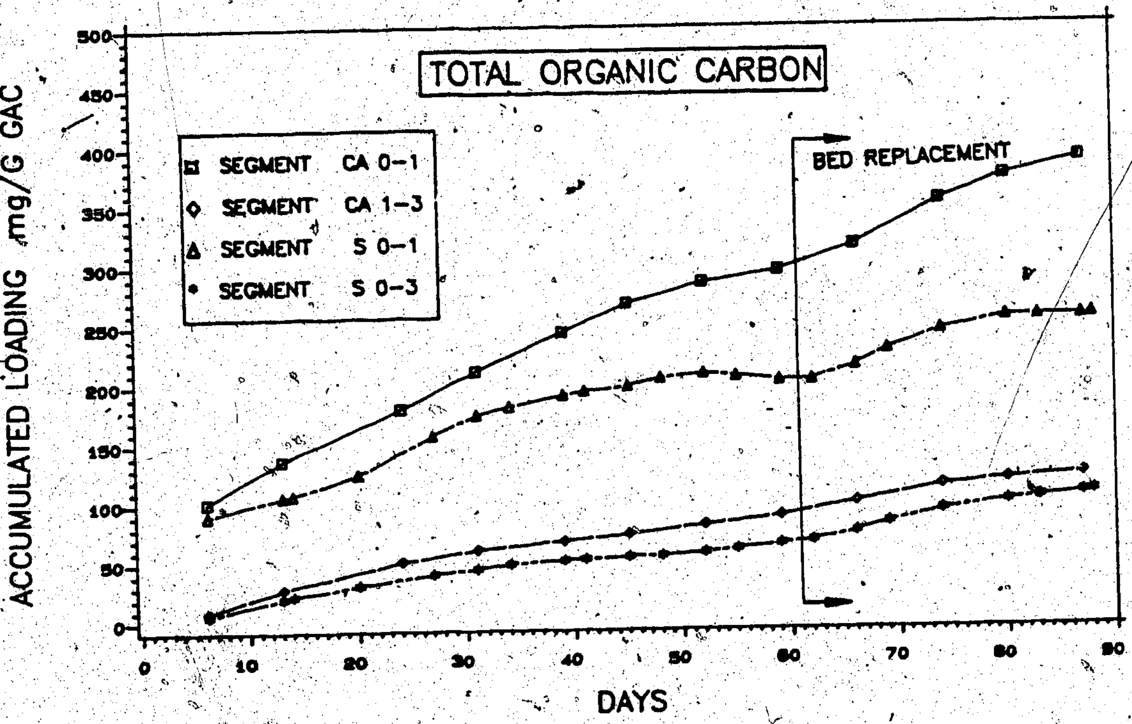

Figure 5.30 TOC Accumulated in Columns CA and S

TOC accumulated in column segments CA 0-1, CA 1-3, S 0-1 and S 1-3 is shown in Figure 5.30. Column CA displayed consistently higher loadings than Column S at segments 0-1 and 1-3. Divergence in accumulation profiles between Columns CA and S is likely due to unexhausted carbon being forced into upper segments of Column CA following backwash. This effect is more prominent in segment 0-1 suggesting that the smallest size particles have the most significant effect on adsorption as noted in TTHM discussions.

At day 59, immediately prior to the replacement, Column S accumulated 68% and 73% as much TOC as Column CA when measured at segments 0-1 and 1-3 respectively. Comparisons at the end of the test period show that segment S 0-1 continued to remove a similar amount (56%) whereas segment S 1-3 now accounted for 123% of Column CA accumulation after the replacement. This suggests that the carbon backwashed into the upper segments of Column CA had a lower rejuvenating effect in segment 1-3 when compared to segment 0-1. Again the enhanced adsorptive effect of the smaller size particles (segment 0-1) is evident.

5.2.5 Removal of TOC by Deep Beds - Columns CA+CB

Adsorption data for series Columns CA+CB are shown in Figure 5.31. Column CA reached apparent exhaustion at day 38 (Figure 5.26). This point is also depicted by the decreased rate of increase of the accumulation curve (Figure 5.31) at approximately the same time. From this point to

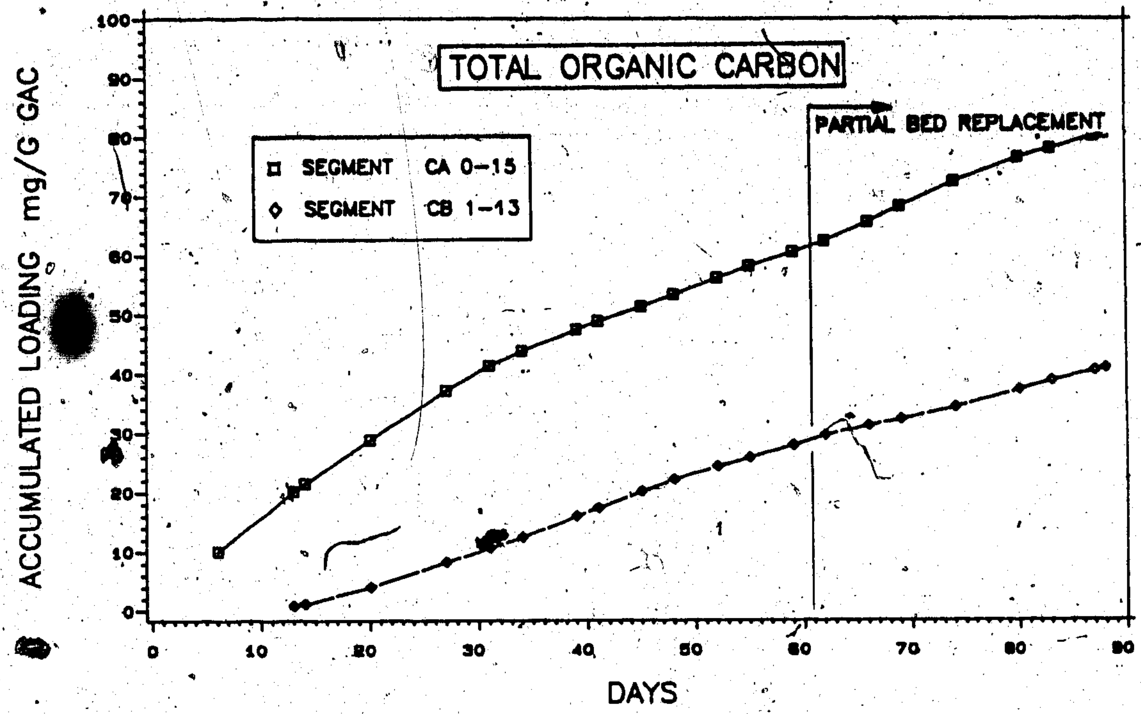

Figure 5.31 TOC Accumulated in Columns CA + CB

the end of the study period accumulation resulting from biological degradation and/or slow adsorption remained constant.

The change in slope of the Column CB accumulation curve indicating apparent exhaustion is less noticeable since the influent concentration to this column was always lower as a result of continued removal by Column CA. Following apparent exhaustion in Column A, divergence of the two curves suggests that the removal mechanisms are more effective in the first of the two series contactors.

5.2.6 Prediction of Segment Adsorption Equilibrium Capacity Using Pilot Studies

Breakthrough data may be used to predict TOC adsorption capacity according using a method described by Roberts and Summers (1982). The formula derived was of the form:

$$q_e = 0.01\ C_e^{0.53}$$

where: q_e = adsorption capacity of GAC (g TOC/g GAC)

C_e = equilibrium concentration at steady state (mg/L TOC)

This equation describes the relationship of adsorption capacity at steady state to the steady state equilibrium concentration when plotted in the Freundlich isotherm form as q_e VS C_e. The numerical coefficient and exponent were derived using many carbon types and TOC concentrations ranging from 1 mg/L to 6 mg/L.

Adsorption data from Columns A, B, and CA are presented using this form in Figure 5.32. These data differ from those analyzed by Roberts and Summers (1982) in that the loadings (q_e) represent segments at different depths rather than a complete column. The slope (1.63) is somewhat steeper than predicted by the equation and indicates that adsorption in a segmented column is more sensitive to concentration (Fochtman and Dobbs, 1980). An intercept value of 0.017 is roughly an order of magnitude less than predicted indicating a lower adsorption capacity in general for the carbons used in this study. Data points numbered according to column segment designation suggest that lower column regions will adsorb lower amounts of TOC as a result of lower C_e levels. As expected this observation is consistent with loading data presented previously.

Data representing Column A most closely coincided to the regression line. For the Buffalo Pound TOC matrix this carbon would be most useful in predicting the adsorptive behavior of others. The general equation would be defined as:

$$q_e = 0.0017\ C_e^{1.63}$$

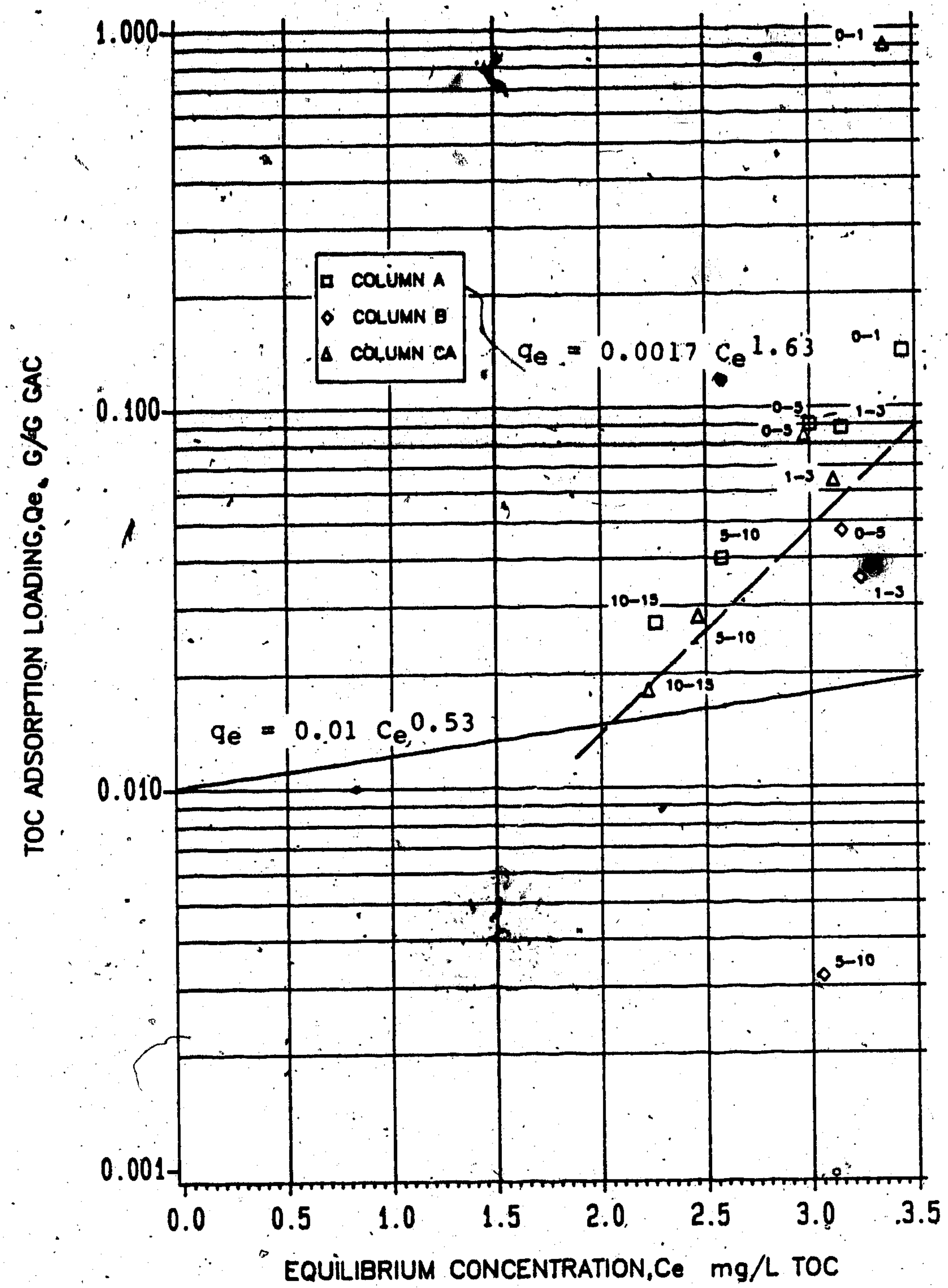

Figure 5.32 Prediction of TOC Adsorption Capacity

5.3 EFFECTS OF GRAIN SIZE DISTRIBUTION ON TTHM AND TOC ADSORPTION

Size classification of particles in a GAC adsorber bed has been reported by Alben and Shpirt (1981, 1983). In these studies the smallest particles were present at the top of the bed whereas larger particles were deposited in lower segments. This classical nature of distribution caused by backwashing and its effects on adsorption have been reviewed by others (Neely and Isacoff, 1982; Weber, 1972; Weber et al., 1983). In theory the adsorption capacity of a nonporous adsorbent varies with the inverse of the particle diameter (Weber 1972). In GAC bed studies adsorption rates have been found to decrease with increasing particle size, resulting in distortion of the mass transfer zone (MTZ) (Neely and Isacoff, 1982).

Experiments by Zogorski and Faust (1978) evaluated GAC columns containing various carbon particle sizes. These studies revealed that the rate of movement of the mass transfer zone using 2,4-dichlorophenol as the adsorbant was independent of the size of the adsorbent. However, the relative steepness of the breakthrough curve was a direct result of different rates of adsorption onto the various sizes of activated carbon. The larger the carbon size, the broader the breakthrough curve. Similar studies conducted by Rosene et al. (1980) compared breakthrough profiles of chloroform at influent concentrations of approximately

200 μg/L using coarse and fine GAC (Figure 5.33). A much broader breakthrough curve was obtained with the coarse carbon indicating slower kinetics and a wider mass transfer zone.

Grain size distribution data for carbon samples extracted from Columns A, B, and CA at Ports 1, 3, 5, 10, and 15 following 14 weeks of operation appear in Figures 5.34, 5.35, and 5.36. To determine if a relationship existed between loadings at apparent exhaustion and particle size distribution an SPSSX multiple stepwise regression routine was applied (Norusis, 1983). For Column CA only, TTHM loadings were calculated immediately prior to the partial bed replacement. The percentages of carbon retained between given U.S. Standard sieve sizes were used as the independent variables. TOC and TTHM served as dependent variables. For example, the TOC loadings measured in segments 0-1, 1-3, 0-5, 5-10, and 10-15 were regressed upon the percentage by weight of carbon particles in the >50 sieve size range from samples collected at Ports 1, 3, 5, 10, and 15. This procedure was repeated for all size ranges. The importance of a particular grain size is reflected by the relative correlation between the dependent and independent variables. The F test at $\alpha = 0.05$ was applied to interpret regression significance.

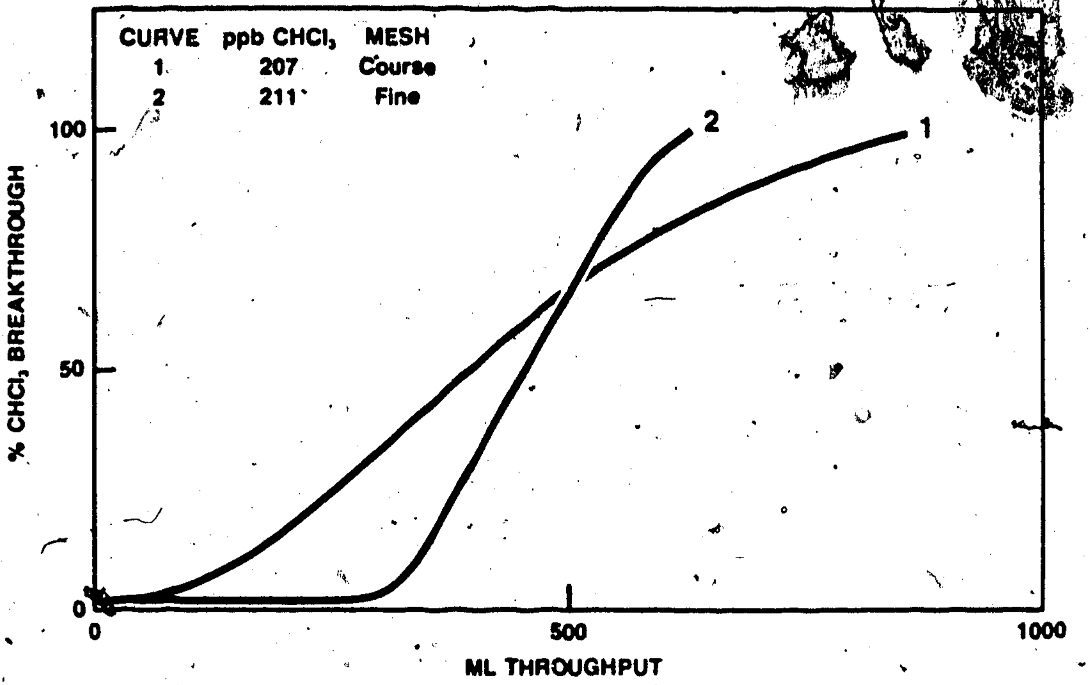

Figure 5.33 Chloroform Removal - Effect of Particle Size

(Source: Rosene et al., 1980)

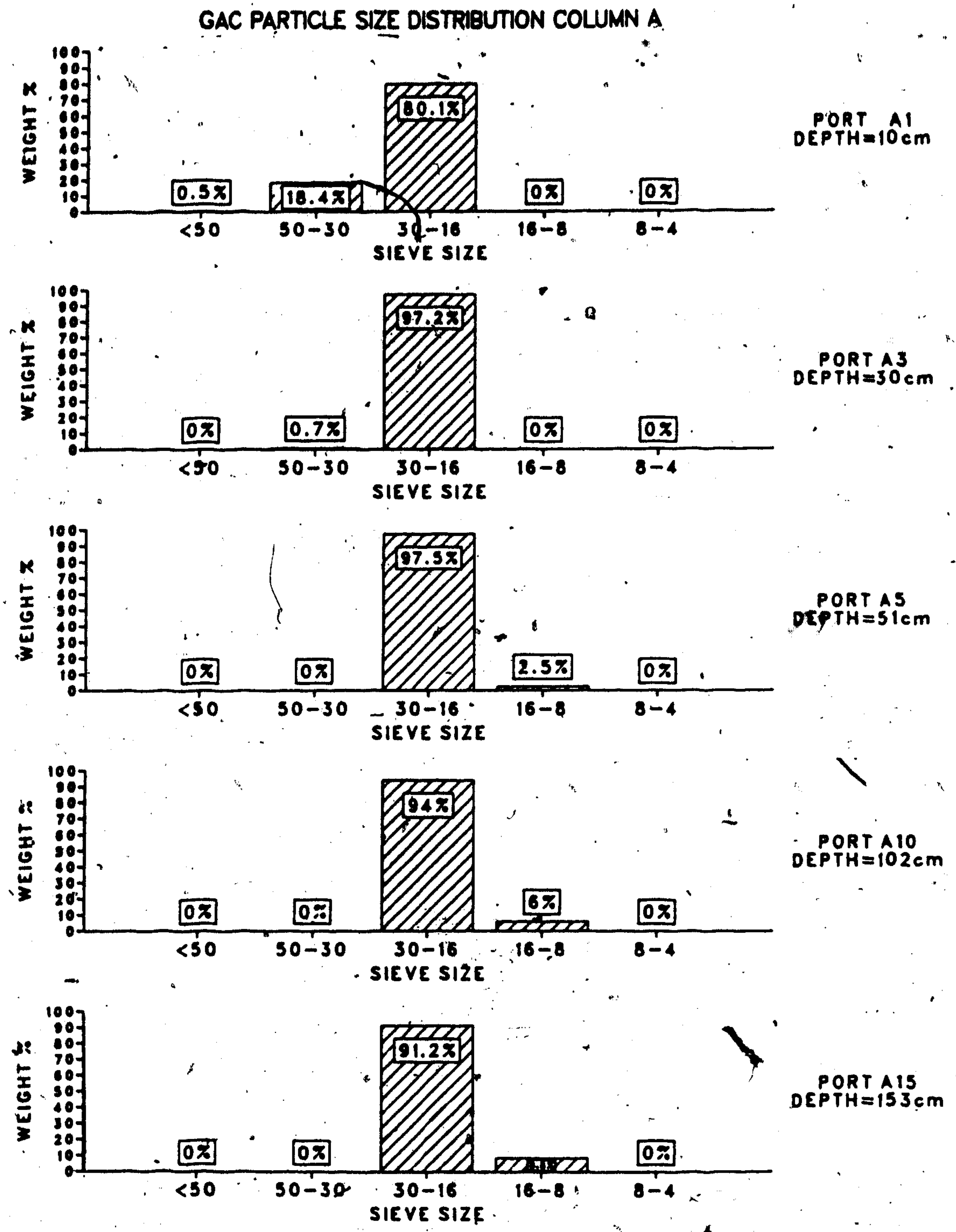

Figure 5.34 GAC Particle Size Distribution - Column A

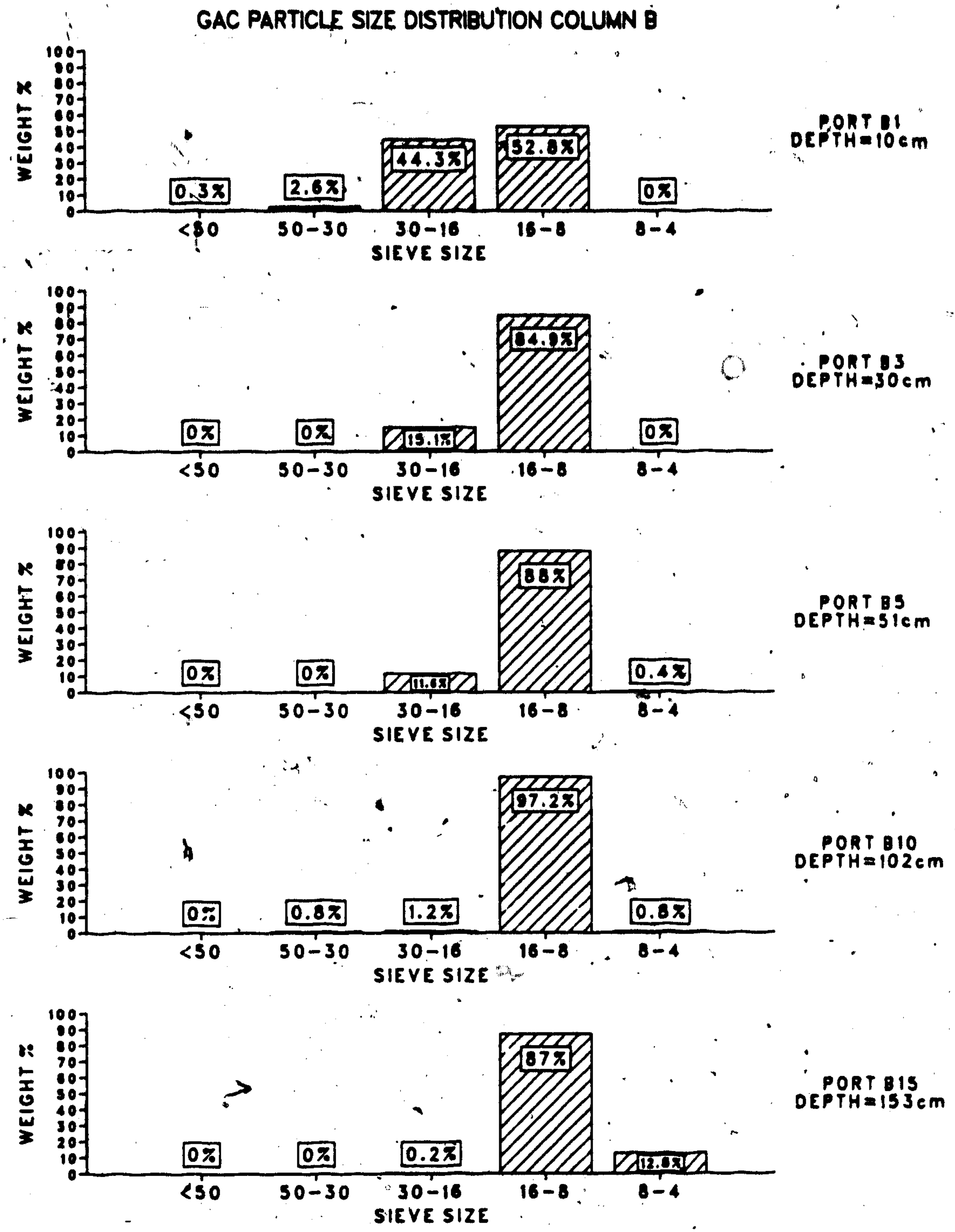

Figure 5.35 GAC Particle Size Distribution
- Column B

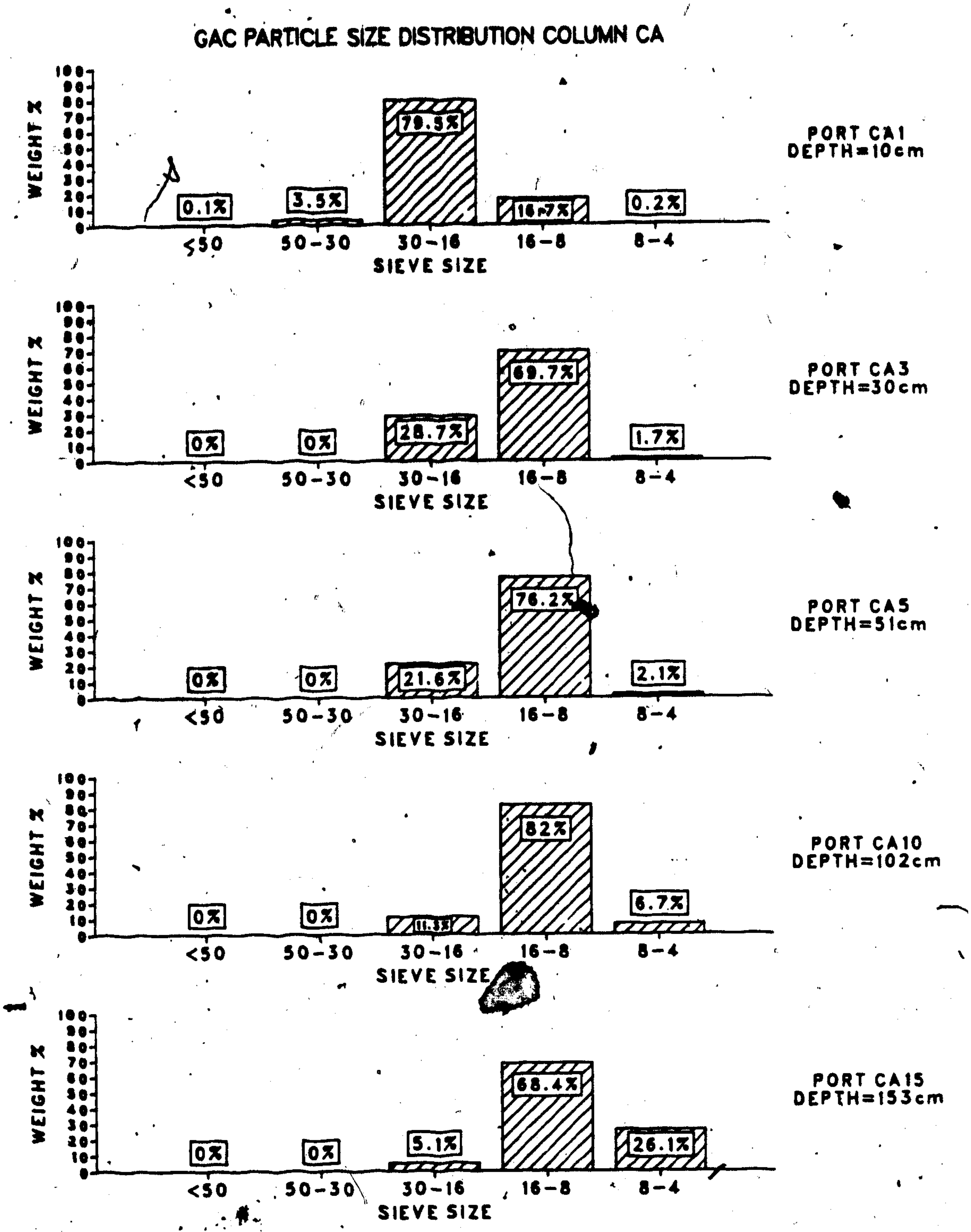

Figure 5.36 GAC Particle Size Distribution - Column CA

5.3.1 TTHM Adsorption

A study by Mullins et al. (1980) suggests that TTHM adsorption capacity at equilibrium should not be greatly influenced by particle size since TTHM are small molecules and would have access to most pores. However, broader breakthrough curves and higher mass transfer zones may be obtained from larger particles as opposed to smaller particles.

Correlation results relating TTHM loadings to the percentage material in a given size range are shown in Table 5.8. For Column A a strong positive correlation was established for sieve sizes less than 30. A negative correlation for the larger grain sizes suggests an inverse relationship between grain size and TTHM loadings. Similar results exist for Column B with one exception. A positive correlation extended to the larger grain sizes found in the sieve range 30-16.

Column CA correlations increased directly with grain size in the sieve size range of 50-30. The trend reversed for mesh sizes greater than 16. A very strong correlation for the mesh size range 30-16 suggests that this size may be preferred for TTHM adsorption.

5.3.2 TOC Adsorption

Weber et al. (1983) examined the effect of carbon particle size on equilibrium capacity. Using humic acid, increases were observed in capacity for smaller size

Table 5.8 Relative Correlation of Dependent Variables TOC and TTHM to Particle Size Distribution

Column A

Correlation Coefficient of TOC	Sieve Size	Significant at α [illegible]05
0.781	<50	No
0.793	50-30	No
0.903	30-16	Yes
-0.509	16-8	No
NC	8-4	No

Correlation Coefficient of TTHM	Sieve Size	Significant at α = 0.05
0.879	<50	Yes (slightly)
0.876	50-30	No
-0.786	30-16	No
-0.482	16-8	No
NC	8-4	No

Column B

Correlation Coefficient of TOC	Sieve Size	Significant at α = 0.05
NC	<50	No
-0.519	50-30	No
0.922	30-16	No
-0.496	16-8	No
-0.639	8-4	No

Correlation Coefficient of TTHM	Sieve Size	Significant at α = 0.05
0.891	<50	Yes (slightly)
0.874	50-30	No
0.679	30-16	No
-0.818	16-8	No
0.114	8-4	No

NC - Correlation could not be computed

Table 5.8 cont'd

Column CA

Correlation Coefficient of TOC	Sieve Size	Significant at α = 0.05
0.337	<50	No
0.891	50-30	No
0.973	30-16	Yes
-0.885	16-8	No
-0.642	8-4	No

Correlation Coefficient of TTHM	Sieve Size	Significant at α = 0.05
0.358	<50	No
0.886	50-30	No
0.981	30-16	Yes
-0.901	16-8	No
-0.624	8-4	No

NC - Correlation could not be computed

particles. Possible reasons for this effect include the ability of smaller particles to more closely approach a true equilibrium and a larger portion of available pore volume.

Correlation results obtained from column studies appear in Table 5.8. Columns A and CA display the expected correlation patterns. Positive correlations exist for the smaller grain sizes, negative correlations exist for the larger grain sizes.

No general trend in correlation was found for Column B. Negative correlations existed for sieve sizes both larger and smaller than the 30-16 range. The highest correlation of 0.922 was determined for the 3-16 sieve range but was not significant at the $\alpha = 0.05$ level.

For purposes of constructing a regression equation relating carbon capacity to particle size, the fraction of material present at a given depth in the sieve range 30-16 would be most useful as shown by the F statistic.

5.3.3 TTHM and TOC Segment Adsorption as a Function of Mean Particle Diameter

TTHM and TOC segment loadings may also be related to mean particle diameter. To determine if a relationship of this type existed, a weighted mean particle diameter, $\bar{d}_w$ was calculated for each column segment. First a geometric mean particle diameter, $\bar{d}_s$ was calculated for each of the adjacent sieve sizes according to the following equation:

$\bar{d}_s = d_1 \times d_2$

d_1 = sieve opening that material passes

d_2 = sieve opening that material is retained on

The four geometric mean particle diameters were then multiplied [illegible] the corresponding weight retained for each pair of adjacent sieves. A weighted mean particle diameter, $\bar{d}_w$ was obtained for each column segment as follows:

$\bar{d}_w$ = % weight retained 50-30 sieve ($\bar{d}_s$ 50-30) +
% weight retained 30-16 sieve ($\bar{d}_s$ 30-16) +
% weight retained 16-8 sieve ($\bar{d}_s$ 16-8) +
% weight retained 8-4 sieve ($\bar{d}_s$ 8-4)

Segment loadings were then examined as a function of weighted mean particle diameter, surface area of a spherical particle, and volume as represented by $\bar{d}_w$, $\bar{d}_w^2$, and $\bar{d}_w^3$. A linear least squares regression routine, MINITAB (University of Alberta, 1981) was applied and a $\alpha = 0.05$ confidence interval calculated for each coefficient. Results are presented in Table 5.9.

5.3.3.1 **TTHM**

Column CA was the only column to display regression coefficients that were significantly different from zero. The strongest correlation for $\bar{d}_w$ suggests that a reduction in particle diameter, rather than surface area or volume will have the most influence on TTHM adsorption. Particle volume as represented by $\bar{d}_w^2$ was the only other significant variable. The lack of a direct relationship to particle

Table 5.9 Relative Correlation of Dependent Variables TOC and TTHM to Weighted Mean Particle Diameter

Column A

TOC

Independent Variable	Regression Coefficient	Correlation Coefficient	C.I. at $\alpha = 0.05$
$\bar{d}_w$	-682.1	0.921	± 346.8
$\bar{d}_w^2$	-399.8	0.913	± 227.1
$\bar{d}_w^3$	-331.0	0.919	± 181.1

TTHM

Independent Variable	Regression Coefficient	Correlation Coefficient	C.I. at $\alpha = 0.05$
$\bar{d}_w$	-7.21	0.559	± 11.76
$\bar{d}_w^2$	-4.09	0.520	± 7.23
$\bar{d}_w^3$	-3.45	0.541	± 5.83

Column B

TOC

Independent Variable	Regression Coefficient	Correlation Coefficient	C.I. at $\alpha = 0.05$
$\bar{d}_w$	-121.8	0.628	± 285.4
$\bar{d}_w^2$	-35.3	0.616	± 84.7
$\bar{d}_w^3$	-13.4	0.600	± 33.3

TTHM

Independent Variable	Regression Coefficient	Correlation Coefficient	C.I. at $\alpha = 0.05$
$\bar{d}_w$	-1.08	0.220	± 3.73
$\bar{d}_w^2$	-0.30	0.167	± 1.23
$\bar{d}_w^3$	-0.11	0.120	± 0.53

Table 5.9 cont'd.

Column CA

TOC

Independent Variable	Regression Coefficient	Correlation Coefficient	C.I. at $\alpha = 0.05$
$\bar{d}_w$	-150.9	0.883	± 101.0
$\bar{d}_w^2$	-47.4	0.804	± 43.1
$\bar{d}_w^3$	-18.5	0.707	± 21.7

TTHM

Independent Variable	Regression Coefficient	Correlation Coefficient	C.I. at $\alpha = 0.05$
$\bar{d}_w$	-1.38	0.876	± 0.95
$\bar{d}_w^2$	-0.43	0.793	± 0.40
$\bar{d}_w^3$	-0.17	0.695	± 0.20

size for the other columns supports Mullins et al., (1980) findings that TTHM adsorption is not greatly dependent upon particle size.

5.3.3.2 TOC

Significant inverse relationships were observed for variables $\bar{d}_w$, $\bar{d}_w^2$, and $\bar{d}_w^3$ in Column A and $\bar{d}_w$ and $\bar{d}_w^2$ in Column CA. As for TTHM, Column B continued to display no direct relationship. The availability of a greater amount of available pore volume as characterized by a decreasing particle diameter appears to be the governing variable in TOC adsorption. The apparent higher functionality for particle diameter as opposed to particle surface area or volume may in part be explained by the narrower range of numerical values prior to being squared or cubed.

5.4 EVALUATION OF MASS TRANSFER ZONE CONCEPTS

5.4.1 General

Removal of a particular adsorbable component conceptually occurs in a band within a GAC column. This band or wavefront is called the mass transfer zone (MTZ). A detailed explanation of this concept is presented elsewhere (Perrich, 1981; Chermisinoff, 1978; Neely and Isacoff, 1982).

Upon startup of a column type contacter, the concentration of a compound entering the column decreases to a very low or undetectable level within the MTZ. During a period of continuous operation the carbon at the top end of the MTZ reaches its equilibrium capacity for the adsorbate. Immediately following, the MTZ begins to move downward through the bed. When the leading edge of the MTZ reaches the effluent end of the bed, the compound will be observed in small but increasing concentrations, denoted as breakthrough. Eventually the effluent concentration will approach or reach the influent concentration as the bed reaches exhaustion. Minimization of the MTZ length is desirable in column operations since the capacity of the carbon for a particular compound increases as the length of the MTZ decreases. The rate of movement of the MTZ is important since it indicates the rate at which the bed will be exhausted. This is ultimately dependent upon the affinity of the adsorbate for the adsorbent, but will be influenced by operational parameters such as flowrate.

The ability of stratified beds to cause distortion in mass transfer zones was noted by Neeley and Isacoff (1982). This distortion resulted from adsorption rates which varied inversely with particle size. Perrich (1981) suggests that a choice of carbon with a smaller mean particle diameter (MPD) is usually accompanied by a reduction in the mass transfer zone and improved utilization of the carbon. Carbons with MPDs ranging between 0.8 and 1.7 mm (approximate sieve range 30-16) were suggested as a good compromise between minimum MTZ values and good hydraulic characteristics.

Particles with lower MPDs may result in higher head losses and an increased backwash frequency.

An equation presented by Perrich (1981) to calculate the height of the MTZ is defined by:

$$MTZ = L(t_s - t_b)/t_s$$

Where: MTZ = height of mass transfer zone (cm)

L = Length of carbon bed (cm)

t_b = Breakthrough time (days)

t_s = Saturation (exhaustion) time (days)

This equation was combined with an equation presented by Neeley and Isacoff (1982) defining the rate of movement of the adsorption front, to describe column behavior in this study. The rate of movement of the mass transfer zone is defined by:

$$S = \frac{MTZ}{(t_s - t_b)}$$

Where: S = Speed of adsorption front (cm/day)

MTZ = Height of mass transfer zone (cm)

t_s = Saturation (exhaustion) time (days)

t_b = breakthrough time (days)

Zogorski and Faust (1978) examined the effect of particle size on the height of MTZ and its rate of movement. The rate of movement for columns of similar depth was found to be independent of the size of the adsorbent and bed depth. MTZ height however displayed an inverse relationship to particle size for sizes less than 0.65 mm and a small, but direct relationship to bed depth.

5.4.2 Comparison of Columns A and B

A summary of MTZ characteristics for Columns A and B is presented in Tables 5.10 and 5.11.

If the rate of MTZ movement is assumed to be independent of bed depth for Columns A and B then particle size may be viewed as the governing variable. In both Columns A and B the MTZ height varied directly with column depth for most trihalomethanes. This observation however must be viewed in conjunction with particle size distribution. A higher percentage of smaller diameter particles was found in the upper segments of both columns. These smaller particles likely have a greater effect on reduction of MTZ height than column depth because of more rapid adsorption.

Competitive adsorption may also be a factor in governing MTZ height (Perrich (1981)) states that more strongly adsorbed compounds may displace weaker compounds and force them to readsorb at lower bed depths. This would result in an extension of the weaker component MTZ as would movement with time. For both Columns A and B dibromochloromethane consistently exhibited the lowest MTZ height followed by bromodichlormethane, chloroform and TTHM especially in lower depths. This observation is consistent with results presented by Mullins et al. (1981) and suggests that dibromochloromethane would be the most strongly adsorbed

Table 5.10 MTZ Characteristics - Column A

5.16a Height of MTZ

Port	Segment	Percentage of Material in Sieve Size					Segment Height (cm)	Height of MTZ (cm)			
		Sieve Size (mm)						Compound			
		<0.30	0.30-0.60	0.60-1.18	1.18-2.36	2.36-4.75		TTHM	$CHCl_3$	$CHCl_2Br$	$CHClBr_2$
1	0-1	0.5	18.7	80.1	0.0	0.0	10	10	ND	10	10
5	0-5	0.0	0.0	97.5	2.5	0.0	51	50	51	51	50
10	0-10	0.0	0.0	94.0	6.0	0.0	102	100	100	99	97
15	0-15	0.0	0.0	91.2	8.8	0.0	153	138	142	146	120

ND - Not Determined

5.16b Rate of MTZ Movement

Port	Segment	Percentage of Material in Sieve Size					Segment Height (cm)	Rate of MTZ Movement (cm/day)			
		Sieve Size (mm)						Compound			
		<0.30	0.30-0.60	0.60-1.18	1.18-2.36	2.36-4.75		TTHM	$CHCl_3$	$CHCl_2Br$	$CHClBr_2$
1	0-1	0.5	18.7	80.1	0.0	0.0	10	0.2	ND	0.4	0.4
5	0-5	0.0	0.0	97.5	2.5	0.0	51	1.0	1.0	0.8	1.2
10	0-10	0.0	0.0	96.0	6.0	0.0	102	1.4	1.9	1.2	1.2
15	0-15	0.0	0.0	91.2	8.8	0.0	153	2.0	2.7	1.7	1.4

ND - Not Determined

Table 5.11 MTZ Characteristics - Column B

5.17a Height of MTZ

Port	Segment	Percentage of Material in Sieve Size					Segment Height (cm)	Height of MTZ (cm)			
		Sieve Size (mm)						Compound			
		<0.30	0.30-0.60	0.60-1.18	1.18-2.36	2.36-4.75		TTHM	$CHCl_3$	$CHCl_2Br$	$CHClBr_2$
1	0-1	0.30	2.6	44.3	52.8	0.0	10	10	10	10	9
5	0-5	0.0	0.0	11.6	88.0	0.4	51	51	50	50	43
10	0-10	0.0	0.8	1.2	97.2	0.8	102	100	100	97	90
15	0-15	0.0	0.0	0.2	87.0	12.8	153	149	150	148	106

5.11b Rate of MTZ Movement

Port	Segment	Percentage of Material in Sieve Size					Segment Height (cm)	Rate of MTZ Movement (cm/day)			
		Sieve Size (mm)						Compound			
		<0.30	0.30-0.60	0.60-1.18	1.18-2.36	2.36-4.75		TTHM	$CHCl_3$	$CHCl_2Br$	$CHClBr_2$
1	0-1	0.30	2.6	44.3	52.8	0.0	10	0.2*	0.4	0.3	0.3
5	0-5	0.0	0.0	11.6	88.0	0.4	51	0.94	1.2	0.7	0.6
10	0-10	0.0	0.8	1.2	97.2	0.8	102	1.6*	1.5	0.9	0.7
15	0-15	0.0	0.0	0.2	87.0	12.8	153	1.2	1.6	0.6	0.8

*Appear anomalous due to extrapolated value for apparent exhaustion time competitor. The rate of MTZ movement followed a similar trend to MTZ height, and may also be influenced by this factor. Strength of adsorption appears to vary inversely with the rate of MTZ movement.

Shallow beds (<51 cm) with a predominant grain size in the range of 0.60-1.18 mm should present the best characteristics for reducing concentrations of TTHM. The short height and low rate of MTZ movement in the top 51 cm confirms the high affinity of TTHM for the carbons tested.

5.5 EVALUATION OF ISOTHERM DATA

5.5.1 Isotherm Results

Isotherm results for the three carbons used in pilot studies appear in Figures 5.37 to 5.41, Table 5.12, and Appendix F. Freundlich constants K and 1/n were obtained using linear least squares. K values for Norit® Row 0.8 (Column A) and Witco® 950 (Column B) are similar in magnitude for $CHCl_3$, $CHCl_2$, and $CHClBr_2$. The increasing magnitude of the respective K values for $CHCl_3$, $CHCl_2Br$, and $CHClBr_2$ indicate the capacity of the carbon to adsorb each of these TTHM components. From these results $CHCl_2Br$ will be adsorbed to a much higher degree than $CHCl_3$, with $CHClBr_2$ adsorbed to a higher degree than either of the others. It is important to note that the relative order is not specific to one carbon (for similar molecules). Similar results were obtained in a study by Youssefi and Faust (1980). Larger K

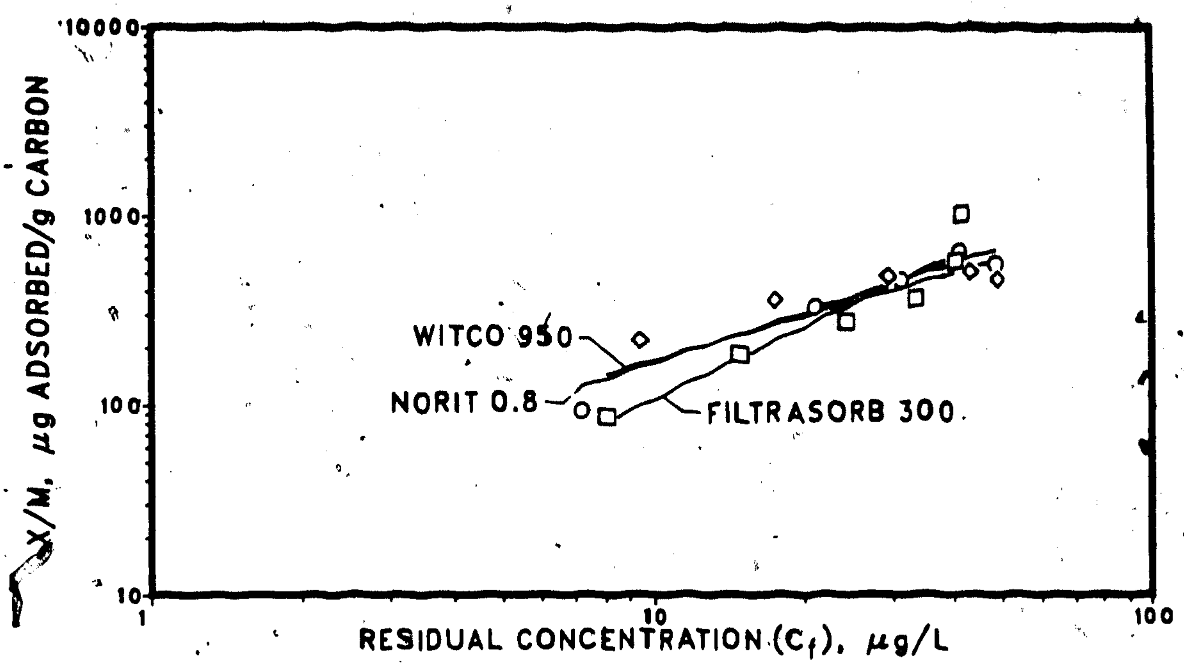

Figure 5.37 Chloroform Adsorption Isotherms – Norit® 0.8, Witco® 950, and Filtrasorb® 300

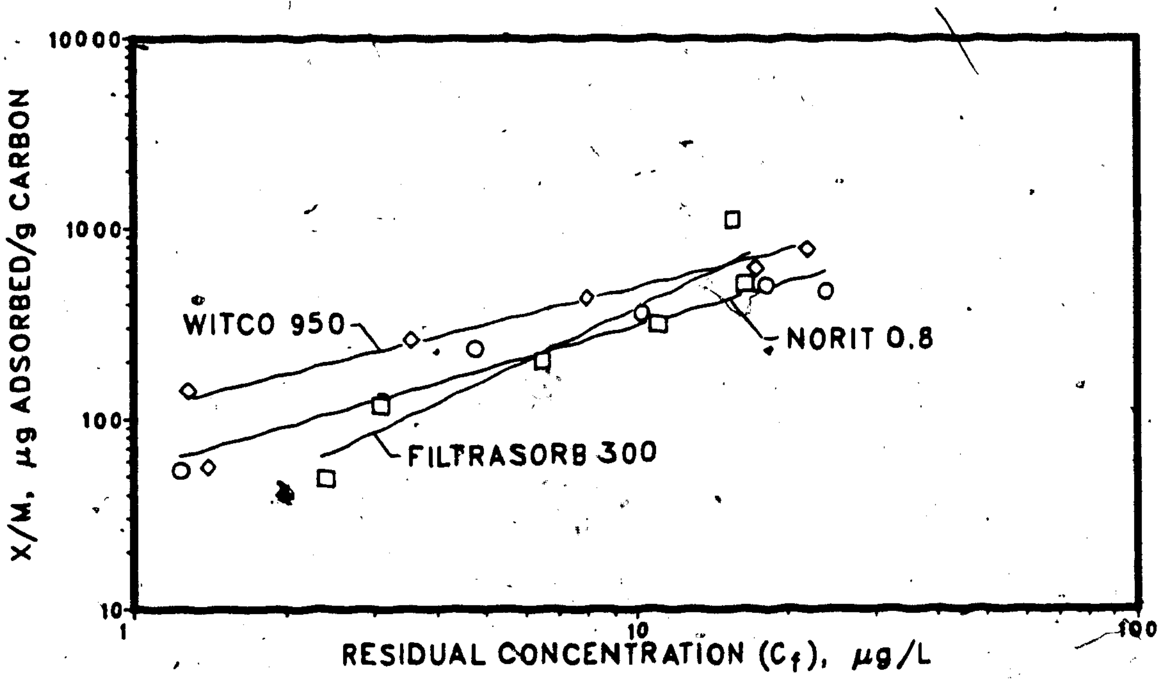

Figure 5.38 Bromodichloromethane Adsorption Isotherms – Norit® 0.8, Witco® 950, and Filtrasorb® 300

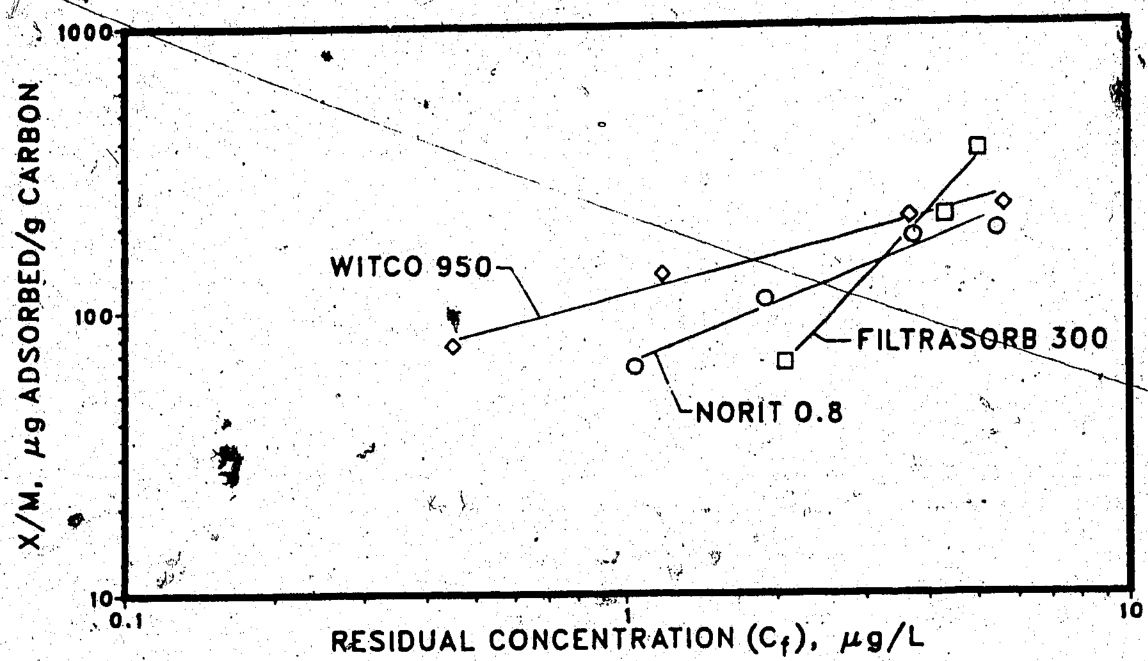

Figure 5.39 Dibromochloromethane Adsorption Isotherms - Norit® 0.8, Witco® 950, and Filtrasorb® 300

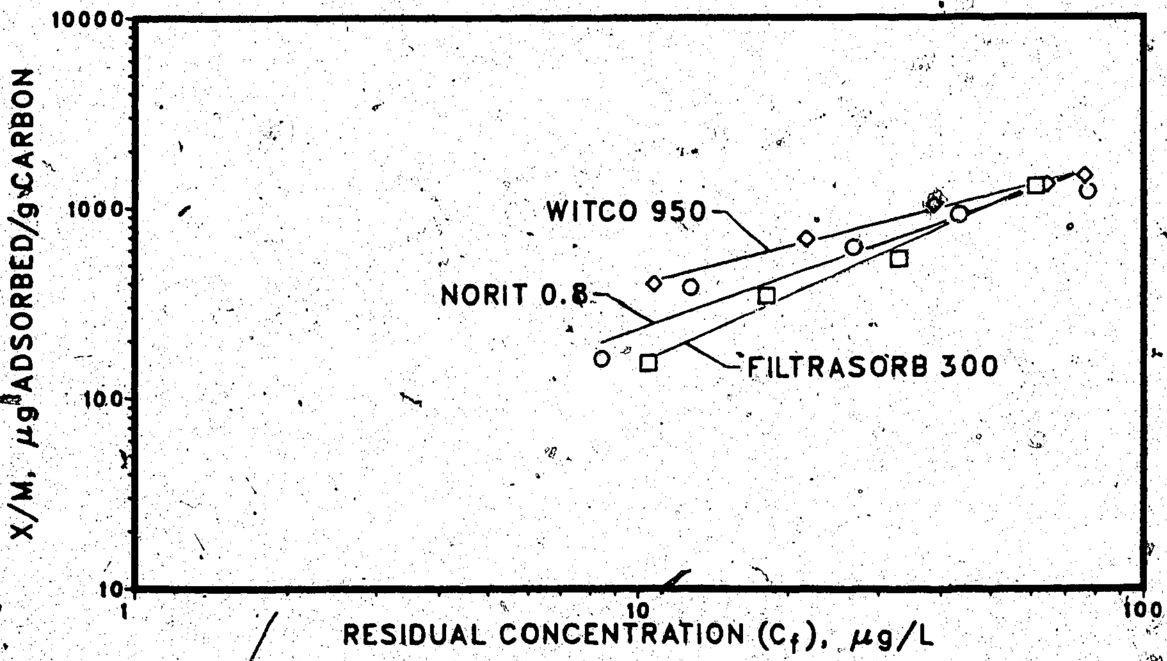

Figure 5.40 TTHM Adsorption Isotherms - Norit® 0.8, Witco® 950, and Filtrasorb® 300

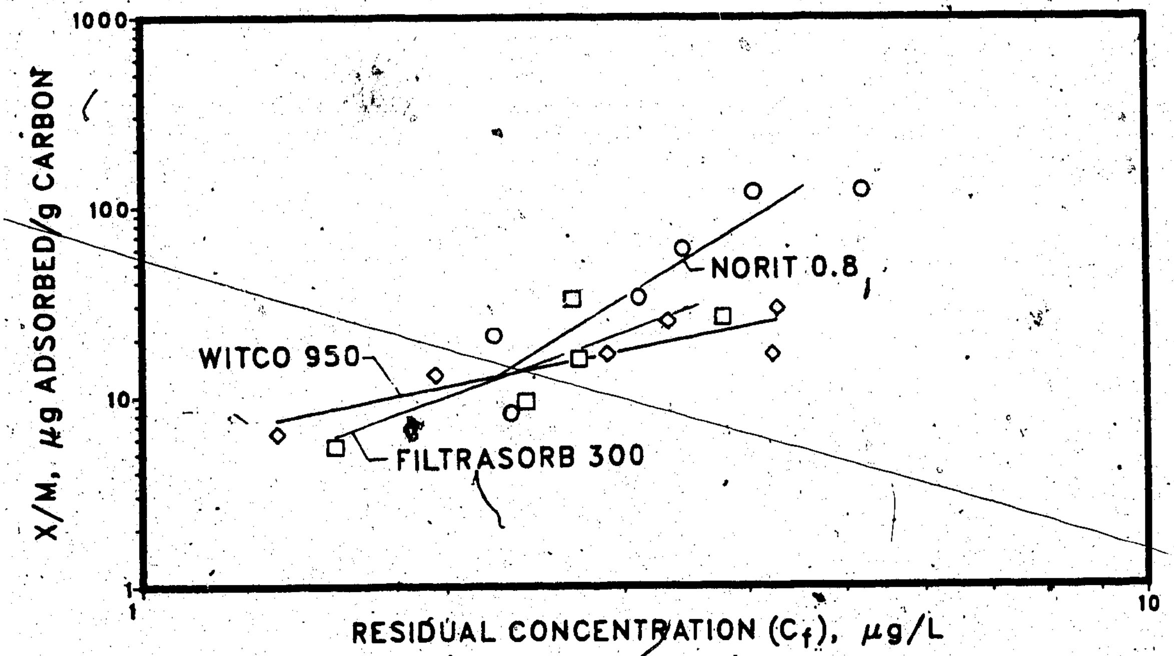

Figure 5.41 TOC Adsorption Isotherms - Norit® 0.8, Witco® 950, and Filtrasorb® 300

Table 5.12 Freundlich Parameters from Isotherm Studies

5.12a Carbon Type - Norit® Row 0.8 (Column A)

Compound	pH	Equilibrium Zone Range (μg/L)	Freundlich Parameters K	1/n	Correlation Coefficient	No. of Data Points
Chloroform	7.38	7.2-48.4	22.3	0.875	0.910	6
Bromodichloromethane	7.38	1.2-23.5	54.3	0.757	0.951	6
Dibromochloromethane	7.38	1.0-5.5	65.9	0.694	0.960	4
TTHM	7.38	8.5-77.4	32.0	0.881	0.945	6
		mg/L				
TOC	7.38	2.3-5.2	1.3	2.963	0.844	6

5.12b Carbon Type - Witco® 950 (Column B)

Compound	pH	Equilibrium Zone Range (μg/L)	Freundlich Parameters K	1/n	Correlation Coefficient	No. of Data Points
Chloroform	7.44	8.9-48.8	29.3	0.770	0.780	6
Bromodichloromethane	7.44	1.4-21.8	79.3	0.758	0.880	6
Dibromochloromethane	7.44	0.5-5.6	114.5	0.452	0.976	4
TTHM	7.44	10.7-76.2	87.9	0.659	0.991	5
		mg/L				
TOC	7.44	1.4-4.3	5.5	1.047	0.791	6

5.12c Carbon Type - Filtrasorb® 300 (Column CA)

Compound	pH	Equilibrium Zone Range (μg/L)	Freundlich Parameters K	1/n	Correlation Coefficient	No. of Data Points
Chloroform	7.49	8.1-41.7	5.8	1.264	0.907	6
Bromodichloromethane	7.49	2.4-15.6	20.0	1.266	0.893	6
Dibromochloromethane	7.49	2.1-5.0	16.6	1.846	0.980	3
TTHM	7.49	10.5-62.3	6.1	1.365	0.940	5
		mg/L				
TOC	7.49	1.6-3.8	2.2	1.912	0.703	5

values obtained for Column B indicate that this column would remove trihalomethanes most effectively.

Filtrasorb® 300 (Column CA) displayed lower K values for $CHCl_3$, $CHCl_2Br$, and $CHClBr_2$ than either the Norit® or Witco® carbons. K values for TTHM exhibited the same relative magnitude relationship between the carbons as the substituent compounds. The actual K value for TTHM fell somewhere between $CHCl_3$ and $CHClBr_2$ values for all three of the carbons. Lower values for relative adsorbability (1/n) combined with high adsorptive capacities (K) suggest that Witco® 950 would remove TTHM components most effectively.

TOC adsorption characteristics followed a similar trend as noted for TTHM. 1/n values greater than one are consistent with findings by Lee and Snoeyink (1980) for similar carbons using humic acids. Of the three carbons tested the Norit® brand would be most effective [illegible] TOC removed followed by F-300® and Witco® 950 respectively.

5.5.2 Comparison of Isotherm and Column Results

A comparison of loadings obtained from isotherm and column studies is presented in Figures 5.42 to 5.46 and Appendix G. Such a comparison allows the usefulness of isotherm results in predicting column behavior to be evaluated. Loading data is complete for Columns A and B since apparent exhaustion either occurred within the study period or could be extrapolated for each of the column segments. Complete data could not be obtained for Column CA

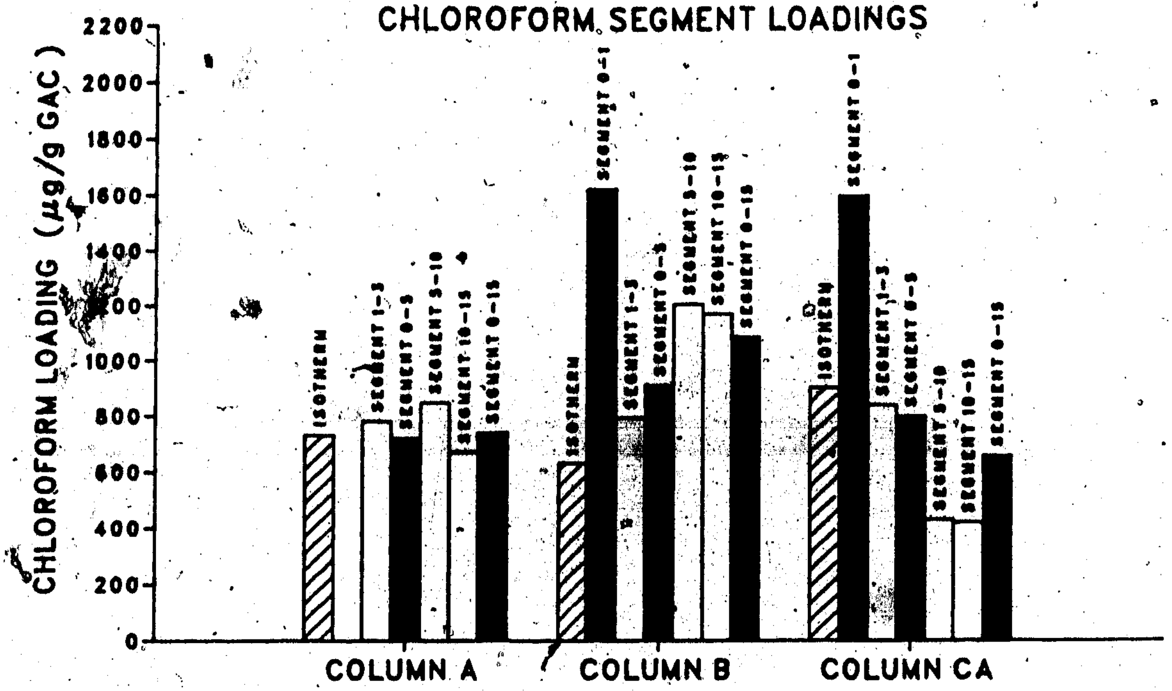

Figure 5.42 Comparison of Isotherm and Column Chloroform Loadings - Columns A, B, and CA

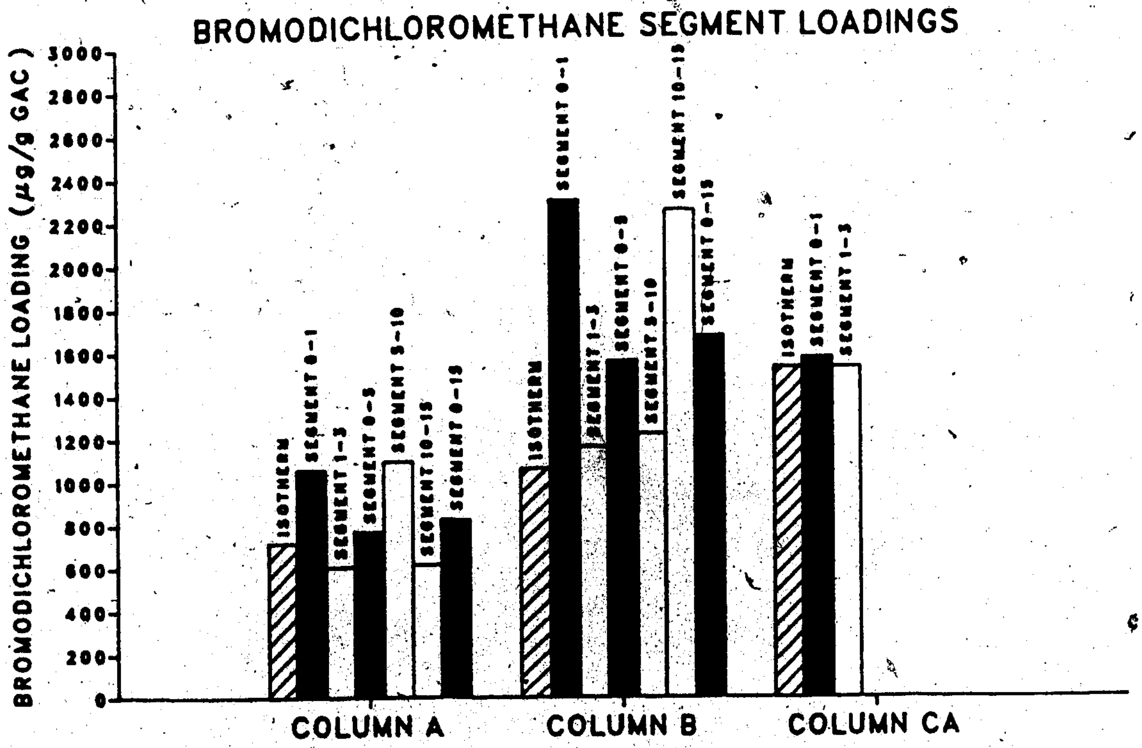

Figure 5.43 Comparison of Isotherm and Column Bromodichloromethane Loadings - Column A, B, and CA

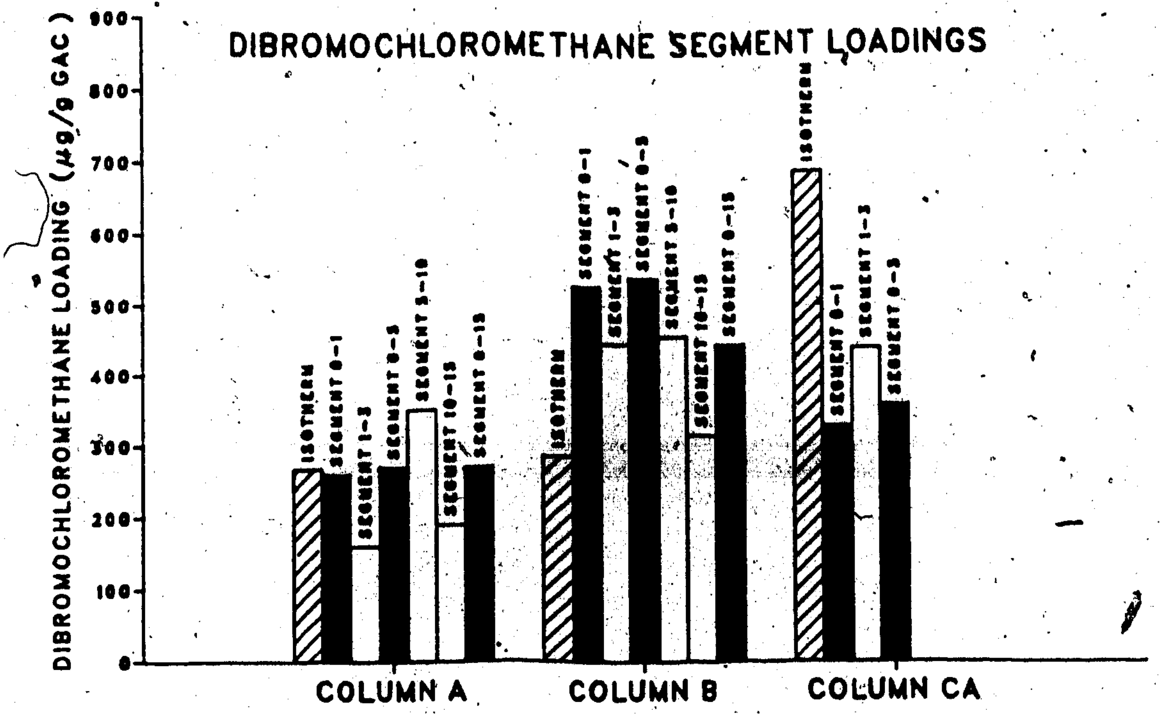

Figure 5.44 Comparison of Isotherm and Column Dibromochloromethane Loadings - Column A, B, and CA

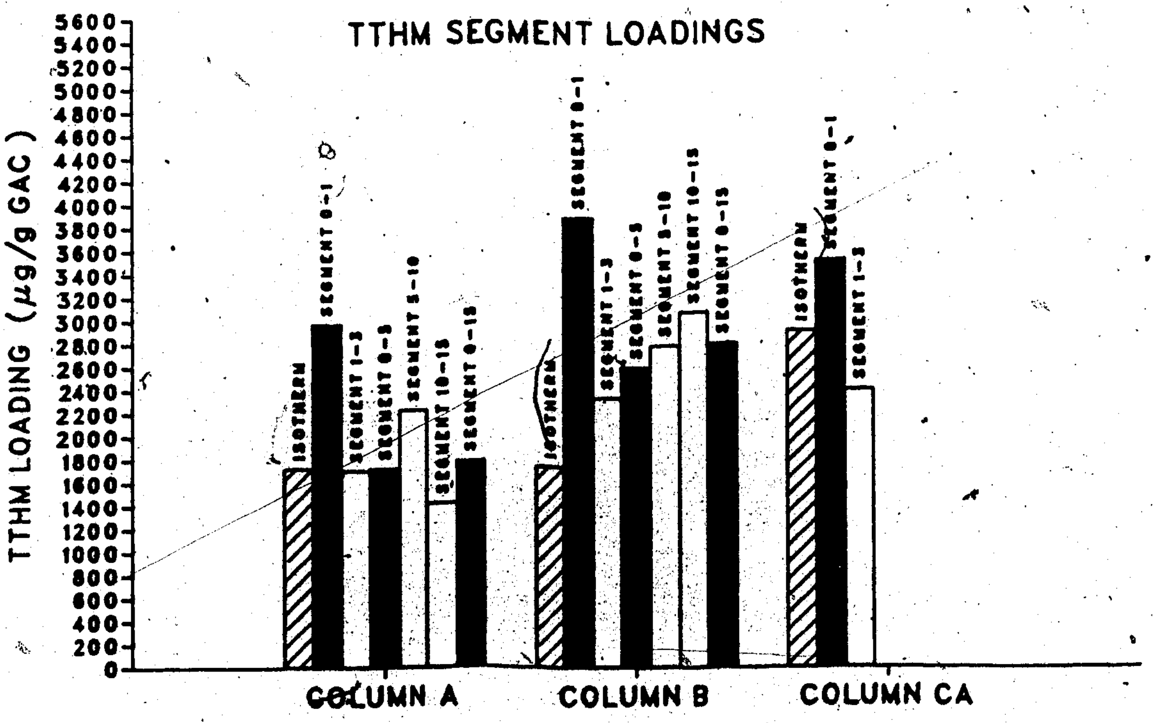

Figure 5.45 Comparison of Isotherm and Column TTHM Loadings - Columns A, B, and CA

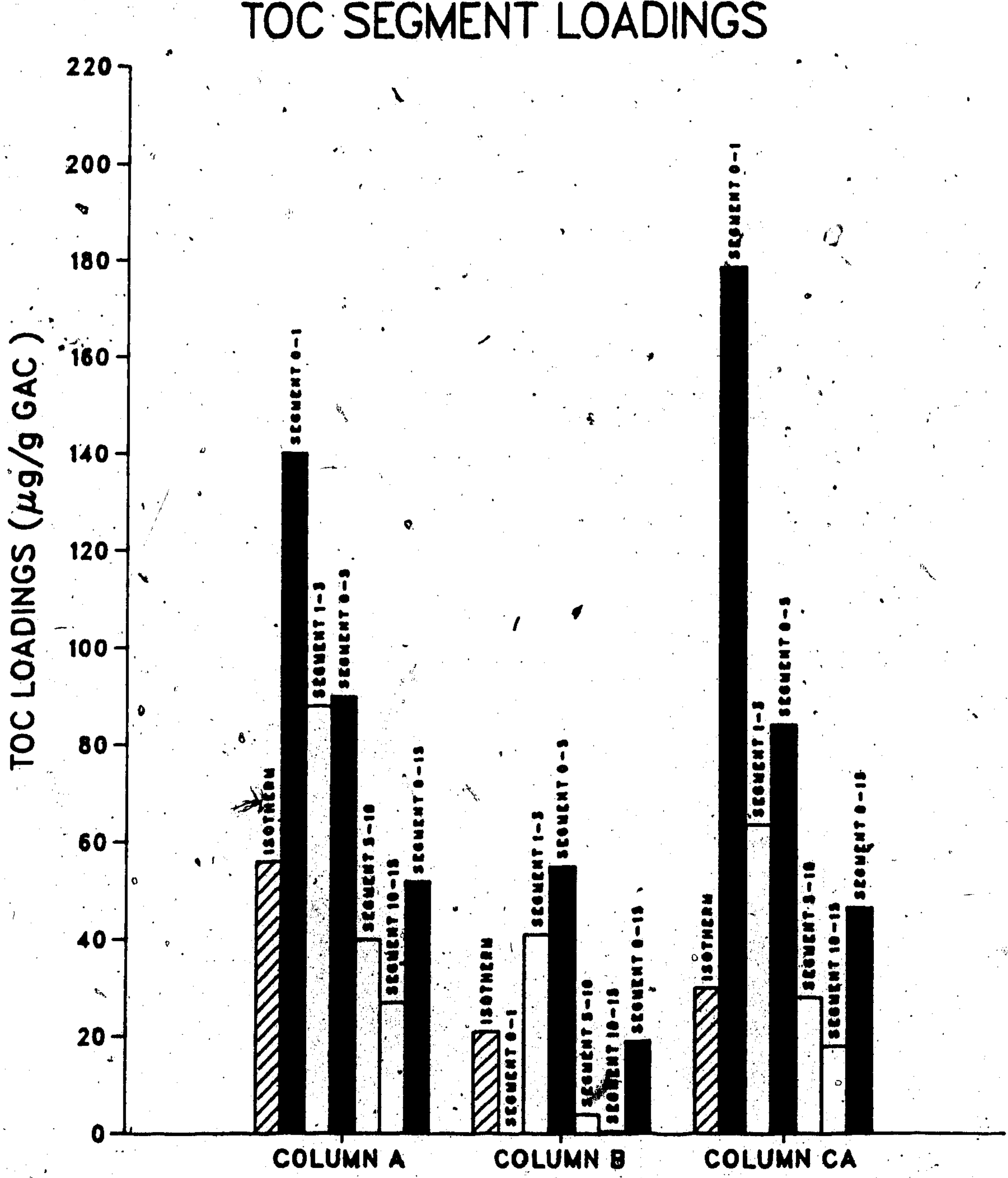

Figure 5.46 Comparison of Isotherm and Column TOC Loadings - Columns A, B, and CA

since the carbon replacement at day 61 occurred prior to lower segment apparent exhaustion. Loadings calculated by extrapolation for these segments would be meaningless since the effect of the replacement on loading behavior could not be accurately defined.

Column A displayed an extremely good agreement between trihalomethane isotherm data and loading data obtained for segments 0-5 and 0-15. in addition, the dibromochloromethane isotherm loading was consistent with segment 0-1 as was TTHM for segment 0-3. Actual segment loadings ranged from 1.5 to 1.7 times isotherm values for $CHCl_2Br$ and TTHM at segment 0-1. These cannot be explained by simple adsorption theory and may be a result of the small grain size present at the influent end of the column. Loadings which exceeded isotherm predictions were also detected at mid-column (segment 5-10) for TTHM and substituent components.

For Column B segment 1-3 provided the best correlation between chloroform and TTHM isotherms and column loading data. Segments 1-3 and 10-15 provided the best correlation for bromodichlormethane and dibromochloromehtane respectively. Almost all other column segments displayed loading values higher than predicted by isotherms. For all compounds except $CHClBr_2$ the highest loadings occurred in segment 0-1 followed by segment 10-15. Loadings for this component varied inversely with depth for the three major segments (0-5, 5-10, and 10-15) suggesting that it competed most effectively in the top one-third of the bed or that exhaustion had not really occurred in lower segm[illegible]. Bromodichloromethane was observed to accumulate to the greatest extent in the lowest major segment (10-15). Chloroform loadings were higher and approximately equally distributed in the lower segments (5-10 and 10-15).

TOC column loadings were not well correlated to isotherm data for either Column A or B. In general the loadings predicted by isotherms describe the behavior of mid to lower column depths. Biological action may in part explain the higher apparent removal capacity of the top one-third (segment 0-5).

As noted earlier, Column CA loading data is limited for most compounds to only the uppermost segments as a result of the carbon replacement at day 61. Chloroform however was observed to have exhausted the adsorptive capacity of the entire carbon bed prior to day 61. Isotherm results could be used to predict the capacity of segment 0-5 but over-estimated lower bed capacity. Both $CHCl_3$ and $CHCl_2Br$ attained higher loadings than predicted by isotherms in segment 0-1. A decrease in column loading of almost 50% was noted in the segment 1-3 immediately below.

Dibromochloromethane loading in segment 0-1 was less than 50% of the amount estimated using isotherms. A higher loading would have been expected assuming a K value very close to that obtained for chloroform.

The loading pattern for TOC in Column CA varied inversely with depth in the three major segments (0-5, 5-10, and 10-15). Isotherm studies were found useful in predicting mid-column loadings (segment 5-10). As observed for Column A, the highest TOC loadings were obtained in the uppermost segment (0-1). As before, the inability of isotherm data to predict the total column loading (segment 0-15) may be attributed to biological degradation of TOC prior to observed apparent exhaustion.

5.6 COMPETITIVE ADSORPTION - FILTRASORB® 300

Competitive adsorption effects for Filtrasorb® 300 (Column CA) may be examined by construction of wavefront profiles as shown in Figure 5.47. Only trihalomethanes will be discussed using the Polanyi-Manes adsorption theory explained in Appendix H.

The scale on the vertical axis (Figure 5.47) represents the average concentration during the study period before the carbon replacement. This value may be obtained for each compound by projecting the tip of each curve horizontally, and reading the value directly. The x-intercept represents the days until breakthrough while the vertical projection of the tip of each curve represents the days to apparent exhaustion. These values are also shown in brackets above each individual curve. Curves of this type may be constructed for various depths in the column since data was collected at five monitoring ports. Data for chloroform is presented for all five segments. Bromodichloromethane and

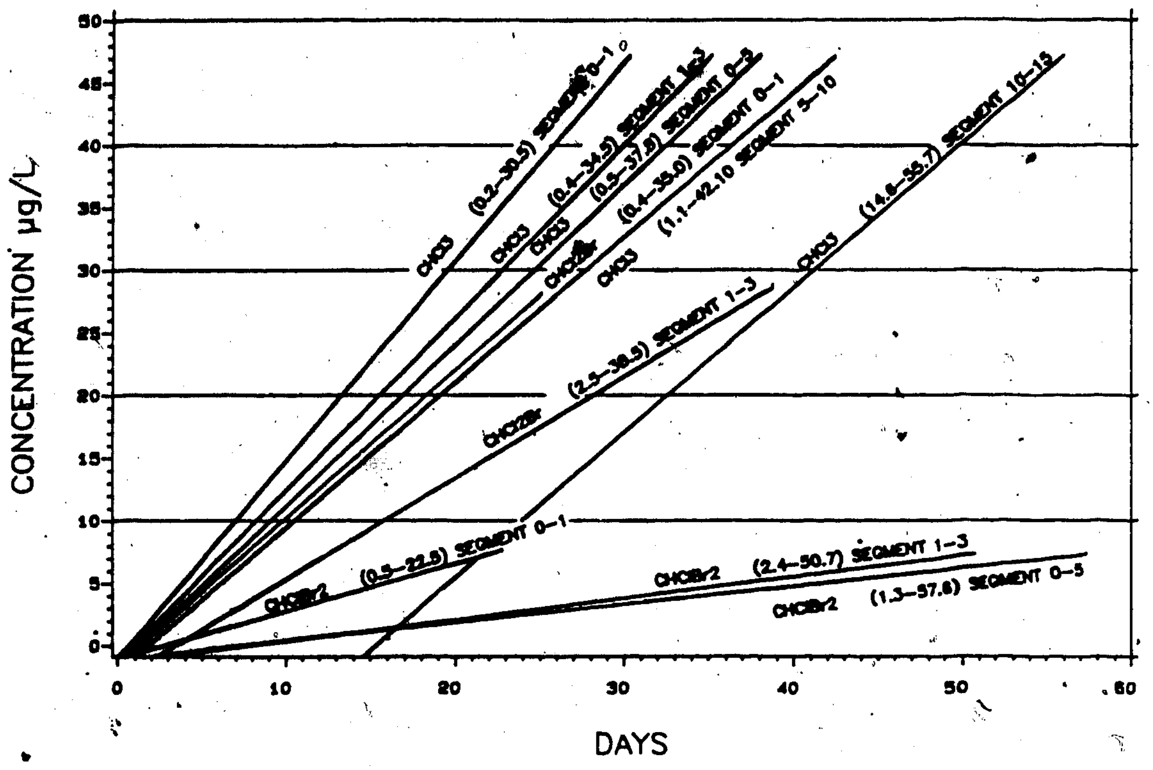

Figure 5.47 Adsorption Wavefront as Defined by Breakthrough and Apparent Exhaustion – Column CA

dibromochloromethane data is limited however, since apparent exhaustion was observed in only the upper segments prior to the carbon replacement.

Of the three compounds, chloroform competes least effectively as shown by its earlier breakthrough and apparent exhaustion times. Bromodichloromethane and dibromochloromethane experience more effective competition as shown by the displacement of their wavefronts to the right.

5.7 APPLICATION OF THE POLANYI-MANES ADSORPTION THEORY - COMPARISON OF THEORETICAL AND ACTUAL ADSORPTION

The Polanyi-Manes theory was used to qualitatively compare actual adsorption occurring in isotherm and column tests to that predicted for pure water. Calculated adsorptive capacities for pure solutions cannot be rigorously applied to mixed solutions without experimental verification. However, a qualitative discussion will illustrate the order of magnitude of competitive effects and indicate whether upper segment values exceed their expected pure water capacities.

First, the theoretical pure water adsorption curves for bromodichloromethane and dibromochloromethane were constructed using the same procedure as for chloroform in Figure H1. For both compounds, the scale factor is greater than unity so the predicted curves appear above the butane gas curve. All three curves (Figures 5.48, 5.49 and 5.50)

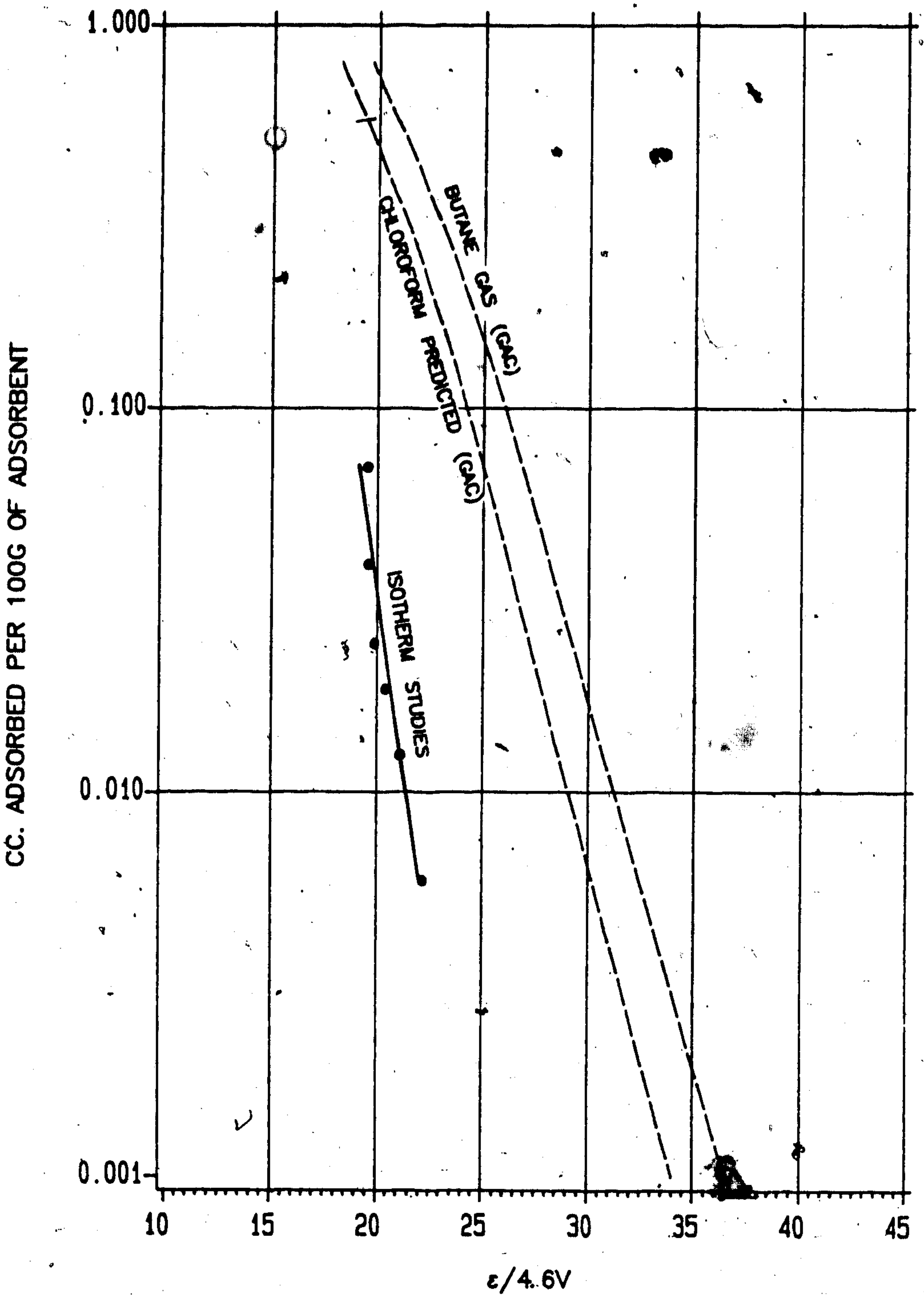

Figure 5.48 Polanyi Adsorption Potential Curve for Chloroform

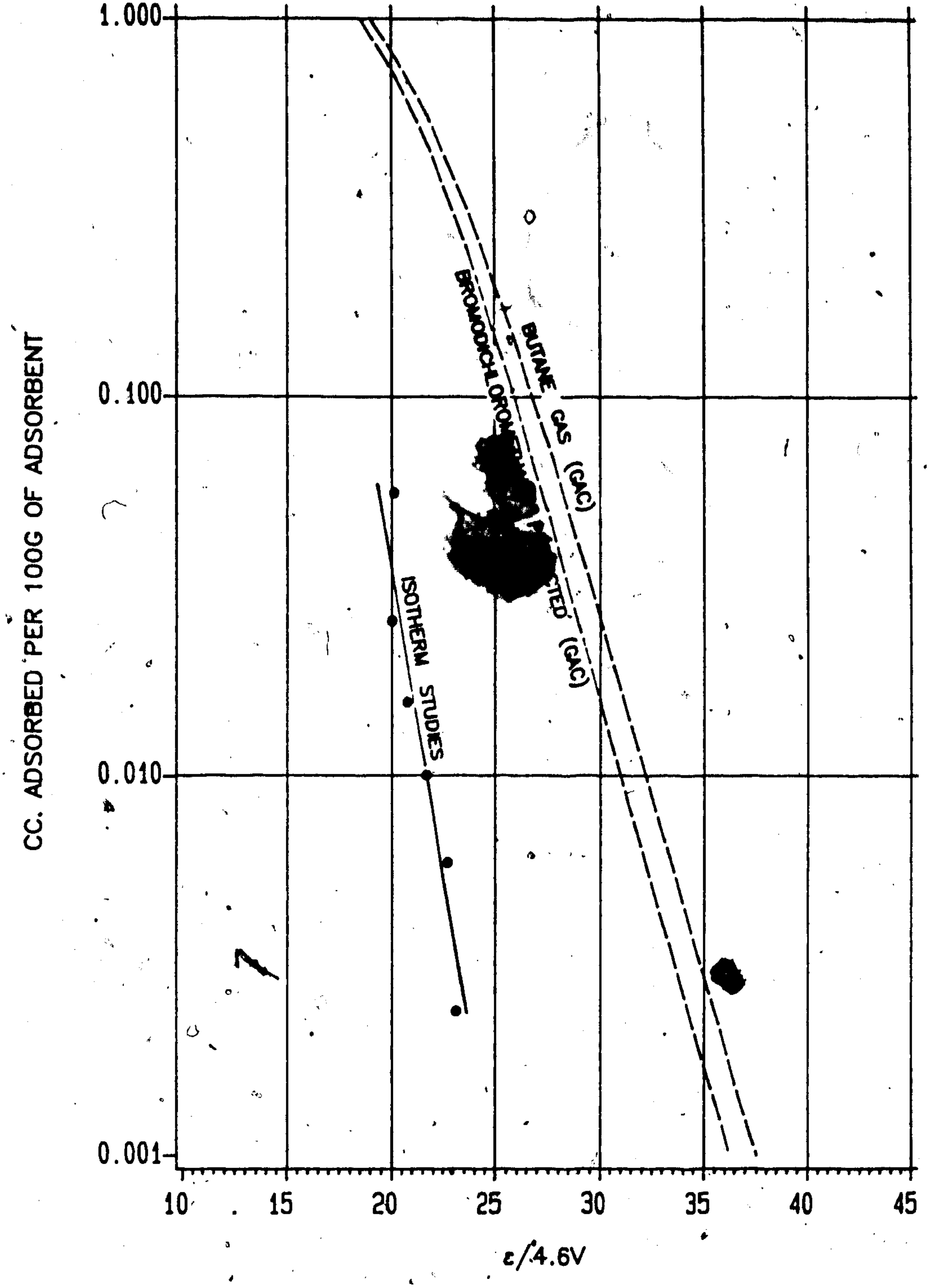

Figure 5.49 Polanyi Adsorption Potential Curve for Bromodichloromethane

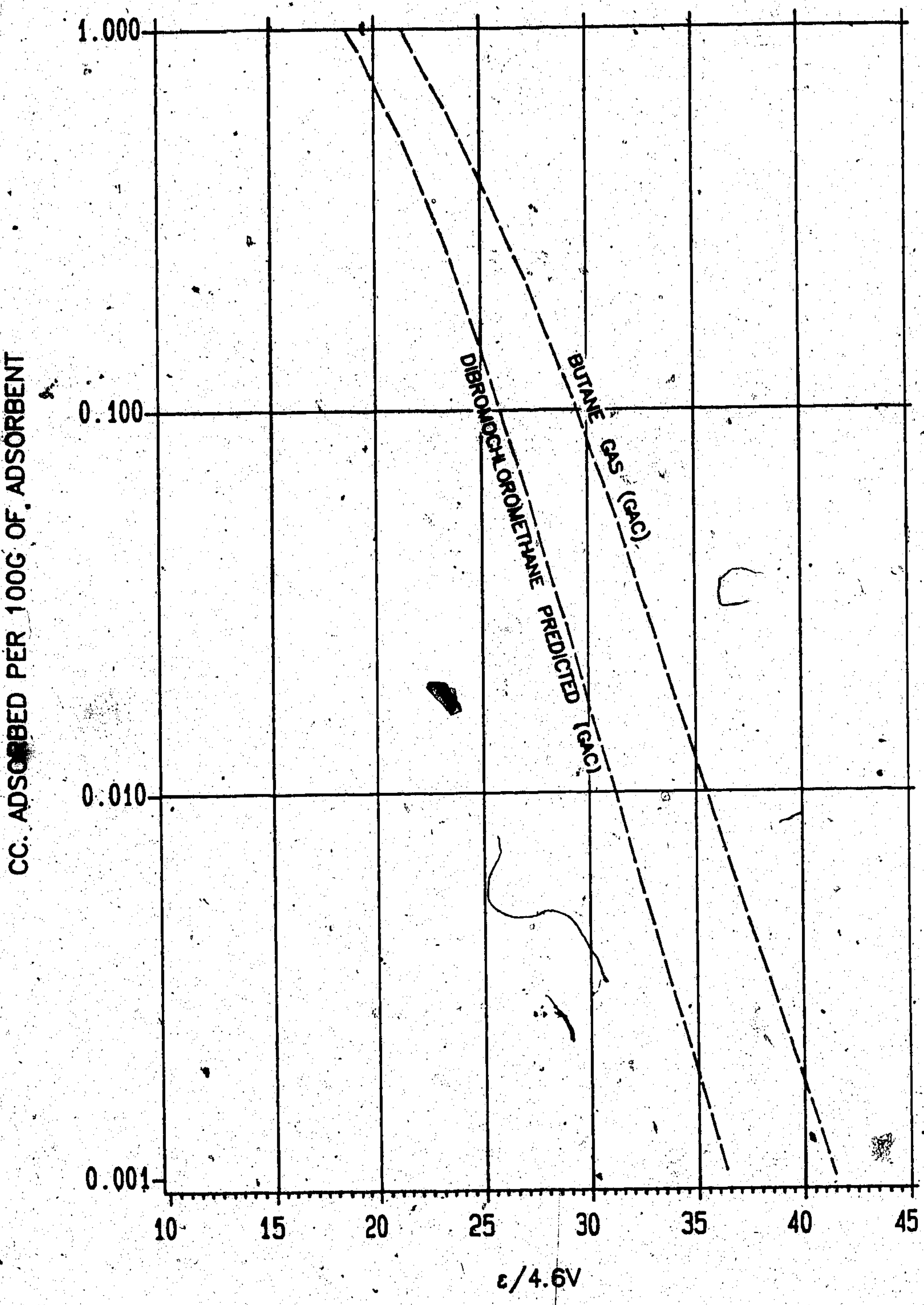

Figure 5.50 Polanyi Adsorption Potential Curve for Dibromochloromethane

were extended an order of magnitude lower than Figure H1. A similar extension was made in the USEPA study (USEPA, 1980).

The Polanyi-Manes theory, being consistent with conventional isotherm theory predicts for a given compound that adsorption capacity will increase as concentration increases. This relationship may be illustrated by considering that the $\epsilon/4.6V$ value is inversely proportional to the logarithm of the influent concentration. For the slope of the predicted adsorption curves given (Figure 5.48 to Figure 5.50), a decrease in $\epsilon/4.6V$ will be interpreted by an increase in adsorptive capacity (cc/100 g). This theory thus provides a reasonable explanation for the increase in adsorptive column capacity noted during a rise in chloroform influent concentration as discussed in section 5.1.2.1.

5.7.1 Isotherm Data Comparison

Isotherm data for the three compounds were converted to the appropriate units and plotted (Figures 5.48, 5.49 and 5.50). The percentage of theoretical adsorption could then be calculated for each isotherm data point (Appendix I) and plotted (Figure 5.51). For example, a chloroform equilibrium value of 41.70 µg/L (Table F1) yields a corresponding $\epsilon/4.6V$ value of 19.52. For this abscissa, Figure 5.48 predicts that 0.543 cc will be adsorbed per 100 g of carbon. The actual adsorption per 100 g of GAC was 0.0684 cc or 12.6% of the predicted value.

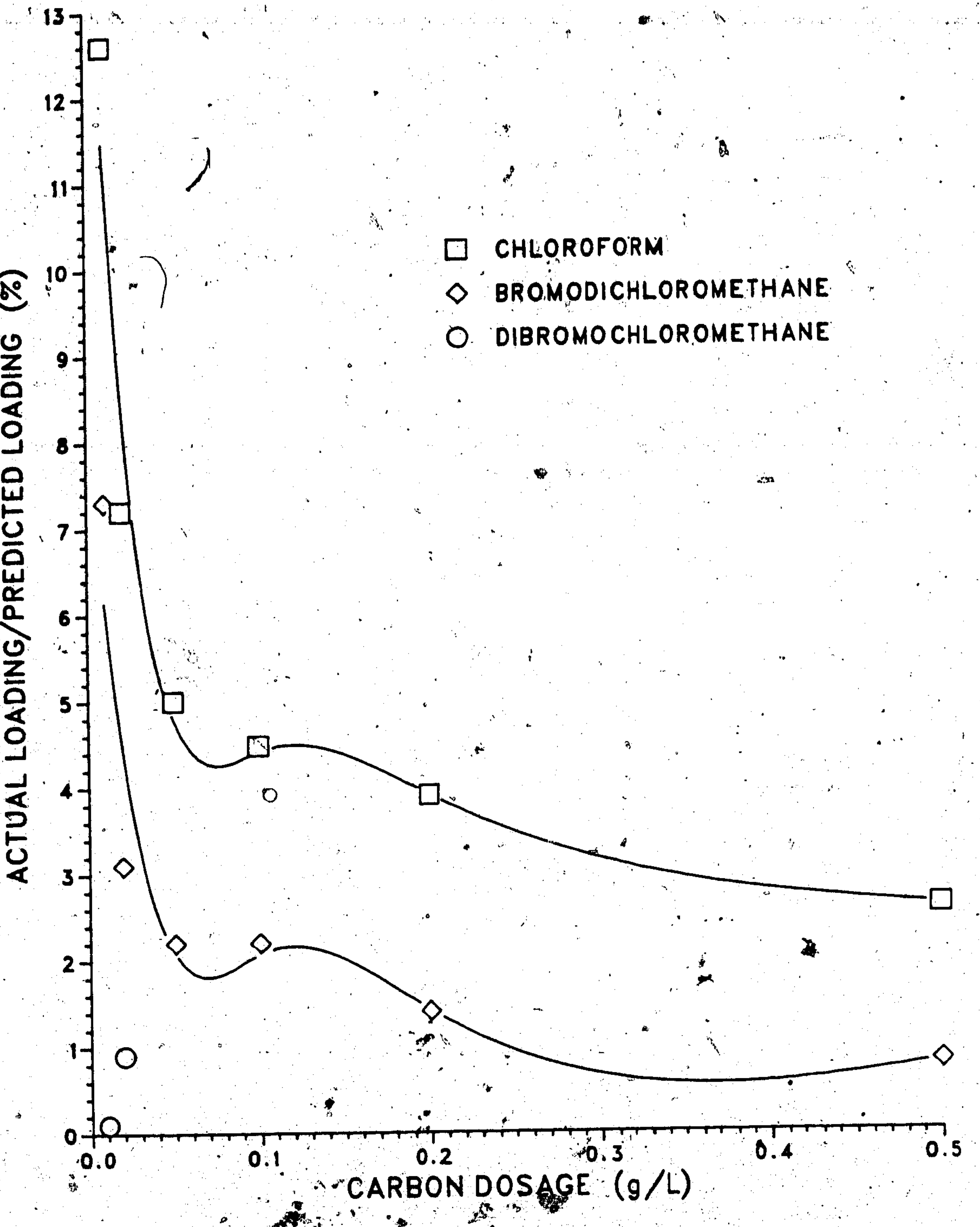

Figure 5.51 Comparison of Observed and Predicted (Pure Water) Isotherm Results

The low percentage of predicted values for all three compounds shows the effect of competition on adsorptive capacity. All compounds displayed a decrease in percentage with increasing carbon dose. These results are consistent with the Polanyi-Manes theory which states that adsorptive capacity decreases with equilibrium concentration.

When percentage of theoretical adsorption values are compared among the three compounds studied, chloroform competes most strongly as evident by the high values for acutal/predicted loadings. Bromodichloromethane and dibromochloromethane follow respectfully. The Freundlich isotherm constant "K" discussed earlier in section 5.5.1 indicated that chloroform would be adsorbed to a lesser extent than bromodichloromethane. This result now contradicts both actual column loading and Polanyi-Manes theory. In the following section column loadings are examined to determine if Polanyi-Manes theory may be used as a predictive tool.

5.7.2 Column Loading Data

Loading capacities predicted by the Polanyi-Manes theory are compared to actual column results in Appendix J and plotted in Figure 5.52. Similar decreases are observed from chloroform and bromodichloromethane when going from segment 0-1 to segment 1-3. It is significant that chloroform loading in the top one-third of the column (segment 0-5) showed the highest percentage of the

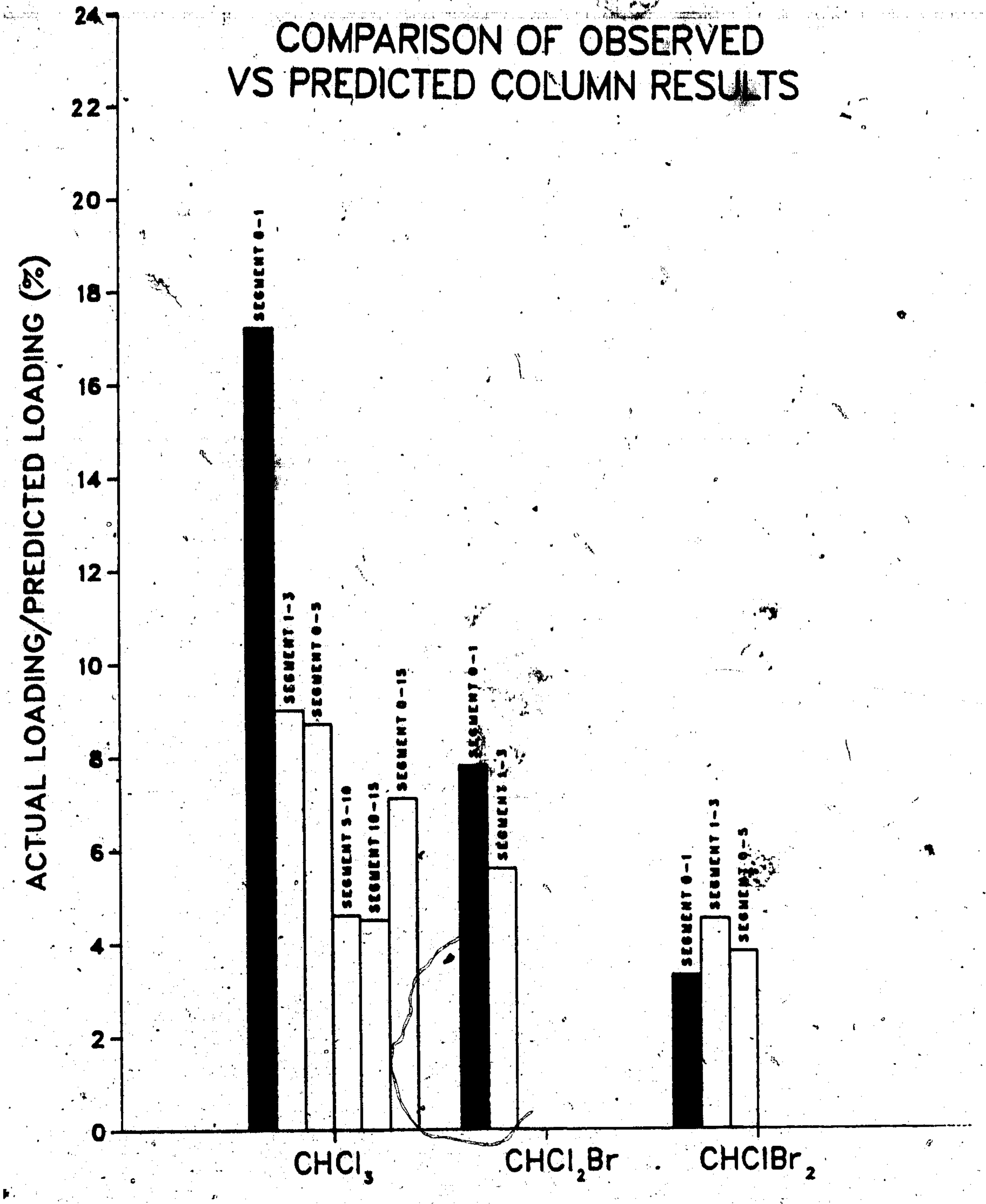

Figure 5.52 Comparison of Observed and Predicted (Pure Water) Column Results

theoretical value, this being especially true in segments 0-1 and 1-3. Percentages in the mid and lower column depths were approximately 50% lower than segment 0-5 and displayed no significant trends.

At average influent concentrations, the Polanyi-Manes theory predicts that bromodichloromethane will be adsorbed to a higher degree than chloroform. Actual column loading data show that the opposite was true. Therefore, in the multicomponent system encountered in practice chloroform is a strong competitor for adsorption sites. This is especially evident in upper column segments where liquid phase concentrations are high and carbon particle sizes are small.

Due to the low percentage of predicted values observed for the three major trihalomethanes competition may indeed be the result of adsorption of other dissolved organic matter, including other halogenated organic compounds.

6. SUMMARY

Granular activated carbon has been proven as an effective treatment measure to reduce concentrations of volatile organics and total organic carbon in drinking water. Previous pilot scale GAC pilot studies conducted at the Buffalo Pound Water Treatment Plant, Saskatchewan, Canada have shown that TTHM exhibit the highest loadings in the uppermost portions of both fresh and extended service down-flow beds. Providing a deeper understanding of THM and TOC loading characteristics combined with an examination of various predictive theories were the major objectives of research presented in this thesis.

An examination of the effects of three different carbon types on the loading characteristics of THM and TOC was conducted using pilot scale columns operated in parallel. Results illustrating competitive loading effects and dependence upon particle size were explained using adsorption isotherms, particle size distribution analyses, and the Polanyi-Manes adsorption potential theory.

A direct relationship was found to exist between particle size and adsorption affinity for THM and TOC in stratified beds. Based upon mas transfer zone evaluations, shallow beds (<51 cm) with a predominant grain size in the range of 0.60 - 1.18 mm should present the best characteristics for reducing TTHM when using the carbons tested under similar influent conditions. These results would aid in the development and operation of a full scale treatment system.

7. CONCLUSIONS

1. TTHM removals most closely followed the pattern defined by chloroform, the major component. Loadings were highest in segment 0-1 which represented 7% of the total bed depth.
2. TOC breakthrough curves exhibited three well defined phases of adsorption. For all columns, loadings were highest in the top one-third of the bed with significant removal taking place in segment 0-1.
3. A 20% bed replacement resulted in enhanced adsorption of both THM and TOC. Significant increases in removal efficiency and loadings were evident in segments 0-1 and 1-3.
4. Based upon MTZ evaluations, shallow beds (<51 cm) with a predominant grain size in the range of 0.60-1.18 mm should present the best characteristics for reducing TTHM using the carbons tested.
5. A direct relationship was found to exist between particle size distribution and adsorption affinity for THM and TOC in stratified beds. The fraction of material present at a given depth with a 0.60-1.18 mm diameter most strongly influences loading capacity for Filtrasorb® 300 carbon.
6. Adsorption of THM in 153 cm bed depths was very close to values predicted by isotherms for Norit® 0.8 and Witco® 950 carbons. However, in upper column segments

(0-1 and 1-3) actual adsorption exceeded isotherm predictions. TOC column loadings could not be predicted well by isotherms. Upper segment loadings appear higher in column tests as a result of biological degradation.

7. The Polanyi-Manes adsorption potential theory was unable to predict preferential adsorption among THMs observed in the columns.

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APPENDIX A

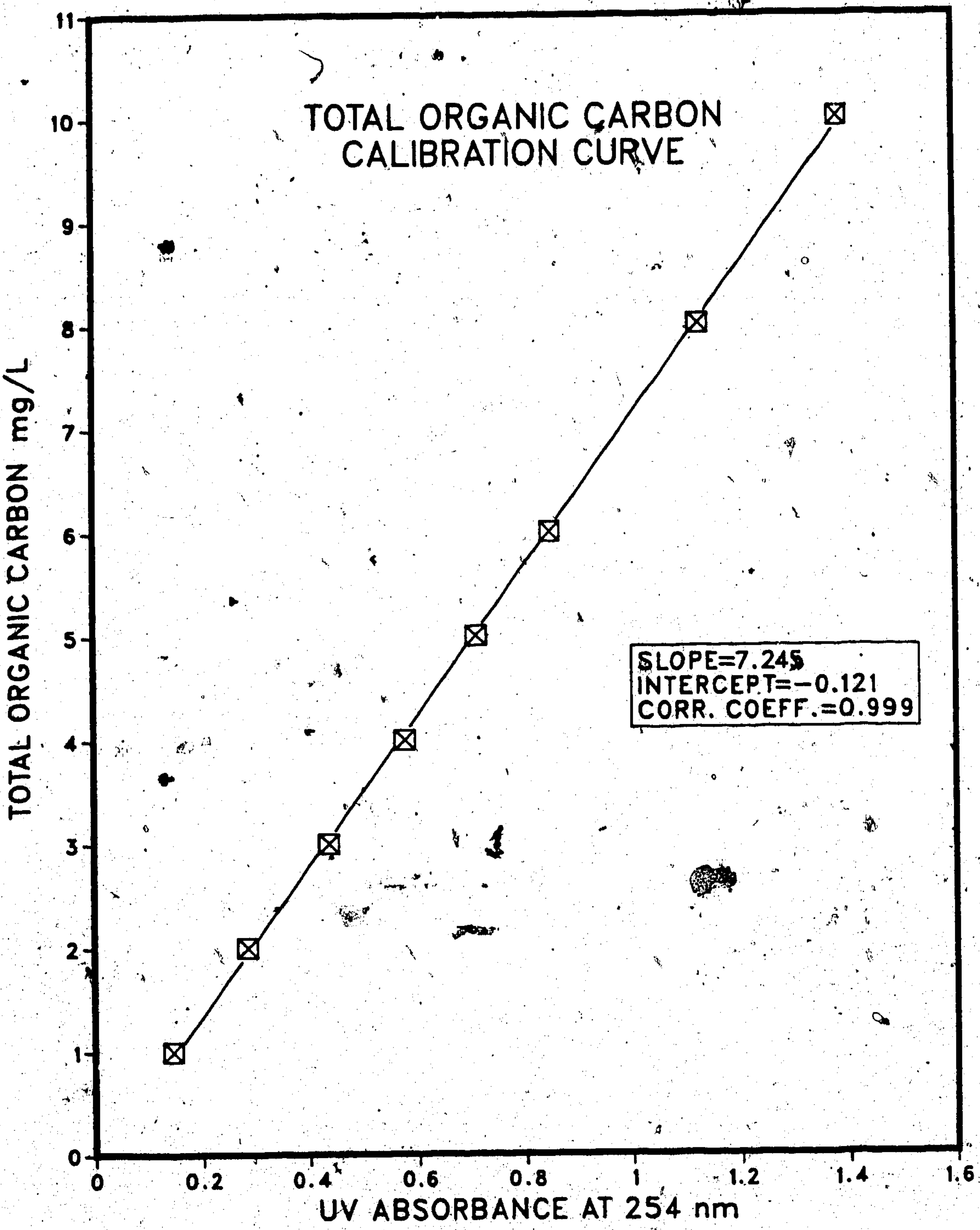

Figure A1 Total Organic Carbon Calibration Curve

APPENDIX B

B1 Computer Program GAC7 Used to Calculate Adsorption Results for Pilot Scale GAC Columns

```
10 PRINT "********************************************"
20 PRINT "ACTIVATED CARBON ADSORPTION CALCULATIONS"
30 PRINT "FOR PILOT SCALE GAC COLUMNS."
35 PRINT "********************************************"
40 REM
50 REM "PROGRAM WRITTEN BY: R.C.ANDREWS FEB.11 1985"
60 PRINT:PRINT:PRINT
70 REM "THIS PROGRAM CALCULATES LOADINGS FOR A "
80 REM "SPECIFIC PARAMETER EXPRESSED AS BOTH GRAMS "
90 REM "AND MILLIGRAMS/GRAM OF GAC."
100 REM
110 REM "THE PROGRAM ALSO CALCULATES % REMOVAL ON"
120 REM "A TIME BASIS."
130 REM "*******************************************"
140 REM
150 REM VARIABLE LIST
160 REM
170 REM TYPE=CARBON TYPE
180 REM AIC=AVERAGE INFLUENT CONCENTRATION DURING SPECIFIED TIME PERIOD
190 REM FLOW=FLOWRATE TO COLUMN,*1000 L/DAY
200 REM COLNO=COLUMN DESIGNATION
210 REM DENSITY=CARBON DENSITY,KG/M3
220 REM PORTDEPTH=DEPTH OF CARBON BETWEEN PORTS,CM
230 REM PARAM=ANALYTICAL PARAMETER
240 REM DAYS=DAYS FROM START OF TEST
250 REM LP=LENGTH BETWEEN PORTS,CM
260 REM COLDIA=COLUMN DIAMETER,CM
270 REM SEGDEPTH=SEGMENT DEPTH,CM
280 REM -999 INDICATES DATA NOT COLLECTED
290 PORTDEPTH=10.2
300 REM -666 INDICATES THE END OF A PARTICULAR SET OF DATA
310 COLDIA=15.2
320 FLOW=5.45
330 REM
340 OPTION BASE 1
350 DIM B(32,8)
360 DIM SUM(30,7)
365 DIM SUMTOT(30)
370 DIM SUMBBB(30,6)
380 DIM SUMB(30,6)
382 DIM SUMBBBB(6)
384 DIM SUMBB(6)
390 DIM SUMA(30)
400 DIM BB(30,6):DIM C(30,7):DIM A(30,6):DIM D(30):DIM SEG(8):DIM BRKTHRU(8):DIM
 MDAYS(8)
402 PRINT "SELECT PARAMETER BY CHOOSING CORRESPONDING NUMBER:":PRINT:PRINT:PRINT
 SPC(6) "(1) CHLOROFORM":PRINT SPC(6) "(2) BROMODICH
LOROMETHANE":PRINT SPC(6) "(3) DIBROMOCHLOROMETHANE":PRINT:PRINT
405 INPUT "SELECT PARAMETER";CHOICE
407 IF CHOICE=1 THEN FILE$="CHCL3.DAT"
408 IF CHOICE=2 THEN FILE$="CHCL2BR.DAT"
409 IF CHOICE=3 THEN FILE$="CHCLBR2.DAT"
410 OPEN "I",#1,FILE$
412 PRINT:PRINT
415 INPUT "SELECT COLUMN (A,B,C,S OR ALL)";COLUMN$
416 IF COLUMN$="ALL" THEN 419
417 IF COLUMN$="A" OR COLUMN$="B" OR COLUMN$="C" OR COLUMN$="S" THEN 419
418 PRINT:PRINT "INVALID COLUMN ENTRY, MUST BE A,B,C,S,OR ALL":PRINT:GOTO 415
419 PRINT:PRINT:PRINT "SEARCHING FILES":PRINT
420 INPUT#1,COLNO1$,COLNO2$,PARAM$,TYPE$,DENSITY,DAYS
422 PRINT COLNO1$
423 IF COLUMN$="ALL" THEN 428
425 IF COLNO1$<>COLUMN$ THEN 460
428 IF COLNO1$="S" THEN 454
430 FOR I=1 TO 32
```

```
440 INPUT#1,B(I,1),B(I,2),B(I,3),B(I,4),B(I,5),B(I,6),B(I,7)
445 B(I,8)=B(I,7)
450 IF B(I,1)=-111  THEN 480
452 NEXT I
453 STOP
454 FOR I=1 TO 32
456 INPUT #1,B(I,1),B(I,2),B(I,3),B(I,4),B(I,5),B(I,6)
457 IF B(I,1)=-111 THEN 2600
458 NEXT I
459 STOP
460 INPUT #1,A,B,C,D,E,F,G
465 IF A<>-111 THEN 460
470 GOTO 420
480 LPRINT "********************************************************************
************"
490 LPRINT
500 LPRINT
510 LPRINT TAB(4) "DATA ANALYSIS FOR "PARAM$
520 LPRINT
530 LPRINT TAB(15) "COLUMN "COLNO1$
540 LPRINT
550 LPRINT TAB(5) "CARBON TYPE: "TYPE$
560 LPRINT TAB(5) "CARBON DENSITY: "DENSITY" KG/M3"
570 LPRINT TAB(5) "DAYS OF OPERATION: "DAYS
580 LPRINT
590 LPRINT
600 LPRINT
670 LPRINT
680 C=0
690 FOR J=1 TO 8
700 FOR I=1 TO 32
710 IF B(I,J)=-666 THEN 740
720 IF (J)>2 THEN MDAYS(J)=B(I,1)
730 NEXT I
740 D(J)=I-1
750 NEXT J
760 LPRINT TAB(33) "CONCENTRATION (Micrograms/L)"
770 LPRINT TAB(13) "-----------------------------------------------------------"
780 LPRINT TAB(42) "PORT NUMBER"
790 LPRINT TAB(24) "______________________________________________"
800 LPRINT SPC(6) "DAYS" SPC(2) "INFLUENT" SPC(7) COLNO$"1" SPC(9) COLNO$"3" SPC
(9) COLNO$"5" SPC(8) COLNO$"10" SPC(8) COLNO$"15"
810 LPRINT TAB(24) "______________________________________________"
820 FOR I=1 TO D(1)
830 LPRINT USING "#######.##";B(I,1);B(I,2);B(I,3);B(I,4);B(I,5);B(I,6);B(I,7)
840 NEXT I
850 REM ********************************************************************
860 REM THIS PART OF THE PROGRAM CALCULATES BREAKTHROUGH (DAYS)
870 FOR J=3 TO 7
880 NOW=0
890 OLD=0
895 OLDVALUE=0
900 FOR I=1 TO D(J)
910 IF B(I,J)=>0 AND (B(I,J)<.02*B(I,2) OR B(I,2)=-999) THEN OLDVALUE=B(I,J):OLD
=B(I,1)
917 IF B(I,2)=-999 THEN 940
920 IF B(I,J)=-999 THEN 940
930 IF B(I,J)=>.02*B(I,2) THEN 950
940 NEXT I
945 BRKTHRU(J)=-999:GOTO 980
950 NOW=B(I,1)
960 SLOPE=(B(I,J)-OLDVALUE)/(NOW-OLD)
970 BRKTHRU(J)=((.02*B(I,2))/SLOPE)+OLD
980 NEXT J
990 REM
```

```
1000 REM ****************************************************************************
*
1010 REM
1020 REM THIS PART OF THE PROGRAM CALCULATES LOADINGS
1030 REM
1040 REM
1050 OLD=0
1060 FOR I=1 TO D(2)
1070 OLD=I
1080 IF B(I,2)=-999 THEN 1110
1090 SUMTOT(I)=B(I,2)*(B(I,1)-B(1,1))*FLOW
1100 SUM=SUMTOT(I):GOTO 1180
1110 NEXT I
1120 REM
1130 REM SUMTOT(I)=INDIVIDUAL LOADING FOR EACH TIME PERIOD
1140 REM SUM=ACCUMULATED TOTAL (MILLIGRAMS)
1150 REM OLD=OLD VALUE FOR I
1160 REM NOW=NEW VALUE FOR I
1170 REM
1180 REM
1190 NOW=0
1200 FOR I=OLD+1 TO D(2)
1210 NOW=I
1220 IF B(I,2)=-999 THEN 1260
1230 SUMTOT(I)=(B(NOW,2)+B(OLD,2))/2*(B(NOW,1)-B(OLD,1))*FLOW
1240 OLD=NOW
1250 SUM=SUM+SUMTOT(I)
1260 NEXT I
1270 AIC=(SUM)/((B(OLD,1)*(FLOW)))
1280 MASS=(((3.1416)*(COLDIA/2)^2*PORTDEPTH)/1000)*DENSITY
1290 SEG(3)=1*MASS
1300 SEG(4)=2*MASS
1310 SEG(5)=5*MASS
1320 SEG(6)=5*MASS
1330 SEG(7)=5*MASS
1331 SEG(8)=15*MASS
1332 FOR J=1 TO 5
1334 FOR I=1 TO 30
1336 A(I,J)=0
1338 NEXT I
1339 NEXT J
1340 NOW=0
1372 FOR Y=1 TO 5
1374 FOR I=1 TO D(Y+2)
1375 SUMB(I,Y)=0
1376 SUMBBB(I,Y)=0
1377 NEXT I
1378 NEXT Y
1379 I=0:Y=0:J=0
1380 FOR J=3 TO 8
1390 Y=Y+1
1400 SUMBB(Y)=0
1410 SUMBBBB(Y)=0
1415 PAST=0
1417 UPTOZEROTOT=0
1420 FOR I=1 TO D(J)
1430 NOW=I
1440 IF I>1 THEN 1540
1450 IF J=5 OR J=8 THEN K=2 ELSE K=J-1
1460 IF B(I,J)=-999 AND B(I,K)>0 AND PAST=0 THEN UPTOZEROTOT=B(I,K)*B(I,1)*FLOW:
PAST=I:GOTO 1505
1470 IF B(I,J)=-999 AND B(I,K)>0 AND PAST>0 THEN UPTOZERO=((B(I,K)+B(PAST,K))/2)
*(B(I,1)-B(PAST,1))*FLOW:UPTOZEROTOT=UPTOZEROTOT+UPT
OZERO:PAST=I:GOTO 1505
```

```
1480 IF B(I,J)=-999 AND B(I,K)=0 THEN PAST=I
1490 IF B(I,J)=0 AND B(I,K)>0 AND PAST>0 THEN GOTO 1525
1495 IF B(I,J)=>0 AND B(I,K)>0 AND PAST=>0 AND BRKTHRU(J)>0 THEN 1526
1496 IF B(I,J)=>0 AND B(I,K)=>0 AND PAST=>0 THEN 1527
1505 I=I+1
1510 NOW=I
1515 IF I=D(J) THEN 1650
1520 GOTO 1450
1525 A(I,Y)=UPTOZEROTOT+(((B(I,K)+B(PAST,K))/2)-B(I,J))*(B(I,1)-B(PAST,1))*FLOW:
GOTO 1600
1526 IF (J=4 OR J=6 OR J=7) THEN A(I,Y)=(((B(I,K)/2)*(B(I,1)-BRKTHRU(K)))-((B(I,
J)/2)*(B(I,1)-BRKTHRU(J))))*FLOW:GOTO 1600
1527 A(I,Y)=(B(I,K)-(B(I,J)/2))*B(I,1)*FLOW:GOTO 1600
1540 IF (B(I,J)=-999) GOTO 1640
1550 IF (J=5 OR J=8) AND (B(I,J)<>-999) THEN GOTO 1580
1560 IF (B(I,J-1)=-999) OR (B(I,J-1)=-666) THEN 1640
1570 K=J-1:GOTO 1590
1580 K=2
1590 A(I,Y)=(((B(NOW,K)+B(OLD,K))/2)-((B(NOW,J)+B(OLD,J))/2))*(B(NOW,1)-B(OLD,1)
)*FLOW
1600 BB(I,Y)=A(I,Y)/SEG(J)
1610 SUMBB(Y)=SUMBB(Y)+BB(I,Y)
1615 SUMB(I,Y)=SUMBB(Y)
1620 SUMBBBB(Y)=SUMBBBB(Y)+A(I,Y)
1625 SUMBBB(I,Y)=SUMBBBB(Y)
1630 OLD=NOW
1640 NEXT I
1650 NEXT J
1660 FOR J=3 TO 7
1670 FOR I=1 TO D(J)
1680 IF B(I,J)=-999 OR B(I,2)=-999 OR B(I,J)=-666 THEN 1698
1690 C(I,J)=((B(I,2)-B(I,J))/B(I,2))*100:GOTO 1700
1698 C(I,J)=-999
1700 NEXT I
1710 NEXT J
1720 REM BB(I,Y)=SEGMENT LOADING (Milligrams/G GAC)
1730 REM C(I,J)=PERCENT REMOVAL BASED UPON INDIVIDUAL DATA VALUES,AS COMPARED TO
 INFLUENT
1740 REM
1750 LPRINT
1760 LPRINT
1770 LPRINT
1780 LPRINT
1790 LPRINT TAB(39) "PERCENT REMOVAL (%)"
1800 LPRINT TAB(13) "---------------------------------------------------------"
1810 LPRINT TAB(42) "PORT NUMBER"
1820 LPRINT TAB(24) "----------------------------------------------"
1830 LPRINT SPC(6) "DAYS" SPC(2) "INFLUENT" SPC(7) COLNO$"1" SPC(9) COLNO$"3" SP
C(9) COLNO$"5" SPC(8) COLNO$"10" SPC(8) COLNO$"15"
1840 LPRINT TAB(24) "----------------------------------------------"
1850 FOR I=1 TO D(2)
1860 LPRINT USING "#######.##";B(I,1);B(I,2);C(I,3);C(I,4);C(I,5);C(I,6);C(I,7)
1870 NEXT I
1880 LPRINT
1890 LPRINT
1900 LPRINT
1910 LPRINT TAB(31) "ACCUMULATED SEGMENT LOADING (Milligrams)"
1920 LPRINT TAB(13) "---------------------------------------------------------"
1930 LPRINT TAB(45) "SEGMENT"
1940 LPRINT TAB(24) "----------------------------------------------"
1950 LPRINT SPC(6) "DAYS" SPC(2) "INFLUENT" SPC(6) "0-1" SPC(7) "1-3" SPC(7) "0-
5" SPC(7) "5-10" SPC(5) "10-15" SPC(6) "0[illegible]5"
1960 LPRINT TAB(24) "----------------------------------------------"
1970 FOR I=1 TO D(2)
```

```
1980 LPRINT USING "#######.##";B(I,1);B(I,2);SUMBBB(I,1);SUMBBB(I,2);SUMBBB(I,3)
;SUMBBB(I,4);SUMBBB(I,5);SUMBBB(I,6)
1990 NEXT I
2000 LPRINT
2010 LPRINT
2020 LPRINT "TOTAL LOADING (mg)  " USING "#######.##";SUMBBBB(1);SUMBBBB(2);SUMB
BBB(3);SUMBBBB(4);SUMBBBB(5);SUMBBBB(6)
2030 LPRINT
2040 LPRINT "DAYS OF MONITORING  " USING "#######.##";MDAYS(3);MDAYS(4);MDAYS(5)
;MDAYS(6);MDAYS(7);MDAYS(8)
2050 SUMTOTAL=0
2060 FOR Y=3 TO 5
2070 SUMTOTAL=SUMTOTAL+SUMBBBB(Y)
2080 NEXT Y
2090 FOR Y=1 TO 5
2100 PRCNT(Y)=(SUMBBBB(Y)/SUMTOTAL)*100
2110 NEXT Y
2120 LPRINT
2130 LPRINT
2140 LPRINT
2150 LPRINT TAB(24) "ACCUMULATED SEGMENT LOADING (Milligrams/G GAC)"
2160 LPRINT TAB(14) "__________________________________________________________"
2170 LPRINT TAB(45) "SEGMENT"
2180 LPRINT TAB(24) "______________________________________________"
2190 LPRINT SPC(6) "DAYS" SPC(2) "INFLUENT" SPC(6) "0-1" SPC(7) "1-3" SPC(7) "0-
5"SPC(7) "5-10" SPC(5) "10-15" SPC(6) "0-15"
2200 LPRINT TAB(24) "______________________________________________"
2210 FOR I=1 TO D(2)
2220 LPRINT USING "#######.##";B(I,1);B(I,2);SUMB(I,1);SUMB(I,2);SUMB(I,3);SUMB(
I,4);SUMB(I,5);SUMB(I,6)
2230 NEXT I
2240 LPRINT
2250 LPRINT
2260 LPRINT "TOTAL LOADING"
2270 LPRINT "  (mg/G GAC)          " USING "#######.##";SUMBB(1);SUMBB(2);SUMBB(3)
;SUMBB(4);SUMBB(5);SUMBB(6)
2280 LPRINT
2290 LPRINT "DAYS OF MONITORING  " USING "#######.##";MDAYS(3);MDAYS(4);MDAYS(5)
;MDAYS(6);MDAYS(7);MDAYS(8):LPRINT:LPRINT:LPRINT
2300 LPRINT "_____________________________________________________________________
_____________"
2310 LPRINT TAB(20) "COLUMN "COLNO1$" "PARAM$" ADSORPTION SUMMARY"
2320 LPRINT "_____________________________________________________________________
_____________"
2330 LPRINT "PORT" SPC(2)" SEGMENT" SPC(2)"SEGMENT" SPC(6) "TEST" SPC(7) "BREAKT
HROUGH" SPC(6) "TOTAL" SPC(7) "% OF TOTAL"
2340 LPRINT TAB(18) "DEPTH" SPC(5) "DURATION" SPC(22) "ADSORBED" SPC(6) "ADSORBE
D"
2350 LPRINT TAB(18) "(cm)" SPC(7) "(DAYS)" SPC(9) "(DAYS)"SPC(10) "(g)" SPC(12)
"(%)"
2360 LPRINT "_____________________________________________________________________
_____________"
2370 LPRINT SPC(2) "1" SPC(6) "0-1" SPC(5) "10.2"SPC(2)  USING "#######.##      "
;MDAYS(3); BRKTHRU(3); SUMBBBB(1)/1000;PRCNT(1)
2380 LPRINT SPC(2) "3" SPC(6) "1-3" SPC(5) "30.6" SPC(2) USING "#######.##      "
; MDAYS(4);BRKTHRU(4);SUMBBBB(2)/1[illegible];PRCNT(2)
2390 LPRINT SPC(2) "5" SPC(6) "0-5"[illegible]PC(5) "51.0" SPC(2) USING "#######.##      "
; MDAYS(5);BRKTHRU(5);SUMBBBB(3)/1000;PRCNT(3)
2400 LPRINT SPC(1) "10" SPC(5) "5-10" SPC(5) "51.0" SPC(2) USING "#######.##
 "; MDAYS(6);BRKTHRU(6);SUMBBBB(4)/1000;PRCNT(4)
2410 LPRINT SPC(1) "15" SPC(4) "10-15" SPC(5) "51.0" SPC(2) USING "#######.##
  "; MDAYS(7);BRKTHRU(7);SUMBBBB(5)/1000;PRCNT(5)
```

```
2420 LPRINT "--------------------------------------------------------------------
-------------"
2430 LPRINT
2440 LPRINT "AVERAGE INFLUENT CONCENTRATION: "AIC"Micrograms/L"
2450 LPRINT "TOTAL ENTERING COLUMN DURING TEST: "SUM" mg"
2460 LPRINT "TOTAL TEST DURATION "DAYS " DAYS":LPRINT:LPRINT
2462 LPRINT "********************************************************************
*************"
2464 IF COLUMN$="ALL" THEN 420
2465 GOTO 405
2600 LPRINT:LPRINT:LPRINT:LPRINT:LPRINT:LPRINT
2610 LPRINT "********************************************************************
*************"
2620 LPRINT
2630 LPRINT
2640 LPRINT TAB(4) "DATA ANALYSIS FOR "PARAM$
2650 LPRINT
2660 LPRINT TAB(10) "COLUMNS "COLNO1$ " AND " COLNO2$
2670 LPRINT
2680 LPRINT TAB(5) "CARBON TYPE: "TYPE$
2690 LPRINT TAB(5) "CARBON DENSITY: "DENSITY" KG/M3"
2700 LPRINT TAB(5) "DAYS OF OPERATION: "DAYS
2710 LPRINT
2720 LPRINT
2730 LPRINT
2800 LPRINT
2810 C=0
2820 FOR J=1 TO 6
2830 FOR I=1 TO 32
2840 IF B(I,J)=-666 THEN 2870
2850 IF (J)>2 THEN MDAYS(J)=B(I,1)
2860 NEXT I
2870 D(J)=I-1
2880 NEXT J
2890 LPRINT TAB(33) "CONCENTRATION (Micrograms/L)"
2900 LPRINT TAB(13) "---------------------------------------------------------"
2910 LPRINT TAB(42) "PORT NUMBER"
2920 LPRINT TAB(24) "_______________________________________________"
2930 LPRINT SPC(6) "DAYS" SPC(2) "INFLUENT" SPC(6) COLNO1$"1" SPC(8) COLNO1$"3"
SPC(8) COLNO2$"A13" SPC(6) COLNO2$"B13"
2940 LPRINT TAB(24) "_______________________________________________"
2950 FOR I=1 TO D(1)
2960 LPRINT USING "#######.##";B(I,1);B(I,2);B(I,3);B(I,4);B(I,5);B(I,6)
2970 NEXT I
2980 REM ***********************************************************************
*
2990 REM THIS PART OF THE PROGRAM CALCULATES BREAKTHROUGH (DAYS)
3000 FOR J=3 TO 5
3010 NOW=0
3020 OLD=0
3025 OLDVALUE=0
3030 FOR I=1 TO D(J)
3040 IF B(I,J)=>0 AND (B(I,J)<.02*B(I,2) OR B(I,2)=-999) THEN OLDVALUE=B(I,J):OL
D=B(I,1)
3048 IF B(I,2)=-999 THEN 3070
3050 IF B(I,J)=-999 THEN 3070
3060 IF B(I,J)=>.02*B(I,2) THEN 3080
3070 NEXT I
3075 BRKTHRU(J)=-999:GOTO 3110
3080 NOW=B(I,1)
3090 SLOPE=(B(I,J)-OLDVALUE)/(NOW-OLD)
3100 BRKTHRU(J)=((.02*B(I,2))/SLOPE)+OLD
```

```
3630 FOR J=3 TO 6
3640 Y=Y+1
3650 SUMBB(Y)=0
3660 SUMBBBB(Y)=0
3662 PAST=0
3664 UPTOZEROTOT=0
3668 COUNT=0
3670 FOR I=1 TO D(J)
3680 NOW=I
3690 IF I>1 THEN 3790
3700 IF J=5 THEN K=2 ELSE K=J-1
3710 IF B(I,J)=-999 AND B(I,K)>0 AND PAST=0 THEN UPTOZEROTOT=B(I,K)*B(I,1)*FLOW
:PAST=I:GOTO 3750
3720 IF B(I,J)=-999 AND B(I,K)>0 AND PAST>0 THEN UPTOZERO=((B(I,K)+B(PAST,K))/2)
*(B(I,1)-B(PAST,1))*FLOW:UPTOZEROTOT=UPTOZEROTOT+UPT
OZERO:PAST=I:GOTO 3750
3730 IF B(I,J)=-999 AND B(I,K)=0 THEN PAST=I
3740 IF B(I,J)=0 AND B(I,K)>0 AND PAST>0 THEN GOTO 3780
3745 IF B(I,J)=>0 AND B(I,K)>0 AND PAST=>0 AND BRKTHRU(J)>0 THEN 3781
3747 IF B(I,J)>0 AND B(I,K)=>0 AND PAST=>0 THEN 3782
3750 I=I+1
3760 NOW=I
3770 IF I=D(J) THEN 3900
3775 GOTO 3700
3780 A(I,Y)=UPTOZEROTOT+(((B(I,K)+B(PAST,K))/2)-B(I,J))*(B(I,1)-B(PAST,1))*FLOW:
GOTO 3850
3781 IF (J=4 OR J=6) THEN A(I,Y)=(((B(I,K)/2)*(B(I,1)-BRKTHRU(K)))-((B(I,J)/2)*(
B(I,1)-BRKTHRU(J))))*FLOW:GOTO 3850
3782 A(I,Y)=(B(I,K)-(B(I,J)/2))*B(I,1)*FLOW:GOTO 3850
3790 IF (B(I,J)=-999) GOTO 3890
3800 IF (J=5) AND (B(I,J)<>-999) THEN GOTO 3830
3810 IF (B(I,J-1)<0) OR (B(I,J-1)<0) THEN 3890
3820 K=J-1:GOTO 3840
3830 K=2
3840 A(I,Y)=(((B(NOW,K)+B(OLD,K))/2)-((B(NOW,J)+B(OLD,J))/2))*(B(NOW,1)-B(OLD,1)
)*FLOW
3850 BB(I,Y)=A(I,Y)/SEG(J)
3860 SUMBB(Y)=SUMBB(Y)+BB(I,Y)
3865 SUMB(I,Y)=SUMBB(Y)
3870 SUMBBBB(Y)=SUMBBBB(Y)+A(I,Y)
3875 SUMBBB(I,Y)=SUMBBBB(Y)
3880 OLD=NOW
3890 NEXT I
3900 NEXT J
3910 FOR J=3 TO 6
3920 FOR I=1 TO D(J)
3930 IF J=6 THEN 3955
3940 IF B(I,J)=-999 THEN 3978
3950 C(I,J)=((B(I,2)-B(I,J))/B(I,2))*100:GOTO 3980
3955 IF B(I,5)=0 AND B(I,J)<=0 THEN C(I,J)=100:GOTO 3980
3960 IF B(I,J)=-999 OR B(I,5)=-999 OR B(I,5)=0  THEN 3978
3970 C(I,J)=((B(I,5)-B(I,J))/B(I,5))*100:GOTO 3980
3978 C(I,J)=-999
3980 NEXT I
3990 NEXT J
4000 REM BB(I,Y)=SEGMENT LOADING (Milligrams/G GAC)
4010 REM C(I,J)=PERCENT REMOVAL BASED UPON INDIVIDUAL DATA VALUES,AS COMPARED TO
 INFLUENT
4020 REM
4030 LPRINT
4040 LPRINT
4050 LPRINT
4060 LPRINT
4070 LPRINT TAB(39) "PERCENT REMOVAL (%)"
```

```
4080 LPRINT TAB(13) "----------------------------------------------------------"
4090 LPRINT TAB(42) "PORT NUMBER"
4100 LPRINT TAB(24) "-----------------------------------------------"
4110 LPRINT SPC(6) "DAYS" SPC(2) "INFLUENT" SPC(6) COLNO1$"1" SPC(8) COLNO1$"3"
SPC(8) COLNO2$"A15" SPC(6) COLNO2$"B13"
4120 LPRINT TAB(24) "-----------------------------------------------"
4130 FOR I=1 TO D(2)
4140 LPRINT USING "#######.##";B(I,1);B(I,2);C(I,3);C(I,4);C(I,5);C(I.6)
4150 NEXT I
4160 LPRINT
4170 LPRINT
4180 LPRINT
4190 LPRINT TAB(31) "ACCUMULATED SEGMENT LOADING (Milligrams)"
4200 LPRINT TAB(13) "----------------------------------------------------------"
4210 LPRINT TAB(45) "SEGMENT"
4220 LPRINT TAB(24) "-----------------------------------------------"
4230 LPRINT SPC(6) "DAYS" SPC(2) "INFLUENT" SPC(4) "(S)0-1" SPC(4) "(S)1-3" SPC(
3) "(CA)0-15" SPC(2) "(CB)0-13"
4240 LPRINT TAB(24) "-----------------------------------------------"
4250 FOR I=1 TO D(2)
4260 LPRINT USING "#######.##";B(I,1);B(I,2);SUMBBB(I,1);SUMBBB(I,2);SUMBBB(I.3)
;SUMBBB(I,4)
4270 NEXT I
4280 LPRINT
4290 LPRINT
4300 LPRINT "TOTAL LOADING (mg)  " USING "#######.##";SUMBBBB(1);SUMBBBB(2);SUMB
BBB(3);SUMBBBB(4)
4310 LPRINT
4320 LPRINT "DAYS OF MONITORING  " USING "#######.##";MDAYS(3);MDAYS(4);MDAYS(5)
;MDAYS(6)
4330 SUMTOTAL=0
4340 FOR Y=1 TO 2
4350 SUMTOTAL=SUMTOTAL+SUMBBBB(Y)
4360 NEXT Y
4370 FOR Y=1 TO 2
4380 PRCNT(Y)=(SUMBBBB(Y)/SUMTOTAL)*100
4390 NEXT Y
4400 SUMTOTAL =0
4410 FOR Y=3 TO 4
4420 SUMTOTAL=SUMTOTAL+SUMBBBB(Y)
4430 NEXT Y
4440 FOR Y=3 TO 4
4450 PRCNT(Y)=(SUMBBBB(Y)/SUMTOTAL)*100
4460 NEXT Y
4470 LPRINT:LPRINT:LPRINT
4480 LPRINT TAB(24) "ACCUMULATED SEGMENT LOADING (Milligrams/G GAC)"
4490 LPRINT TAB(14) "________________________________________________________"
4500 LPRINT TAB(45) "SEGMENT"
4510 LPRINT TAB(24) "_______________________________________________"
4520 LPRINT SPC(6) "DAYS" SPC(2) "INFLUENT" SPC(4) "(S)0-1" SPC(4) "(S)1-3" SPC(
3) "(CA)0-15"SPC(2) "(CB)0-13"
4530 LPRINT TAB(24) "_______________________________________________"
4540 FOR I=1 TO D(2)
4550 LPRINT USING "#######.##";B(I,1);B(I,2);SUMB(I,1);SUMB(I,2);SUMB(I,3);SUMB(
I,4)
4560 NEXT I
4570 LPRINT
4580 LPRINT
4590 LPRINT "TOTAL LOADING"
4600 LPRINT "  (mg/G GAC)          " USING "#######.##";SUMBB(1);SUMBB(2);SUMBB(3)
;SUMBB(4);
4610 LPRINT:LPRINT
4620 LPRINT "DAYS OF MONITORING  " USING "#######.##";MDAYS(3);MDAYS(4);MDAYS(5)
;MDAYS(6):LPRINT:LPRINT:LPRINT
```

```
4630 LPRINT "-------------------------------------------------------------------
-------------"
4640 LPRINT TAB(20) "COLUMN S,CA AND CB " PARAMS" ADSORPTION SUMMARY"
4650 LPRINT "-------------------------------------------------------------------
-------------"
4660 LPRINT "PORT" SPC(2)" SEGMENT" SPC(2)"SEGMENT" SPC(6) "TEST" SPC(7) "BREAKT
HROUGH" SPC(6) "TOTAL" SPC(7) "% OF TOTAL"
4670 LPRINT TAB(18) "DEPTH" SPC(5) "DURATION" SPC(22) "ADSORBED" SPC(6) "ADSORBE
D"
4680 LPRINT TAB(18) "(cm)" SPC(7) "(DAYS)" SPC(9) "(DAYS)"SPC(10) "(g)" SPC(12)
"(%)"
4690 LPRINT "-------------------------------------------------------------------
-------------"
4700 LPRINT SPC(1) "S1" SPC(6) "0-1" SPC(5) "10.2"SPC(2)  USING "#######.##
";MDAYS(3); BRKTHRU(3); SUMBBBB(1)/1000;PRCNT(1)
4710 LPRINT SPC(1) "S3" SPC(6) "1-3" SPC(5) "30.6" SPC(2) USING "#######.##
"; MDAYS(4);BRKTHRU(4);SUMBBBB(2)/1000;PRCNT(2)
4720 LPRINT  "CA15" SPC(4) "0-15" SPC(5) "51.0" SPC(2) USING "#######.##      ";
MDAYS(5);BRKTHRU(5);SUMBBBB(3)/1000;PRCNT(3)
4730 LPRINT  "CB13" SPC(4) "0-13" SPC(5) "51.0" SPC(2) USING "#######.##      ";
MDAYS(6);BRKTHRU(6);SUMBBBB(4)/1000;PRCNT(4)
4740 LPRINT "-------------------------------------------------------------------
-------------"
4750 LPRINT
4760 LPRINT "AVERAGE INFLUENT CONCENTRATION (COLUMNS S,CA): "AIC(2)"Micrograms/L
"
4770 LPRINT "TOTAL ENTERING COLUMNS (S AND CA) DURING TEST: "SUMM(2)" mg"
4775 LPRINT
4780 LPRINT "AVERAGE INFLUENT CONCENTRATION (COLUMN CB): "AIC(5)"Micrograms/L"
4785 LPRINT "TOTAL ENTERING COLUMN CB DURING TEST; "SUMM(5)" mg"
4787 LPRINT
4790 LPRINT "TOTAL TEST DURATION "DAYS " DAYS":LPRINT:LPRINT
4791 LPRINT "*******************************************************************
*************"
4792 GOTO 405
4795 END
```

B2 Computer Program used to Load Data into Main Program GAC7 Including Sample Data

```
50 C$=","
100 OPEN "O",#1,"CHCL3.DAT"
200 READ COLNO1$,COLNO2$,PARAM$,TYPE$,DENSITY,DAYS
250 PRINT COLNO1$
300 PRINT#1,COLNO1$C$COLNO2$C$PARAM$C$TYPE$C$DENSITY,DAYS
400 READ A,B,C,D,E,F,G
500 PRINT#1,A,B,C,D,E,F,G
600 IF A<>-111 THEN 400
700 READ COLNO1$,COLNO2$,PARAM$,TYPE$,DENSITY,DAYS
800 PRINT #1,COLNO1$C$COLNO2$C$PARAM$C$TYPE$C$DENSITY,DAYS
900 READ A,B,C,D,E,F,G
1000 PRINT #1,A,B,C,D,E,F,G
1010 IF A<>-111 THEN 900
1020 READ COLNO1$,COLNO2$,PARAM$,TYPE$,DENSITY,DAYS
1030 PRINT #1,COLNO1$C$COLNO2$C$PARAM$C$TYPE$C$DENSITY,DAYS
1040 READ A,B,C,D,E,F,G
1050 PRINT #1,A,B,C,D,E,F,G
1060 IF A<>-111 THEN 1040
1070 READ COLNO1$,COLNO2$,PARAM$,TYPE$,DENSITY,DAYS
1080 PRINT #1,COLNO1$C$COLNO2$C$PARAM$C$TYPE$C$DENSITY,DAYS
1090 READ A,B,C,D,E,F
1100 PRINT #1,A,B,C,D,E,F
1110 IF A<>-111 THEN 1090
1120 CLOSE #1
10000 DATA A,,CHLOROFORM,NORIT ROW 0.8,355,88
10010 DATA 0,-999,-999,-999,-999,-999,-999
10020 DATA 3,49.52,30.62,20.06,-999,-999,-999
10030 DATA 6,44.27,36.09,24.13,-999,-999,1.48
10040 DATA 13,33.1,35.16,31.34,-999,-999,.47
10050 DATA 14,36.57,-999,-999,29.87,13.31,3.11
10060 DATA 24,45.77,47.1,-999,-999,-999,15.79
10070 DATA 27,52.11,-999,-999,46.43,30.98,19.93
10080 DATA 31,43.68,44.52,42.51,-999,-999,25.12
10090 DATA 34,43.18,-999,-999,45.39,35.71,26.36
10100 DATA 39,45.18,45.18,44.39,-999,-999,31.92
10110 DATA 41,47.94,-999,-999,44.02,37.87,33.89
10120 DATA 45,52.07,51.07,47.06,-999,-999,36.7
10130 DATA 48,51.98,-999,-999,48.56,45.1,39.83
10140 DATA 49,56.45,-999,-999,-999,-999,-999
10150 DATA 52,55.82,53.36,-999,-999,-999,44.52
10160 DATA 55,51.48,-999,-999,50.4,50.4,44.72
10170 DATA 59,53.94,49.27,48.4,-999,-999,46.39
10180 DATA 62,55.61,-999,-999,49.69,46.89,47.81
10190 DATA 63,58.49,-999,-999,-999,-999,-999
10200 DATA 66,58.91,52.82,55.03,-999,-999,50.19
10210 DATA 69,59.66,-999,-999,56.07,55.99,53.32
10220 DATA 70,61.95,-999,-999,-999,-999,-999
10230 DATA 74,82.31,75.68,74.89,-999,-999,63.79
10240 DATA 76,77.77,-999,-999,67.71,62.83,61.41
10250 DATA 80,77.22,72.26,-999,67.8,-999,59.53
10260 DATA 83,83.02,-999,-999,68.96,63.75,60.41
10270 DATA 84,75.6,-999,-999,-999,-999,-999
10280 DATA 87,75.18,74.64,69.75,-999,-999,58.24
10290 DATA 88,76.6,-666,-666,66.92,60.83,56.32
10300 DATA -666,-666,-666,-666,-666,-666,-666
10302 DATA -111,-111,-111,-111,-111,-111,-111
10305 DATA B,,CHLOROFORM,WITCO 950,495,88
10309 DATA 0,-999,-999,-999,-999,-999,-999
10310 DATA 3,49.52,21.09,11.84,-999,-999,-999
10320 DATA 6.44.27,27.78,18,-999,-999,-999
10330 DATA 13,33.1,32.53,25.16,-999,-999,6.58
10340 DATA 14,36.57,-999,-999,18.39,9.37,7.67
```

```
10350 DATA 24,45.77,44.81,-999,-999,-999,11.07
10360 DATA 27,52.11,-999,-999,37.13,16.48,10.89
10370 DATA 31,43.68,51.98,46.18,-999,-999,12.67
10380 DATA 34,43.18,-999,-999,42.64,23.73,12.02
10390 DATA 39,45.18,45.6,45.5,45.98,-999,15.69
10400 DATA 41,47.94,-999,-999,45.56,27.17,15.53
10410 DATA 45,52.07,50.57,51.48,-999,-999,18.05
10420 DATA 48,51.98,-999,-999,45.14,34.85,19.62
10430 DATA 49,56.45,-999,-999,-999,-999,-999
10440 DATA 52,55.82,51.9,54.4,-999,-999,21.35
10450 DATA 55,51.48,-999,-999,55.7,41.76,25.46
10460 DATA 59,53.94,51.78,55.24,-999,-999,29.07
10470 DATA 62,55.61,-999,-999,53.94,43.76,32.19
10480 DATA 63,58.49,-999,-999,-999,-999,-999
10490 DATA 66,58.91,-999,57.82,-999,-999,31.43
10500 DATA 69,59.66,-999,-999,-999,49.27,35.15
10510 DATA 70,61.95,-999,-999,-999,-999,-999
10520 DATA 74,82.31,-999,80.94,-999,-999,44.47
10530 DATA 76,77.77,-999,-999,72.43,63.83,45.35
10540 DATA 80,77.22,71.3,-999,-999,-999,47.23
10550 DATA 83,83.02,-999,-999,71.55,61.7,46.39
10560 DATA 84,75.6,-999,-999,-999,-999,-999
10570 DATA 87,75.18,75.51,73.09,-999,-999,49.15
10580 DATA 88,76.6,-666,-666,66.88,61.33,47.31
10590 DATA -666,-666,-666,-666,-666,-666,-666
10592 DATA -111,-111,-111,-111,-111,-111,-111
10600 DATA C,,CHLOROFORM,FILTRASORB 300,420,88
10610 DATA 0,-999,-999,-999,-999,-999,-999
10620 DATA 3,49.52,16.5,5.84,-999,-999,-999
10630 DATA 6,44.27,29.96,16.93,-999,-999,-999
10640 DATA 13,33.1,34.45,26.68,-999,-999,0
10650 DATA 14,36.57,-999,-999,23.14,9.45,0
10660 DATA 24,45.77,45.06,-999,-999,-999,15.3
10670 DATA 27,52.11,-999,-999,40.23,30.57,-999
10680 DATA 31,43.68,47.51,43.93,-999,-999,26.15
10690 DATA 34,43.18,-999,-999,40.1,37.57,30.56
10700 DATA 39,45.18,45.98,45.43,-999,-999,32.71
10710 DATA 41,47.94,-999,-999,41.72,39.84,35.63
10720 DATA 45,52.07,45.39,47.39,-999,-999,39.45
10730 DATA 48,51.98,-999,-999,44.89,44.1,40.25
10740 DATA 49,56.45,-999,-999,-999,-999,-999
10750 DATA 52,55.82,51.65,44.31,-999,-999,39.16
10760 DATA 55,51.48,-999,-999,47.81,46.64,41.43
10770 DATA 59,53.94,54.03,50.94,-999,-999,42.93
10780 DATA 62,55.61,-999,-999,47.85,46.94,42.93
10790 DATA 63,58.49,-999,18.35,-999,-999,30.28
10800 DATA 66,58.91,52.61,42.85,-999,-999,30.74
10810 DATA 69,59.66,-999,-999,45.23,40.82,38.31
10820 DATA 70,61.95,-999,53.03,-999,-999,-999
10830 DATA 74,82.31,75.85,70.22,-999,-999,44.81
10840 DATA 76,77.77,-999,-999,62.75,50.94,47.19
10850 DATA 80,77.22,72.68,66.09,-999,-999,48.48
10860 DATA 83,83.02,-999,-999,67.96,58.62,46.65
10870 DATA 84,75.6,-999,-999,-999,-999,-999
10880 DATA 87,75.18,69.13,69.21,-999,-999,48.94
10890 DATA 88,76.6,-666,-666,62.16,59.19,48.73
10900 DATA -666,-666,-666,-666,-666,-666,-666
10902 DATA -111,-111,-111,-111,-111,-111,-111
10910 DATA S,C,CHLOROFORM,FILTRASORB 300,420,88
10920 DATA 0,-999,-999,-999,-999,-999
10930 DATA 3,49.52,32.02,22.75,-999,-999
10940 DATA 6,44.27,33.31,27.31,-999,-999
```

```
10950 DATA 13,33.1,35.89,30.65,0,-999
10960 DATA 14,36.97,38.34,32.95,0,-999
10970 DATA 24,45.77,42.56,38.17,15.3,0
10980 DATA 27,52.11,-999,47.22,-999,-999
10990 DATA 31,43.68,41.35,44.78,26.15,1.81
11000 DATA 34,43.18,-999,-999,30.56,2.58
11010 DATA 39,45.18,46.81,44.06,32.71,4.52
11020 DATA 41,47.94,44.64,44.76,35.63,6.34
11030 DATA 45,52.07,46.69,47.56,39.45,10.17
11040 DATA 48,51.98,48.73,50.06,40.25,9.23
11050 DATA 49,56.45,-999,-999,-999,-999
11060 DATA 52,55.82,55.28,54.45,39.16,14.51
11070 DATA 55,51.48,-999,-999,41.63,16.57
11080 DATA 59,53.94,57.53,53.19,42.93,21.07
11090 DATA 62,55.61,-999,-999,42.93,27.93
11100 DATA 63,58.49,-999,-999,30.28,22.73
11110 DATA 66,58.91,50.36,35.08,30.74,24.29
11120 DATA 69,59.66,53.07,46.43,38.31,26.7
11130 DATA 70,61.95,-999,50.9,-999,-999
11140 DATA 74,82.31,77.72,73.72,44.81,35.2
11150 DATA 76,77.77,74.01,69.21,47.19,32.57
11160 DATA 80,77.22,72.51,70.72,48.48,34.25
11170 DATA 83,83.02,78.56,75.1,46.65,35.65
11180 DATA 84,75.6,-999,-999,-999,-999
11190 DATA 87,75.18,71.93,74.43,48.94,35.6
11200 DATA 88,76.6,-666,74.43,48.73,37.29
11210 DATA -666,-666,-666,-666,-666,-666
11212 DATA -111,-111,-111,-111,-111,-111
```

B3 Computer Program GAC7 Sample Output

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

   DATA ANALYSIS FOR CHLOROFORM

             COLUMN A

    CARBON TYPE: NORIT ROW 0.8
    CARBON DENSITY:  355  KG/M3
    DAYS OF OPERATION:  88


                                CONCENTRATION (Micrograms/L)
                  -----------------------------------------------------------
                                         PORT NUMBER
                             ----------------------------------------------
      DAYS   INFLUENT          1         3         5        10        15
                             ----------------------------------------------
      0.00    -999.00    -999.00   -999.00   -999.00   -999.00   -999.00
      3.00      49.52      30.62     20.06   -999.00   -999.00   -999.00
      6.00      44.27      36.09     24.13   -999.00   -999.00      1.48
     13.00      33.10      35.16     31.34   -999.00   -999.00      0.47
     14.00      36.57    -999.00   -999.00     29.87     13.31      3.11
     24.00      45.77      47.10   -999.00   -999.00   -999.00     15.79
     27.00      52.11    -999.00   -999.00     46.43     30.98     19.93
     31.00      43.68      44.52     42.51   -999.00   -999.00     25.12
     34.00      43.18    -999.00   -999.00     45.39     35.71     26.36
     39.00      45.18      45.18     44.39   -999.00   -999.00     31.92
     41.00      47.94    -999.00   -999.00     44.02     37.87     33.89
     45.00      52.07      51.07     47.06   -999.00   -999.00     36.70
     48.00      51.98    -999.00   -999.00     48.56     45.10     39.83
     49.00      56.45    -999.00   -999.00   -999.00   -999.00   -999.00
     52.00      55.82      53.36   -999.00   -999.00   -999.00     44.52
     55.00      51.48    -999.00   -999.00     50.40     50.40     44.72
     59.00      53.94      49.27     48.40   -999.00   -999.00     46.39
     62.00      55.61    -999.00   -999.00     49.69     46.89     47.81
     63.00      58.49    -999.00   -999.00   -999.00   -999.00   -999.00
     66.00      58.91      52.82     55.03   -999.00   -999.00     50.19
     69.00      59.66    -999.00   -999.00     56.07     55.99     53.32
     70.00      61.95    -999.00   -999.00   -999.00   -999.00   -999.00
     74.00      82.31      75.68     74.89   -999.00   -999.00     63.79
     76.00      77.77    -999.00   -999.00     67.71     62.83     61.41
     80.00      77.22      72.26   -999.00     67.80   -999.00     59.53
     83.00      83.02    -999.00   -999.00     68.96     63.75     60.41
     84.00      75.60    -999.00   -999.00   -999.00   -999.00   -999.00
     87.00      75.18      74.64     69.75   -999.00   -999.00     58.24
     88.00      76.60    -666.00   -666.00     66.92     60.83     56.32


                                      PERCENT REMOVAL
                  -----------------------------------------------------------
                                         PORT NUMBER
                             ----------------------------------------------
      DAYS   INFLUENT          1         3         5        10        15
                             ----------------------------------------------
      0.00    -999.00    -999.00   -999.00   -999.00   -999.00   -999.00
      3.00      49.52      38.17     59.49   -999.00   -999.00   -999.00
      6.00      44.27      18.48     45.49   -999.00   -999.00     96.66
     13.00      33.10      -6.22      5.32   -999.00   -999.00     98.58
     14.00      36.57    -999.00   -999.00     18.32     63.60     91.50
     24.00      45.77      -2.91   -999.00   -999.00   -999.00     65.50
     27.00      52.11    -999.00   -999.00     10.90     40.55     61.75
     31.00      43.68      -1.92      2.68   -999.00   -999.00     42.49
     34.00      43.18    -999.00   -999.00     -5.12     17.30     38.95
     39.00      45.18       0.00      1.75   -999.00   -999.00     29.35
     41.00      47.94    -999.00   -999.00      8.18     21.01     29.31
     45.00      52.07       1.92      9.62   -999.00   -999.00     29.52
     48.00      51.98    -999.00   -999.00      6.58     13.24     23.37
     49.00      56.45    -999.00   -999.00   -999.00   -999.00   -999.00
     52.00      55.82       4.41   -999.00   -999.00   -999.00     20.24
     55.00      51.48    -999.00   -999.00      2.10      2.10     13.13
     59.00      53.94       8.66     10.27   -999.00   -999.00     14.00
     62.00      55.61    -999.00   -999.00     10.65     15.68     14.03
     63.00      58.49    -999.00   -999.00   -999.00   -999.00   -999.00
     66.00      58.91      10.34      6.59   -999.00   -999.00     14.80
     69.00      59.66    -999.00   -999.00      6.02      6.15     10.63
     70.00      61.95    -999.00   -999.00   -999.00   -999.00   -999.00
     74.00      82.31       8.05      9.01   -999.00   -999.00     22.50
     76.00      77.77    -999.00   -999.00     12.94     19.21     21.04
     80.00      77.22       6.42   -999.00     12.20   -999.00     22.91
     83.00      83.02    -999.00   -999.00     16.94     23.21     27.23
     84.00      75.60    -999.00   -999.00   -999.00   -999.00   -999.00
     87.00      75.18       0.72      7.22   -999.00   -999.00     22.53
     88.00      76.60       0.00      0.00     12.64     20.59     26.48
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ACCUMULATED SEGMENT LOADING (Milligrams)

DAYS	INFLUENT	SEGMENT 0-1	1-3	0-5	5-10	10-15	0-15
0.00	-999.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	49.52	559.33	86.33	0.00	0.00	0.00	0.00
6.00	44.27	780.71	270.43	0.00	0.00	0.00	1423.43
13.00	33.10	897.45	571.43	0.00	0.00	0.00	2862.07
14.00	36.57	0.00	0.00	1650.75	631.76	391.65	3042.16
24.00	45.77	795.84	0.00	0.00	0.00	0.00	4770.90
27.00	52.11	0.00	0.00	2089.31	1765.72	1144.43	5279.06
31.00	43.68	754.44	857.39	0.00	0.00	0.00	5832.13
34.00	45.18	0.00	0.00	2155.50	2245.07	1533.56	6121.36
39.00	45.18	736.13	918.43	0.00	0.00	0.00	6531.20
41.00	47.94	0.00	0.00	2188.12	2547.03	1787.83	6680.04
45.00	52.07	752.48	996.91	0.00	0.00	0.00	7000.72
48.00	51.98	0.00	0.00	2328.13	2730.34	1964.27	7225.69
49.00	56.45	0.00	0.00	0.00	0.00	0.00	0.00
52.00	55.82	818.48	0.00	0.00	0.00	0.00	7481.30
55.00	51.48	0.00	0.00	2413.97	2796.[illegible]4	2173.14	7628.94
59.00	53.94	954.49	1183.09	0.00	0.00	0.00	7784.92
62.00	55.61	0.00	0.00	2547.49	2849.75	2263.94	7910.40
63.00	58.49	0.00	0.00	0.00	0.00	0.00	0.00
66.00	58.91	1159.73	1157.53	0.00	0.00	0.00	8090.47
69.00	59.66	0.00	0.00	2728.90	2904.49	2297.32	8213.59
70.00	61.95	0.00	0.00	0.00	0.00	0.00	0.00
74.00	82.31	1437.03	1126.57	0.00	0.00	0.00	8552.30
76.00	77.77	0.00	0.00	2989.27	2999.30	2375.34	8742.40
80.00	77.22	1626.53	0.00	3201.60	0.00	0.00	9113.55
83.00	83.02	0.00	0.00	3393.55	3191.77	2466.14	9443.00
84.00	75.60	0.00	0.00	0.00	0.00	0.00	0.00
87.00	75.18	1731.44	1327.78	0.00	0.00	0.00	9874.09
88.00	76.60	0.00	0.00	3717.01	3345.73	2573.09	9975.52
TOTAL LOADING (mg)		1731.44	1327.78	3717.01	3345.73	2573.09	9975.52
DAYS OF MONITORING		87.00	87.00	88.00	88.00	88.00	88.00

ACCUMULATED SEGMENT LOADING (Milligrams/G GAC)

DAYS	INFLUENT	SEGMENT 0-1	1-3	0-5	5-10	10-15	0-15
0.00	-999.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	49.52	0.85	0.07	0.00	0.00	0.00	0.00
6.00	44.27	1.19	0.21	0.00	0.00	0.00	0.14
13.00	33.10	1.37	0.43	0.00	0.00	0.00	0.29
14.00	36.57	0.00	0.00	0.50	0.19	0.12	0.31
24.00	45.77	1.21	0.00	0.00	0.00	0.00	0.48
27.00	52.11	0.00	0.00	0.64	0.54	0.35	0.54
31.00	43.68	1.15	0.65	0.00	0.00	0.00	0.59
34.00	43.18	0.00	0.00	0.66	0.68	0.47	0.62
39.00	45.18	1.12	0.70	0.00	0.00	0.00	0.66
41.00	47.[illegible]	[illegible].00	0.00	0.67	0.78	0.54	0.68
45.00	52.0[illegible]	[illegible].15	0.76	0.00	0.00	0.00	0.71
48.00	51.9[illegible]	0.00	0.00	0.71	0.83	0.60	0.73
49.00	56.45	0.00	0.00	0.00	0.00	0.00	0.00
52.00	55.82	1.25	0.00	0.00	0.00	0.00	0.76
55.00	51.48	0.00	0.00	0.73	0.85	0.66	0.77
59.00	53.94	1.45	0.90	0.00	0.00	0.00	0.79
62.00	55.61	0.00	0.00	0.78	0.87	0.69	0.80
63.00	58.49	0.00	0.00	0.00	0.00	0.00	0.00
66.00	58.91	1.77	0.88	0.00	0.00	0.00	0.82
69.00	59.66	0.00	0.00	0.83	0.88	0.70	0.83
70.00	61.95	0.00	0.00	0.00	0.00	0.00	0.00
74.00	82.31	2.19	0.86	0.00	0.00	0.00	0.87
76.00	77.77	0.00	0.00	0.91	0.91	0.72	0.89
80.00	77.22	2.48	0.00	0.97	0.00	0.00	0.92
83.00	83.02	0.00	0.00	1.03	0.97	0.75	0.96
84.00	75.60	0.00	0.00	0.00	0.00	0.00	0.00
87.00	75.18	2.64	1.01	0.00	0.00	0.00	1.00
88.00	76.60	0.00	0.00	1.13	1.02	0.78	1.01
TOTAL LOADING (mg/G GAC)		2.64	1.01	1.13	1.02	0.78	1.01
DAYS OF MONITORING		87.00	87.00	88.00	88.00	88.00	88.00

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                              COLUMN A CHLOROFORM ADSORPTION SUMMARY
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PORT   SEGMENT   SEGMENT      TEST       BREAKTHROUGH          TOTAL        % OF TOTAL
          #       DEPTH     DURATION                          ADSORBED       ADSORBED
                  (cm)       (DAYS)         (DAYS)              (g)            (%)
-------------------------------------------------------------------------------------------------------
  1      0-1      10.2       87.00           0.10               1.73          17.97

  3      1-3      30.6       87.00           0.15               1.33          13.78

  5      0-5      51.0       88.00           0.34               3.72          38.57

 10      5-10     51.0       88.00           0.77               3.35          34.72

 15     10-15     51.0       88.00           3.59               2.57          26.70

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AVERAGE INFLUENT CONCENTRATION:  54.0481 Micrograms/L
TOTAL ENTERING COLUMN DURING TEST:  25921.5  mg
TOTAL TEST DURATION  88  DAYS

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DATA ANALYSIS FOR CHLOROFORM

COLUMN B
A

CARBON TYPF: WITCO 950
CARBON DENSITY: 495 KG/M3
DAYS OF OPERATION: 88

CONCENTRATION (Micrograms/L)

DAYS	INFLUENT	PORT NUMBER 1	3	5	10	15
0.00	-999.00	-999.00	-999.00	-999.00	-999.00	-999.00
3.00	49.52	21.09	11.84	-999.00	-999.00	-999.00
6.00	44.27	27.78	18.00	-999.00	-999.00	-999.00
13.00	33.10	32.53	25.16	-999.00	-999.00	6.58
14.00	36.57	-999.00	-999.00	18.39	9.37	7.67
24.00	45.77	44.81	-999.00	-999.00	-999.00	11.07
27.00	52.11	-999.00	-999.00	37.13	16.48	10.89
31.00	43.68	51.98	46.18	-999.00	-999.00	12.67
34.00	43.18	-999.00	-999.00	42.64	23.75	12.02
[illegible]	45.18	45.60	45.50	45.98	-999.00	15.69
[illegible]	47.94	-999.00	-999.00	45.56	27.17	15.53
[illegible]	52.07	50.57	51.48	-999.00	-999.00	18.05
[illegible]	51.98	-999.00	-999.00	45.14	34.85	19.62
49.00	56.45	-999.00	-999.00	-999.00	-999.00	-999.00
52.00	55.82	51.90	[illegible]	-999.00	-999.00	21.35
55.00	51.48	-999.00	-999.00	55.70	41.76	25.46
59.00	53.94	51.78	55.24	-999.00	-999.00	29.07
62.00	55.61	-999.00	-999.00	[illegible]	43.76	32.19
63.00	58.49	-999.00	-999.00	-999.00	-999.00	-999.00
66.00	58.91	-999.00	57.82	-999.00	-999.00	31.43
69.00	59.66	-999.00	-999.00	-999.00	49.27	35.15
70.00	61.95	-999.00	-999.00	-999.00	-999.00	-999.00
74.00	82.31	-999.00	80.94	-999.00	-999.00	44.47
76.00	77.77	-999.00	-999.00	72.43	63.83	45.35
80.00	77.22	71.30	-999.00	-999.00	-999.00	47.23
83.00	83.02	-999.00	-999.00	71.55	61.70	46.39
84.00	75.60	-999.00	-999.00	-999.00	-999.00	-999.00
87.00	75.18	75.51	73.09	-999.00	-999.00	[illegible]
88.00	76.60	-666.00	-666.00	66.88	61.33	47.31

PERCENT REMOVAL (%)

DAYS	INFLUENT	PORT NUMBER 1	3	5	10	15
0.00	-999.00	-999.00	-999.00	-999.00	-999.00	-999.00
3.00	49.52	57.41	76.09	-999.00	-999.00	-999.00
6.00	44.27	37.25	59.34	-999.00	-999.00	-999.00
13.00	33.10	1.72	23.99	-999.00	-999.00	80.12
14.00	36.57	-999.00	-999.00	49.71	74.38	79.03
24.00	45.77	2.10	-999.00	-999.00	-999.00	75.81
27.00	52.11	-999.00	-999.00	28.75	68.37	79.10
31.00	43.68	-19.00	-5.72	-999.00	-999.00	70.99
34.00	43.18	-999.00	-999.00	1.25	45.04	72.16
39.00	45.18	-0.93	-0.71	-1.77	-999.00	65.27
41.00	47.94	-999.00	-999.00	4.96	43.32	67.61
45.00	52.07	2.88	1.13	-999.00	-999.00	65.34
48.00	51.98	-999.00	-999.00	13.16	32.95	62.25
49.00	56.45	-999.00	-999.00	-999.00	-999.00	-999.00
52.00	55.82	7.02	2.54	-999.00	-999.00	61.75
55.00	51.48	-999.00	-999.00	-8.20	18.88	50.54
59.00	53.94	4.00	-2.41	-999.00	-999.00	46.11
62.00	55.61	-999.00	-999.00	3.00	21.31	42.11
63.00	58.49	-999.00	-999.00	-999.00	-999.00	-999.00
66.00	58.91	-999.00	1.85	-999.00	-999.00	46.65
69.00	59.66	-999.00	-999.00	-999.00	17.42	41.08
70.00	61.95	-999.00	-999.00	-999.00	-999.00	-999.00
74.00	82.31	-999.00	1.66	-999.00	-999.00	45.97
76.00	77.77	-999.00	-999.00	6.87	17.92	41.69
80.00	77.22	7.67	-999.00	-999.00	-999.00	38.84
83.00	83.02	-999.00	-999.00	13.82	25.68	44.12
84.00	75.60	-999.00	-999.00	-999.00	-999.00	-999.00
87.00	75.18	-0.44	2.78	-999.00	-999.00	34.62
88.00	76.60	0.00	0.00	12.69	19.93	38.24

ACCUMULATED SEGMENT LOADING (Milligrams)

DAYS	INFLUENT	SEGMENT 0-1	1-3	0-5	5-10	10-15	0-15
0.00	-999.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	49.52	637.24	75.62	0.00	0.00	0.00	0.00
6.00	44.27	1004.46	231.19	0.00	0.00	0.00	1423.43
13.00	33.10	1329.88	558.33	0.00	0.00	0.00	2112.04
14.00	36.57	0.00	0.00	2088.71	344.11	64.29	2263.06
24.00	45.77	1375.74	0.00	0.00	0.00	0.00	3996.16
27.00	52.11	0.00	0.00	3263.41	1395.17	322.54	4616.80
31.00	43.68	1235.73	1204.31	0.00	0.00	0.00	5404.11
34.00	43.18	0.00	0.00	3559.45	2149.78	682.53	5912.35
39.00	45.18	1045.64	1332.93	3555.91	0.00	0.00	6738.71
41.00	47.94	0.00	0.00	3564.52	2861.28	1097.94	7076.06
45.00	52.07	1063.30	1319.69	0.00	0.00	0.00	[illegible]
48.00	51.98	0.00	0.00	3740.39	3408.35	1610.48	[illegible]
49.00	56.45	0.00	0.00	0.00	0.00	0.00	[illegible]
52.00	55.82	1166.68	1254.64	0.00	0.00	0.00	[illegible]
55.00	51.48	0.00	0.00	3790.37	3870.54	2211.92	[illegible]
59.00	53.94	[illegible]	[illegible]	0.00	0.00	0.00	[illegible]
62.00	55.61	0.00	0.00	3741.72	4330.62	2743.54	[illegible]
63.00	58.49	0.00	0.00	0.00	0.00	0.00	[illegible]
66.00	58.91	0.00	0.00	0.00	0.00	0.00	[illegible]
69.00	59.66	0.00	0.00	0.00	0.00	3233.57	[illegible]
70.00	61.95	0.00	0.00	[illegible]	0.00	0.00	0.00
74.00	82.31	0.00	0.00	[illegible]	0.00	0.00	12344.60
76.00	77.77	0.00	0.00	[illegible]	[illegible]	3855.42	12727.50
80.00	77.22	1745.04	0.00	[illegible]	0.00	0.00	13407.80
83.00	83.02	0.00	0.00	[illegible]	[illegible]	4499.96	13952.40
84.00	75.60	0.00	0.00	[illegible]	0.00	0.00	0.00
87.00	75.18	1851.67	1061.60	[illegible]	0.00	0.00	14635.40
88.00	76.60	0.00	0.00	[illegible]	[illegible]	4899.58	14786.10
TOTAL LOADING (mg)		1851.67	1061.60	[illegible]	5608.84	4899.58	14786.10
DAYS OF MONITORING		87.00	87.00	88.00	88.00	88.00	88.00

ACCUMULATED SEGMENT LOADING (Milligrams/G GAC)

DAYS	INFLUENT	SEGMENT 0-1	1-3	0-5	5-10	10-15	0-15
0.00	-999.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	49.52	0.70	0.04	0.00	0.00	[illegible]	0.00
6.00	44.27	1.10	0.13	0.00	0.00	[illegible]	0.14
13.00	33.10	1.45	0.30	0.00	0.00	[illegible]	0.15
14.00	36.57	0.00	0.00	0.46	0.08	0.01	0.16
24.00	45.77	1.50	0.00	0.00	0.00	0.00	0.29
27.00	52.11	0.00	0.00	0.71	0.30	0.07	0.34
31.00	43.68	1.35	0.66	0.80	0.00	0.00	0.39
34.00	43.18	0.00	0.00	0.78	0.47	0.14	0.43
39.00	45.18	1.14	0.73	0.78	0.00	0.00	0.49
41.00	47.94	0.00	0.00	0.78	0.62	0.24	0.51
45.00	52.07	1.16	0.72	0.00	0.00	0.00	0.57
48.00	51.98	0.00	0.00	0.82	0.74	0.35	0.61
49.00	56.45	0.00	0.00	0.00	0.00	0.00	0.00
52.00	55.82	1.27	0.68	0.00	0.00	0.00	0.66
55.00	51.48	0.00	0.00	0.83	0.84	0.48	0.70
59.00	53.94	1.40	0.62	0.00	0.00	0.00	0.74
62.00	55.61	0.00	0.00	0.82	0.95	0.60	0.77
63.00	58.49	0.00	0.00	0.00	0.00	0.00	0.00
66.00	58.91	0.00	0.00	0.00	0.00	0.00	0.81
69.00	59.66	0.00	0.00	0.00	0.00	0.71	0.84
70.00	61.95	0.00	0.00	0.00	0.00	0.00	0.00
74.00	82.31	0.00	0.00	0.00	0.00	0.00	0.90
76.00	77.77	0.00	0.00	0.88	1.10	0.84	0.93
80.00	77.22	1.90	0.00	0.00	0.00	0.00	0.98
83.00	83.02	0.00	0.00	0.95	1.18	0.98	1.02
84.00	75.60	0.00	0.00	0.00	0.00	0.00	0.00
87.00	75.18	2.02	0.58	0.00	0.00	0.00	1.06
88.00	76.60	0.00	0.00	1.01	1.22	1.07	1.08
TOTAL LOADING (mg/G GAC)		2.02	0.58	1.01	1.22	1.07	1.08
DAYS OF MONITORING		87.00	87.00	88.00	88.00	88.00	88.00

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                    COLUMN 6 CHLOROFORM ADSORPTION SUM[illegible]
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PORT  SEGMENT  SEGMENT      TEST        BREAKTHROUGH        TOTAL        % OF TOTAL
                DEPTH     DURATION                         ADSORBED       ADSORBED
                 (cm)      (DAYS)          (DAYS)            (g)            (%)
---------------------------------------------------------------------------------------------------
  1     0-1     10.2       87.00            0.14             1.85          12.24

  3     1-3     30.6       87.00            0.25             1.06           7.02

  5     0-5     51.0       88.00            0.56             4.62          30.53

 10     5-10    51.0       88.00            1.09             5.61          3[illegible].08

 15    10-15    51.0       88.00            1.31             4.90          32.39

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AVERAGE INFLUENT CONCENTRATION:  54.0481 Micrograms/L
TOTAL ENTERING COLUMN DURING TEST:  25921.5  mg
TOTAL TEST DURATION  88  DAYS

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DATA ANALYSIS FOR CHLOROFORM

COLUMN C

CARBON TYPE: FILTRASORB 300
CARBON DENSITY: 420 KG/M3
DAYS OF OPERATION: 88

CONCENTRATION (Micrograms/L)

DAYS	INFLUENT	PORT NUMBER 1	3	5	10	15
0.00	-999.00	-999.00	-999.00	-999.00	-999.00	-999.00
3.00	49.52	16.50	5.84	-999.00	-999.00	-999.00
6.00	44.27	29.96	16.93	-999.00	-999.00	-999.00
13.00	33.10	34.45	26.68	-999.00	-999.00	0.00
14.00	36.57	-999.00	-999.00	23.14	9.45	0.00
24.00	45.77	45.06	-999.00	-999.00	-999.00	15.30
27.00	52.11	-999.00	-999.00	40.23	30.57	-999.00
31.00	43.68	47.51	43.93	-999.00	-999.00	26.15
34.00	43.18	-999.00	-999.00	40.10	37.57	30.56
39.00	45.18	45.98	45.43	-999.00	-999.00	32.71
41.00	47.94	-999.00	-999.00	41.72	39.84	35.63
45.00	52.07	45.39	47.39	-999.00	-999.00	39.45
48.00	51.98	-999.00	-999.00	44.89	44.10	40.25
49.00	56.45	-999.00	-999.00	-999.00	-999.00	-999.00
52.00	55.82	51.65	44.31	-999.00	-999.00	39.16
55.00	51.48	-999.00	-999.00	47.8[illegible]	46.64	41.43
59.00	53.94	54.03	50.94	-999.00	-999.00	42.93
62.00	55.61	-999.00	-999.00	47.85	46.94	42.93
63.00	58.49	-999.00	18.35	-999.00	-999.00	30.28
66.00	58.91	52.61	42.85	-999.00	-999.00	30.74
69.00	59.66	-999.00	-999.00	45.23	40.82	38.31
70.00	61.95	-999.00	53.03	-999.00	-999.00	-999.00
74.00	82.31	[illegible]	70.22	-999.00	-999.00	44.81
76.00	77.77	-999.00	-999.00	62.75	50.94	47.19
80.00	[illegible]	72.68	66.09	-999.00	-999.00	48.48
83.00	[illegible]	-999.00	-999.00	67.96	58.62	46.65
84.00	[illegible]	-999.00	-999.00	-999.00	-999.00	-999.00
87.00	[illegible]	69.13	69.21	-999.00	-999.00	48.94
88.00	76.60	-666.00	-666.00	62.16	59.19	48.73

PERCENT REMOVAL (%)

DAYS	INFLUENT	PORT NUMBER 1	3	5	10	15
0.00	-999.00	-999.00	-999.00	-999.00	-999.00	-999.00
3.00	49.52	66.68	88.21	-999.00	-999.00	-999.00
6.00	44.27	32.32	61.76	-999.00	-999.00	-999.00
13.00	33.10	-4.08	19.40	-999.00	-999.00	100.00
14.00	36.57	-999.00	-999.00	36.72	74.16	100.00
24.00	45.77	1.55	-999.00	-999.00	-999.00	66.57
27.00	52.11	-999.00	-999.00	22.80	41.34	-999.00
31.00	43.68	-8.77	-0.57	-999.00	-999.00	40.13
34.00	43.18	-999.00	-999.00	7.13	12.99	29.23
39.00	45.18	-1.77	-0.55	-999.00	-999.00	27.60
41.00	47.94	-999.00	-999.00	12.97	16.90	25.68
45.00	52.07	12.83	8.99	-999.00	-999.00	24.24
48.00	51.98	-999.00	-999.00	13.64	15.16	22.57
49.00	56.45	-999.00	-999.00	-999.00	-999.00	-999.00
52.00	55.82	7.47	20.62	-999.00	-999.00	29.85
55.00	51.48	-999.00	-999.00	7.13	9.40	19.52
59.00	53.94	-0.17	5.56	-999.00	-999.00	20.41
62.00	55.61	-999.00	-999.00	13.95	15.59	22.80
63.00	58.49	-999.00	68.63	-999.00	-999.00	48.23
66.00	58.91	10.69	27.26	-999.00	-999.00	47.82
69.00	59.66	-999.00	-999.00	24.19	31.58	35.79
70.00	61.95	-999.00	14.40	-999.00	-999.00	-999.00
74.00	82.31	7.85	14.69	-999.00	-999.00	45.56
76.00	77.77	-999.00	-999.00	19.31	34.50	39.32
80.00	77.22	5.88	14.41	-999.00	-999.00	37.22
83.00	83.02	-999.00	-999.00	18.14	29.39	43.81
84.00	75.60	-999.00	-999.00	-999.00	-999.00	-999.00
87.00	75.18	8.05	7.94	-999.00	-999.00	34.90
88.00	76.60	0.00	0.00	18.85	22.73	36.38

ACCUMULATED SEGMENT LOADING (Milligrams)

DAYS	INFLUENT	SEGMENT 0-1	1-3	0-5	5-10	10-15	0-15
0.00	-999.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	49.52	474.76	87.15	0.00	0.00	0.00	0.00
6.00	[illegible]	1061.69	280.81	0.00	0.00	0.00	1423.43
13.00	[illegible]	[illegible]	677.57	0.00	0.00	0.00	3052.22
14.00	[illegible]	0.00	0.00	1907.50	522.27	332.61	3242.07
24.00	45.77	1289.72	0.00	0.00	0.00	0.00	5068.91
27.00	52.11	0.00	0.00	2804.11	1349.45	0.00	4616.80
31.00	[illegible]	[illegible]	1234.29	0.00	0.00	0.00	5984.51
34.00	[illegible]	0.00	0.00	3089.47	1581.97	1229.68	6230.99
39.00	45.18	1129.27	1324.32	0.00	0.00	0.00	6572.84
41.00	47.94	0.00	0.00	[illegible]	1666.09	1443.71	6707.89
45.00	[illegible]	1225.41	1300.62	0.00	0.00	0.00	6979.62
48.00	[illegible]	0.00	0.00	3520.75	1717.02	1597.45	7178.69
49.00	[illegible]	[illegible]	0.00	0.00	0.00	0.00	0.00
52.00	55.82	1432.37	1402.48	0.00	0.00	0.00	7488.14
55.00	51.48	0.00	0.00	3726.00	1754.41	1770.27	7706.49
59.00	53.94	1510.20	1601.45	0.00	0.00	0.00	7936.04
62.00	[illegible]	0.00	0.00	3944.03	1794.09	1946.14	8129.71
63.00	[illegible]	0.00	0.00	0.00	0.00	0.00	8241.14
66.00	[illegible]	1628.65	1846.54	0.00	0.00	0.00	8702.04
69.00	[illegible]	0.00	0.00	4367.30	1895.56	2070.51	9106.87
70.00	[illegible]	0.00	0.00	0.00	0.00	0.00	0.00
74.00	[illegible]	[illegible]	2182.04	0.00	0.00	0.00	9908.70
76.00	[illegible]	0.00	0.00	4929.06	2204.96	2189.92	10279.70
80.00	[illegible]	[illegible]	2381.84	0.00	0.00	0.00	10926.30
83.00	[illegible]	0.00	0.00	5502.84	2608.40	2489.78	11458.60
84.00	[illegible]	0.00	0.00	0.00	0.00	0.00	0.00
87.00	75.18	2288.67	2506.02	0.00	0.00	0.00	12141.00
88.00	[illegible]	0.00	0.00	5904.78	2776.12	2795.39	12288.50
TOTAL LOADING	[illegible]	2288.67	2506.02	5904.78	2776.12	2795.39	12288.50
DAYS OF MONITORING		87.00	87.00	88.00	88.00	88.00	88.00

ACCUMULATED SEGMENT LOADING (Milligrams/G GAC)

[illegible]	INFLUENT	SEGMENT 0-1	1-3	0-5	5-10	10-15	0-15
0.00	-999.00	0.00	0.00	0.00	0.00	0.00	0.00
[illegible]	[illegible]	0.87	0.06	0.00	0.00	0.00	0.00
[illegible]	[illegible]	1.37	0.18	0.00	0.00	0.00	0.14
[illegible]	33.10	1.68	0.44	0.00	0.00	0.00	0.26
14.00	36.57	0.00	0.00	0.49	0.13	0.09	0.28
24.00	45.77	1.66	0.00	0.00	0.00	0.00	0.43
27.00	52.11	0.00	0.00	0.72	0.35	0.00	0.34
31.00	[illegible]	1.58	0.79	0.00	0.00	0.00	0.51
34.00	[illegible]	0.00	0.00	0.79	0.41	0.32	0.53
39.00	45.18	1.45	0.85	0.00	0.00	0.00	0.56
41.00	47.94	0.00	0.00	0.84	0.43	0.37	0.58
45.00	52.07	1.58	0.84	0.00	0.00	0.00	0.60
48.00	51.98	0.00	0.00	0.91	0.44	0.41	0.62
49.00	56.45	0.00	0.00	0.00	0.00	0.00	0.00
52.00	55.82	1.84	0.90	0.00	0.00	0.00	0.64
55.00	51.48	0.00	0.00	0.96	0.45	0.46	0.66
59.00	53.94	1.94	1.03	0.00	0.00	0.00	0.68
62.00	55.61	0.00	0.00	1.01	0.46	0.50	0.70
63.00	58.49	0.00	0.00	0.00	0.00	0.00	0.71
66.00	58.91	2.10	1.19	0.00	0.00	0.00	0.75
69.00	59.66	0.00	0.00	1.12	0.49	0.53	0.78
70.00	61.95	0.00	0.00	0.00	0.00	0.00	0.00
74.00	82.31	2.45	1.40	0.00	0.00	0.00	0.85
76.00	77.77	0.00	0.00	1.27	0.57	0.56	0.88
80.00	77.22	2.68	1.53	0.00	0.00	0.00	0.94
83.00	83.02	0.00	0.00	1.42	0.67	0.64	0.98
84.00	75.60	0.00	0.00	0.00	0.00	0.00	0.00
87.00	75.18	2.94	1.61	0.00	0.00	0.00	1.04
88.00	76.60	0.00	0.00	1.52	0.71	0.72	1.05
TOTAL LOADING (mg/G GAC)		2.94	1.61	1.52	0.71	0.72	1.05
DAYS OF MONITORING		87.00	87.00	88.00	88.00	88.00	88.00

COLUMN C CHLOROFORM ADSORPTION SUMMARY

PORT #	SEGMENT	SEGMENT DEPTH (cm)	TEST DURATION (DAYS)	BREAKTHROUGH (DAYS)	TOTAL ADSORBED (g)	% OF TOTAL ADSORBED (%)
1	0-1	10.2	87.00	0.18	2.29	19.94
3	1-3	30.6	87.00	0.51	2.51	21.84
5	0-5	51.0	88.00	0.44	5.90	51.45
10	5-10	51.0	88.00	1.08	2.78	24.19
15	10-15	51.0	88.00	14.60	2.80	24.36

AVERAGE INFLUENT CONCENTRATION: [illegible].0481 Micrograms/L
TOTAL ENTERING COLUMN DURING TEST: 25921.5 mg
TOTAL TEST DURATION 88 DAYS

DATA ANALYSIS FOR CHLOROFORM

COLUMNS S AND C

CARBON TYPE: FILTRASORB 300
CARBON DENSITY: 420 KG/M3
DAYS OF OPERATION: 88

CONCENTRATION (Micrograms/L)

		PORT NUMBER			
DAYS	INFLUENT	S1	S3	CA15	CB13
0.00	-999.00	-999.00	-999.00	-999.00	-999.00
3.00	49.52	32.02	22.75	-999.00	-999.00
6.00	44.27	33.31	27.31	-999.00	-999.00
13.00	33.10	35.89	30.65	0.00	-999.00
14.00	36.57	38.34	32.95	0.00	-999.00
24.00	45.77	42.56	38.17	15.30	0.00
27.00	52.11	-999.00	47.22	-999.00	-999.00
31.00	43.68	41.35	44.78	26.15	1.81
34.00	43.18	-999.00	-999.00	30.56	2.58
39.00	45.18	46.81	44.06	32.71	4.52
41.00	47.94	44.64	44.76	35.63	6.34
45.00	52.07	46.69	47.56	39.45	10.17
48.00	51.98	48.73	50.06	40.25	9.23
49.00	56.45	-999.00	-999.00	-999.00	-999.00
52.00	55.82	55.28	54.45	39.16	14.51
55.00	51.48	-999.00	-999.00	41.63	16.57
59.00	53.94	57.53	53.19	42.93	21.07
62.00	55.61	-999.00	-999.00	42.93	27.93
63.00	58.49	-999.00	-999.00	30.28	22.73
66.00	58.91	50.36	35.08	30.74	24.29
69.00	59.66	53.07	46.43	38.31	26.70
70.00	61.95	-999.00	50.90	-999.00	-999.00
74.00	82.31	77.72	73.72	44.81	35.20
76.00	77.77	74.01	69.21	47.19	32.57
80.00	77.22	72.51	70.72	48.48	34.25
83.00	83.02	78.56	75.10	46.65	35.65
84.00	75.60	-999.00	-999.00	-999.00	-999.00
87.00	75.18	71.93	74.43	48.94	35.60
88.00	76.60	-666.00	74.43	48.73	37.29

PERCENT REMOVAL (%)

		PORT NUMBER			
DAYS	INFLUENT	S1	S3	CA15	CB13
0.00	-999.00	-999.00	-999.00	-999.00	-999.00
3.00	49.52	35.34	54.06	-999.00	-999.00
6.00	44.27	24.76	38.31	-999.00	-999.00
13.00	33.10	-8.43	7.40	100.00	100.00
14.00	36.57	-4.84	9.90	100.00	100.00
24.00	45.77	7.01	16.60	66.57	100.00
27.00	52.11	-999.00	9.38	-999.00	-999.00
31.00	43.68	5.33	-2.52	40.13	93.08
34.00	43.18	-999.00	-999.00	29.23	91.56
39.00	45.18	-3.61	2.48	27.60	86.18
41.00	47.94	6.88	6.63	25.68	82.21
45.00	52.07	10.33	8.66	24.24	74.22
48.00	51.98	6.25	3.69	22.57	77.07
49.00	56.45	-999.00	-999.00	-999.00	-999.00
52.00	55.82	0.97	2.45	29.85	62.95
55.00	51.48	-999.00	-999.00	19.13	60.20
59.00	53.94	-6.66	1.39	20.41	50.92
62.00	55.61	-999.00	-999.00	22.80	34.94
63.00	58.49	-999.00	-999.00	48.23	24.93
66.00	58.91	14.51	40.48	47.82	20.98
69.00	59.66	11.05	22.18	35.79	30.31
70.00	61.95	-999.00	17.84	-999.00	-999.00
74.00	82.31	5.58	10.44	45.56	21.45
76.00	77.77	4.83	11.01	39.32	30.98
80.00	77.22	6.10	8.42	37.22	29.35
83.00	83.02	5.37	9.54	43.81	23.58
84.00	75.60	-999.00	-999.00	-999.00	-999.00
87.00	75.18	4.32	1.00	34.90	27.26
88.00	76.60	0.00	2.83	36.38	23.48

ACCUMULATED SEGMENT LOADING (Milligrams)

DAYS	INFLUENT	SEGMENT			
		(S)0-1	(S)1-3	(CA)0-15	(CB)0-13
0.00	-999.00	0.00	0.00	0.00	0.00
3.00	49.52	547.89	75.78	0.00	0.00
6.00	44.27	780.55	200.61	0.00	0.00
13.00	33.10	936.39	415.02	3052.22	0.00
14.00	36.57	923.97	443.98	3242.07	0.00
24.00	45.77	963.21	710.49	5068.91	416.93
27.00	52.11	0.00	0.00	0.00	0.00
31.00	43.68	1068.88	728.80	5984.51	1173.06
34.00	43.18	0.00	0.00	6230.99	1600.77
39.00	45.18	1084.14	713.98	6572.84	2366.09
41.00	47.94	1093.24	728.31	6707.89	2679.36
45.00	52.07	1187.85	717.52	6979.62	3317.77
48.00	51.98	1258.40	699.53	7178.69	3810.72
49.00	56.45	0.00	0.00	0.00	0.00
52.00	55.82	1299.72	694.08	7488.14	4417.53
55.00	51.48	0.00	0.00	7704.86	4823.90
59.00	53.94	1241.54	792.70	7932.23	5335.33
62.00	55.61	0.00	0.00	8125.90	5636.66
63.00	58.49	0.00	0.00	8237.32	5698.11
66.00	58.91	1336.15	1166.95	8698.23	5812.56
69.00	59.66	1459.92	1346.15	9103.08	5940.20
70.00	61.95	0.00	0.00	0.00	0.00
74.00	82.31	1612.25	1491.12	9904.88	6249.32
76.00	77.77	1657.75	1539.08	10275.90	6381.38
80.00	77.22	1750.08	1610.91	10922.80	6695.84
83.00	83.02	1825.04	1653.83	11454.[illegible]	6902.10
84.00	75.60	0.00	0.00	0.00	0.00
87.00	75.18	1909.08	1664.29	12132.[illegible]	7167.41
88.00	76.60	0.00	0.00	12284.70	7234.93
TOTAL LOADING (mg)		1909.08	1664.29	12284.70	7234.93
DAYS OF MONITORING		87.00	88.00	88.00	88.00

ACCUMULATED SEGMENT LOADING (Milligrams/G GAC)

DAYS	INFLUENT	SEGMENT			
		(S)0-1	(S)1-3	(CA)0-15	(CB)0-13
0.00	-999.00	0.00	0.00	0.00	0.00
3.00	49.52	0.70	0.05	0.00	0.00
6.00	44.27	1.00	0.13	0.00	0.00
13.00	33.10	1.20	0.27	0.26	0.00
14.00	36.57	1.19	0.29	0.28	0.00
24.00	45.77	1.24	0.46	0.43	0.04
27.00	52.11	0.00	0.00	0.00	0.00
31.00	43.68	1.37	0.47	0.51	0.12
34.00	43.18	0.00	0.00	0.53	0.16
39.00	45.18	1.39	0.46	0.56	0.23
41.00	47.94	1.4[illegible]	0.47	0.58	0.27
45.00	52.07	1.53	0.46	0.60	0.33
48.00	51.98	1.62	0.45	0.62	0.38
49.00	56.45	0.00	0.00	0.00	0.00
52.00	55.82	1.67	0.45	0.64	0.44
55.00	51.48	0.00	0.00	0.66	0.48
59.00	53.94	1.60	0.51	0.68	0.53
62.00	55.61	0.00	0.00	0.70	0.56
63.00	58.49	0.00	0.00	0.71	0.56
66.00	58.91	1.72	0.75	0.75	0.58
69.00	59.66	1.88	0.87	0.78	0.59
70.00	61.95	0.00	0.00	0.00	0.00
74.00	82.31	2.07	0.96	0.85	0.62
76.00	77.77	2.13	0.99	0.88	0.63
80.00	77.22	2.28	1.04	0.94	0.66
83.00	83.02	2.35	1.06	0.98	0.68
84.00	75.60	0.00	0.00	0.00	0.00
87.00	75.18	2.46	1.07	1.04	0.71
88.00	76.60	0.00	0.00	1.05	0.72
TOTAL LOADING (mg/G GAC)		2.46	1.07	1.05	0.72
DAYS OF MONITORING		87.00	88.00	88.00	88.00

```
---------------------------------------------------------------------------------------
                   COLUMN S,CA AND CB CHLOROFORM ADSORPTION SUMMARY
---------------------------------------------------------------------------------------
PORT   SEGMENT  SEGMENT     TEST      BREAKTHROUGH       TOTAL       % OF TOTAL
                 DEPTH    DURATION                     ADSORBED      ADSORBED
                 (cm)      (DAYS)        (DAYS)          (g)           (%)
---------------------------------------------------------------------------------------
 S1      0-1     10.2      87.00          0.09           1.91          53.43

 S3      1-3     30.6      88.00          0.13           1.66          46.57

CA15    0-15     51.0      88.00         14.60          12.28          62.94

CB13    0-13     51.0      88.00         26.02           7.23          37.06

---------------------------------------------------------------------------------------
AVERAGE INFLUENT CONCENTRATION (COLUMNS S,CA):  54.0481 Micrograms/L
TOTAL ENTERING COLUMNS (S AND CA) DURING TEST:  25921.5  mg

AVERAGE INFLUENT CONCENTRATION (COLUMN CB): 28.2539 Micrograms/L
TOTAL ENTERING COLUMN CB DURING TEST:  13550.6  mg

TOTAL TEST DURATION  88  DAYS

***************************************************************************************
```

APPENDIX C

BROMODICHLOROMETHANE ADSORPTION

COLUMN A AND COLUMN B

C1 Column A

Following chloroform, bromodichloromethane was the second largest contributor to TTHM with an average influent concentration of 30.8 µg/L. Results are presented in Table C1 and Figures C1, C2, and C3. In general this compound displayed apparent exhaustion times that exceeded both chloroform and TTHM. At exhaustion, the highest loading of 1.10 mg/g GAC occurred in segment 5-10. The increasing loading trend of segment 5-10 (Figure C3) following day 42 helps explain the increasing trend of TTHM in segment 5-10 (Figure 5.3). Following apparent exhaustion in the top one-third of the bed (segment 0-5), segment 5-10 provides the greatest contribution to bromodichloromethane removal. However, an adsorptive loading of 1.06 mg/g GAC at segment 0-1 was only slightly lower. The relative segment loading pattern at apparent exhaustion is consistent with end-of-test data. Therefore, an increasing influent trend did not significantly affect the pattern of relative segment loading for this readily adsorbed compound.

TABLE C1 Bromodichloromethane Adsorption Data - Column A and Column B

Column A

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
		cm	Days	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.1	23.7	1254	1.25	697	1.06
3	1-3	20.4	0.4	47.9	1021	1.02	803	0.61
5	0-5	51.0	0.5	66.4	3173	3.17	2533	0.77
10	5-10	51.0	1.8	83.1	3725	3.73	3607	1.10
15	10-15	51.0	13.8	93.2*	2017	2.02	2025*	0.62*

Column B

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
		cm	Days	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.3	36.2	2758	3.51	1812	2.21
3	1-3	20.4	0.7	63.3	2049	1.30	1836	1.17
5	0-5	51.0	1.3	73.3	6813	1.74	6118	1.56
10	5-10	51.0	4.8	119.5*	3652	0.93	4800*	1.22*
15	10-15	51.0	6.8	264.7*	2380	0.61	8902*	2.26*

Average influent concentration: 30.8 µg/L
Total entering column during test: 14785 mg
Test duration: 88 days
*Extrapolated value

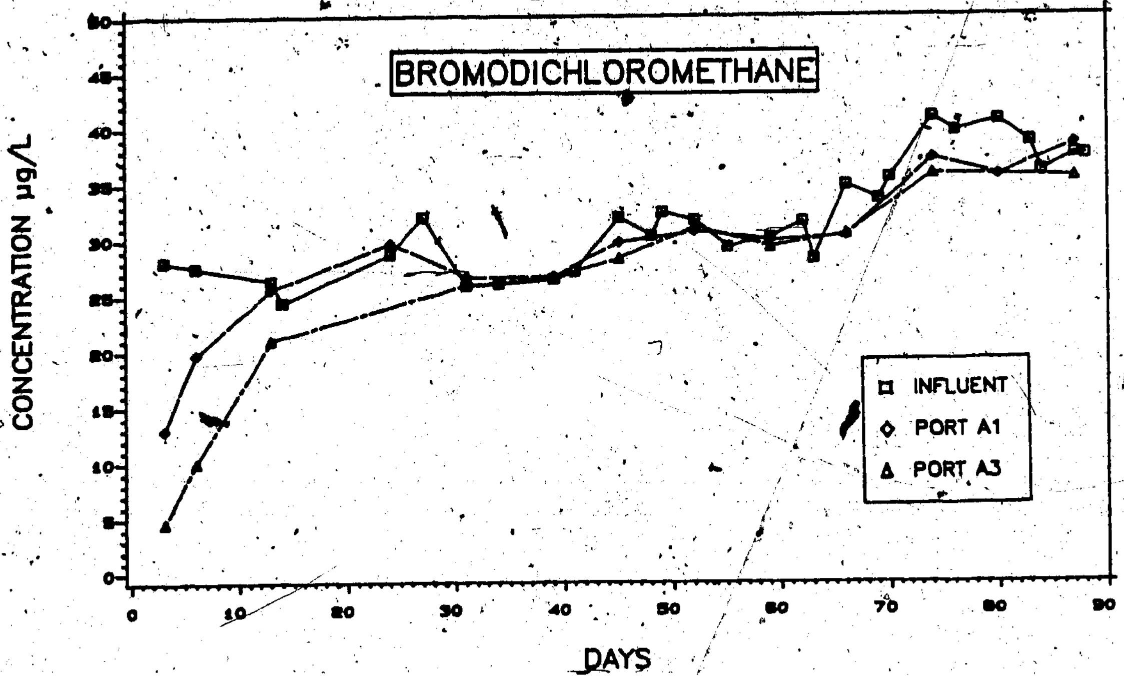

Figure C1 Bromodichloromethane in Finished Water and Removal by 10 and 31 cm GAC (Column A)

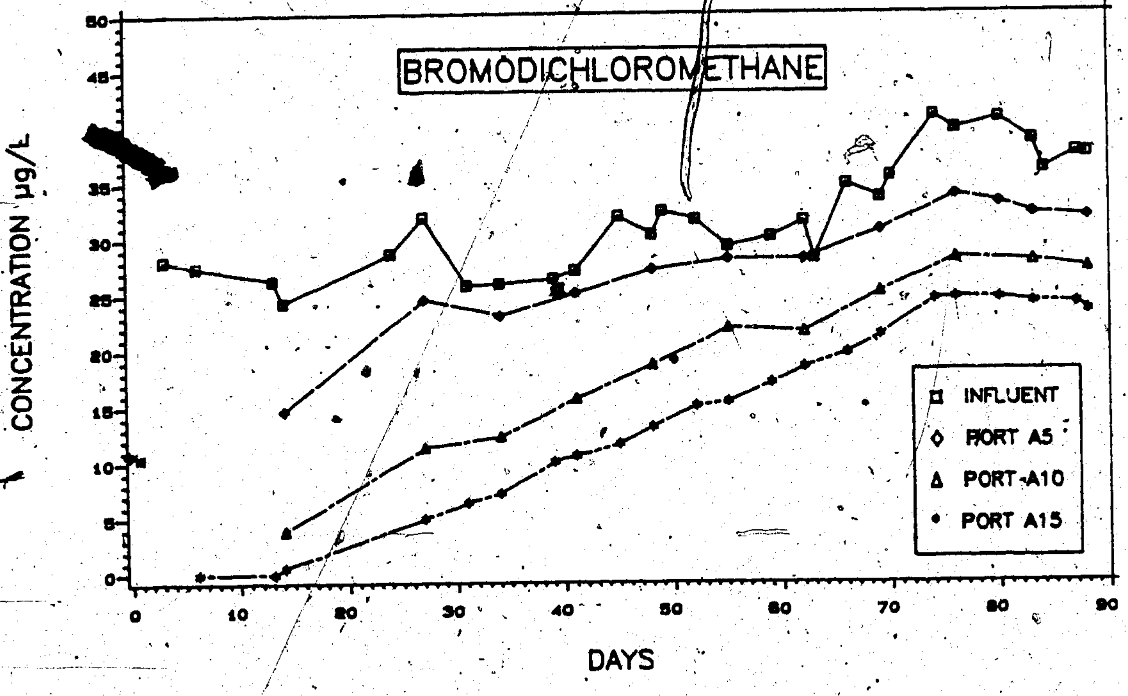

Figure C2 Bromodichloromethane in Finished Water and Removal by 51, 102, and 153 cm GAC (Column A)

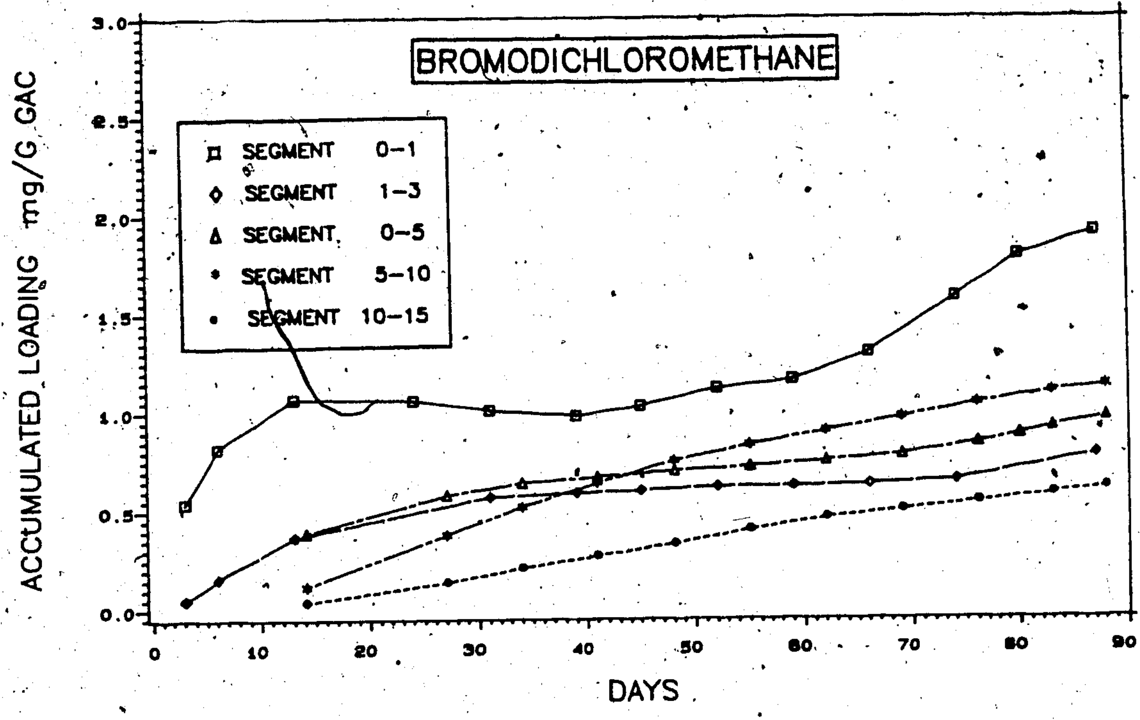

Figure C3 Bromodichloromethane Accumulated in Column A

C2 Column B

Bromodichloromethane apparent exhaustion data (Table C1) display values higher than for any other compound/column combination. This indicates very strong adsorption. At both apparent exhaustion and end of the test period, very high loadings of 2.31 mg/g GAC and 3.51 mg/g GAC respectively were achieved. The strong competitive nature of this compound is readily apparent.

Concentration and loading profiles appear in Figures C4, C5, and C6. At the end of the test period loadings of the three major segments varied inversely with column depth as expected since exhaustion was only observed in segment 0-5. Loadings calculated at extrapolated apparent exhaustion for the three major segments indicate that the highest loadings will eventually occur in segment 10-15. These results should be viewed with caution however since the extrapolated apparent exhaustion period far exceeded the actual test period.

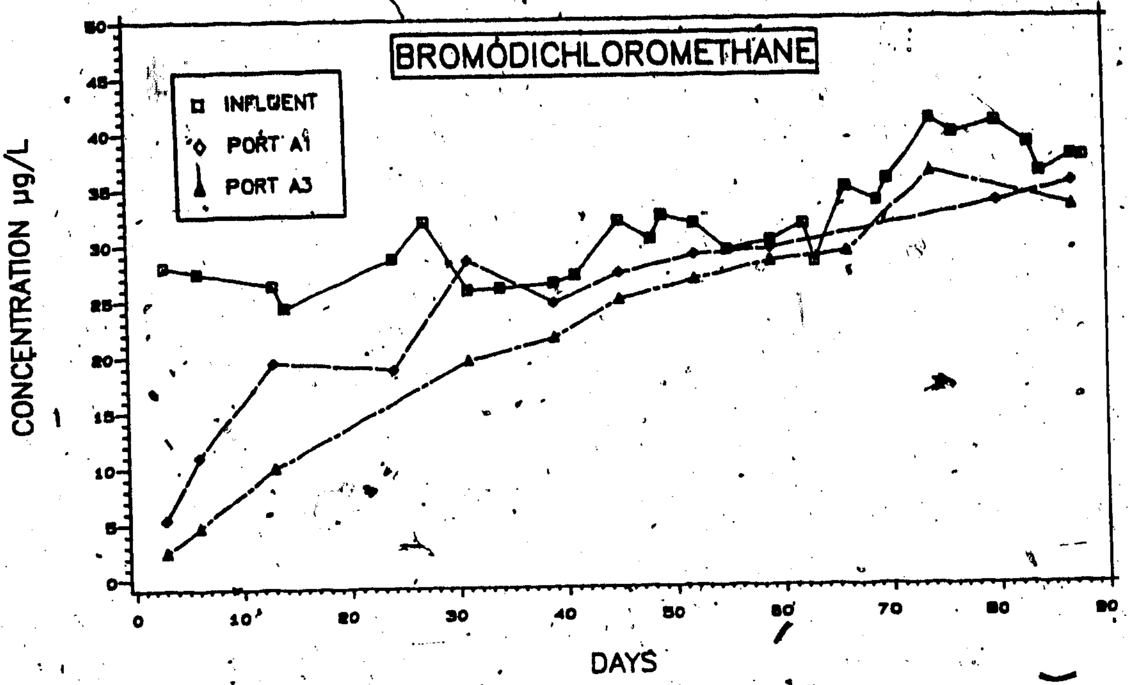

Figure C4 Bromodichloromethane in Finished Water and Removal by 10 and 31 cm GAC (Column B)

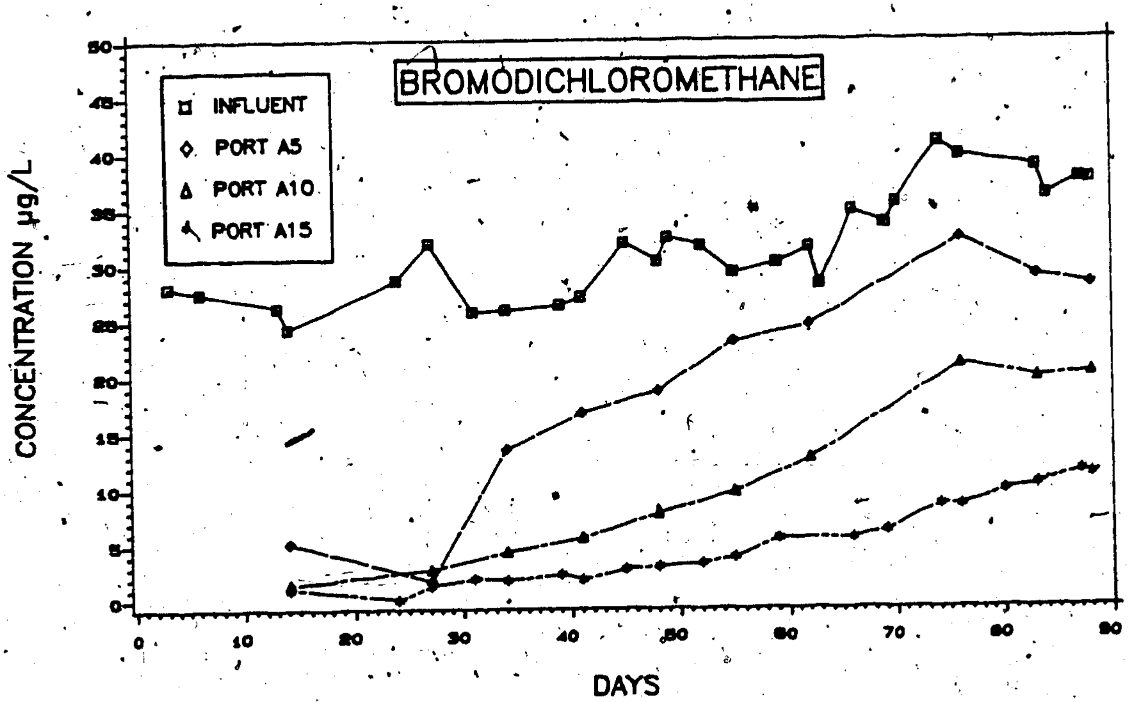

Figure C5 Bromodichloromethane in Finished Water and Removal by 51, 102, and 153 cm GAC (Column B)

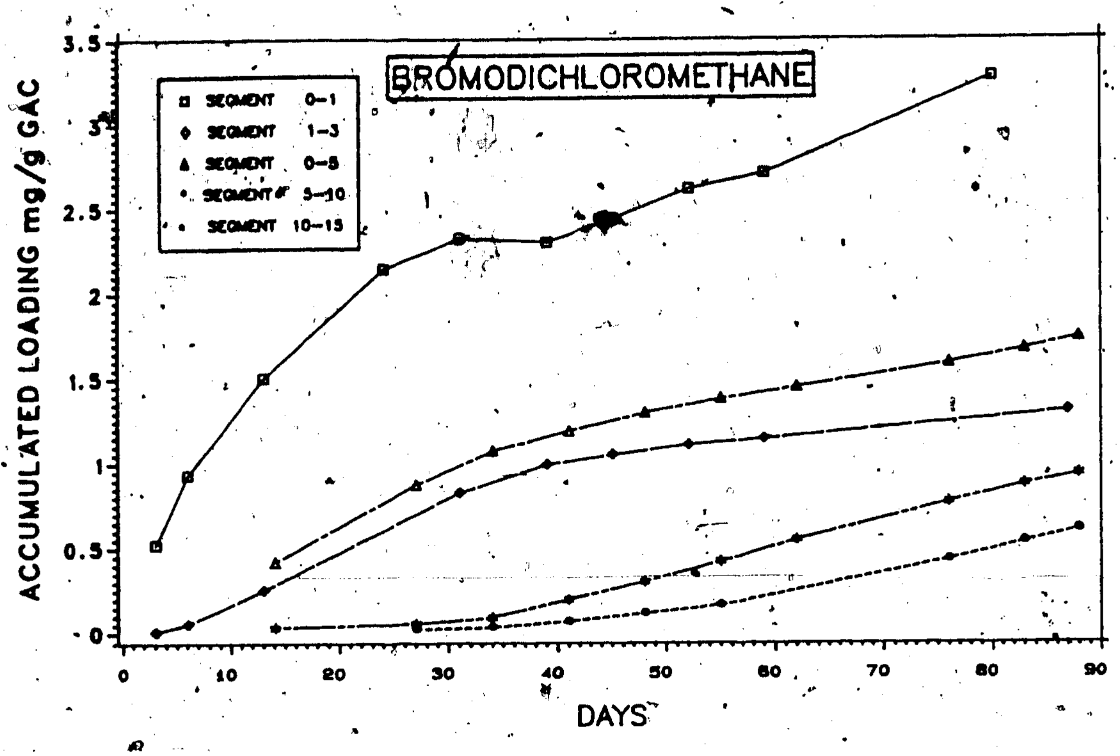

Figure C6 Bromodichloromethane Accumulated in Column B

APPENDIX D

DIBROMOCHLOROMETHANE ADSORPTION
- COLUMN A AND COLUMN B

D1 Column A

Dibromochlormethane was second only to bromodichloromethane in its GAC adsorption affinity as measured by operating time to apparent exhaustion (Table D1). Concentration and loading profiles appear in Figures D1, D2, and D3.

The influent concentration did not display the increasing trend shown by TTHM or other TTHM contributors. In contrast, the concentration for this minor contributor averaging only 7.5 μg/L increased for days 0-34, levelled from days 34-74, and finally decreased from days 74-88. This pattern appeared to directly influence the loading in segment 1-3 (Figure D3). Immediately following apparent exhaustion at day 29.9 segment 1-3 displayed a declining loading condition indicating displacement for the remainer of the test period whereas segment 0-1 above, appeared to parallel influent trends.

An examination of the three major segments (Figure D2) shows that following apparent exhaustion (day 42.3) the segment 0-5 concentration profile varied directly with the influent concentration, lower segments appeared to largely damp this effect. In general, the loading of these three

TABLE D1 Dibromochloromethane Adsorption Data - Column A and Column B

Column A

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
		cm	Days	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	0.1	25.5	244	0.37	169	0.26
3	1-3	20.4	0.2	29.9	34	0.03	207	0.16
5	0-5	51.0	0.9	42.3	875	0.27	876	0.27
10	5-10	51.0	4.0	87.0	1156	0.35	1148	0.35
15	10-15	51.0	24.6	113.1*	502	0.15	640*	0.19*

Column B

Port	Segment	Segment Depth	Breakthrough	Apparent Exhaustion	Total Adsorbed at End of Test		Total Adsorbed at Apparent Exhaustion	
		cm	Days	Days	mg	mg/g GAC	mg	mg/g GAC
1	0-1	10.2	8.1	30.6	443	0.57	414	0.52
3	1-3	20.4	1.0	54.1	911	0.58	703	0.44
5	0-5	51.0	15.1	92.0*	2105	0.53	2108*	0.54*
10	5-10	51.0	21.7	154.4*	1085	0.28	1796*	0.44*
15	10-15	51.0	60.6	194.7*	298	0.08	1262*	0.31*

Average influent concentration: 7.5 µg/L
Total entering column during test: 3607 mg
Test duration: 88 days
*Extrapolated values

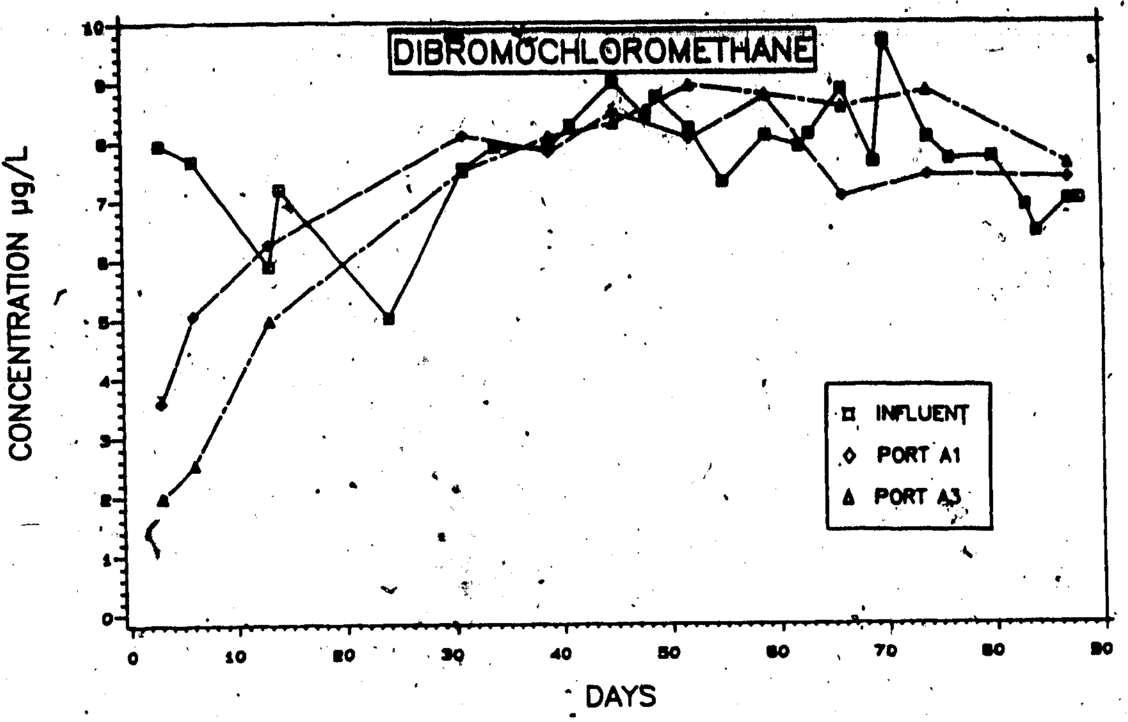

Figure D1 Dibromochlormethane in Finished Water and Removal by 10 and 31 cm GAC (Column A)

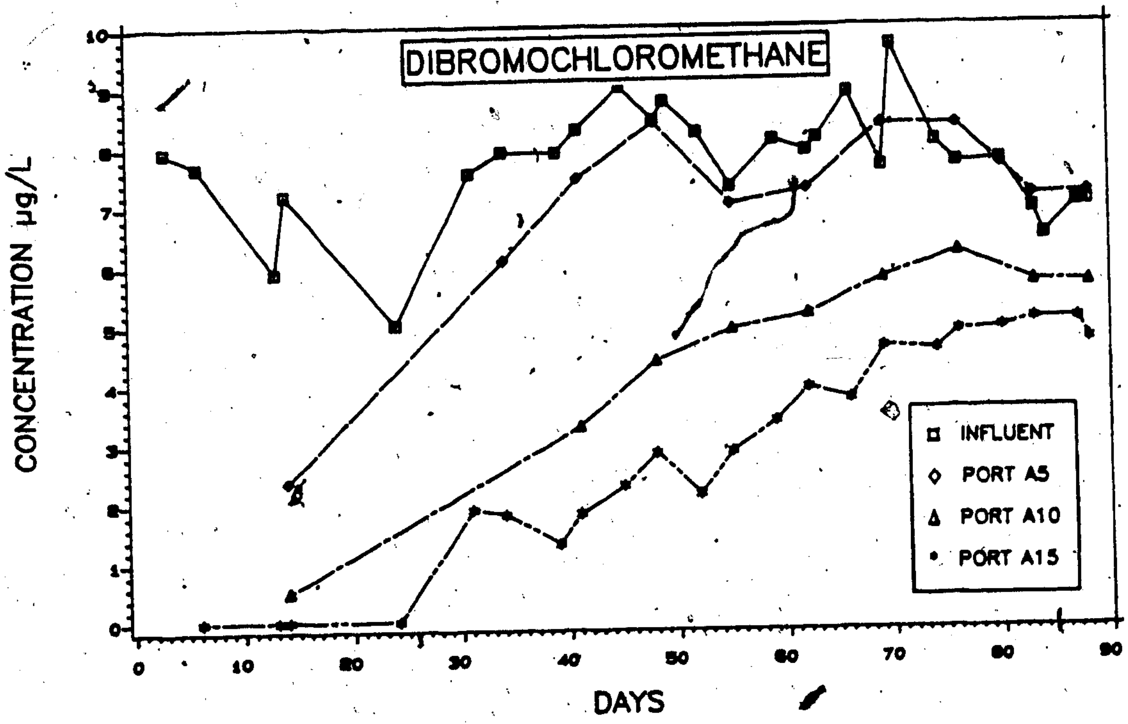

Figure D2 Dibromochloromethane in Finished Water and Removal by 51, 102, and 153 cm GAC (Column A)

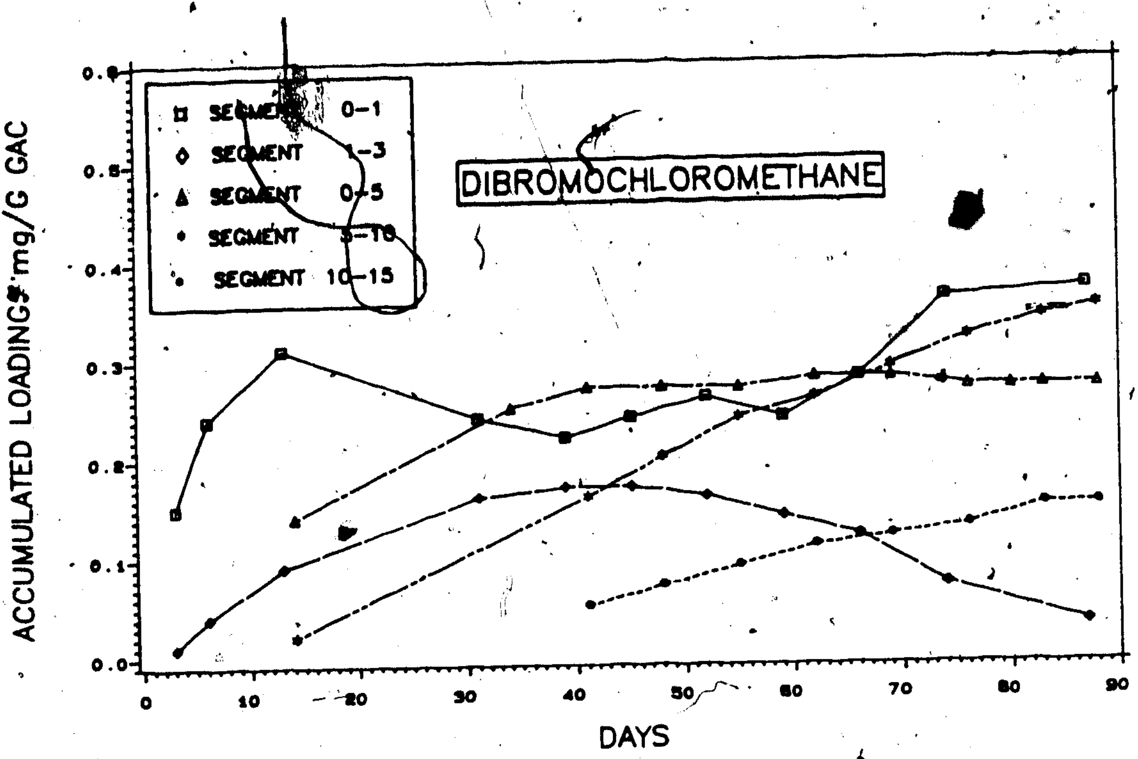

Figure D3 Dibromochloromethane Accumulated in Column A segments is consistent with TTHM and all contributors, displaying the highest loading in segment 5-10 at apparent exhaustion.

D2 Column B

Data regarding removal of dibromochloromethane by Column B appear in Table D1 and Figures D4, D5, and D6. Apparent exhaustion was not reached by any of the three major segments during the 88 day study period.

In contrast to Column A, a negative rate of accumulation occurred after day 50 in segment 0-1 whereas a positive accumulation was present in segment 1-3 throughout the study period. This indicates less successful competition in the uppermost segment. On the basis of mg/g GAC loadings, very little difference was noted among segments 0-1, 1-3, or 0-5 at the end of the test (Table D1). Segments 5-10 and 10-15 displayed loadings which decreased with column depth, both at the end of the test and at apparent exhaustion. Dibromochloromethane was either more readily adsorbable in the upper one-third of the column or else extrapolated apparent exhaustion values did not truly represent lower segment behavior.

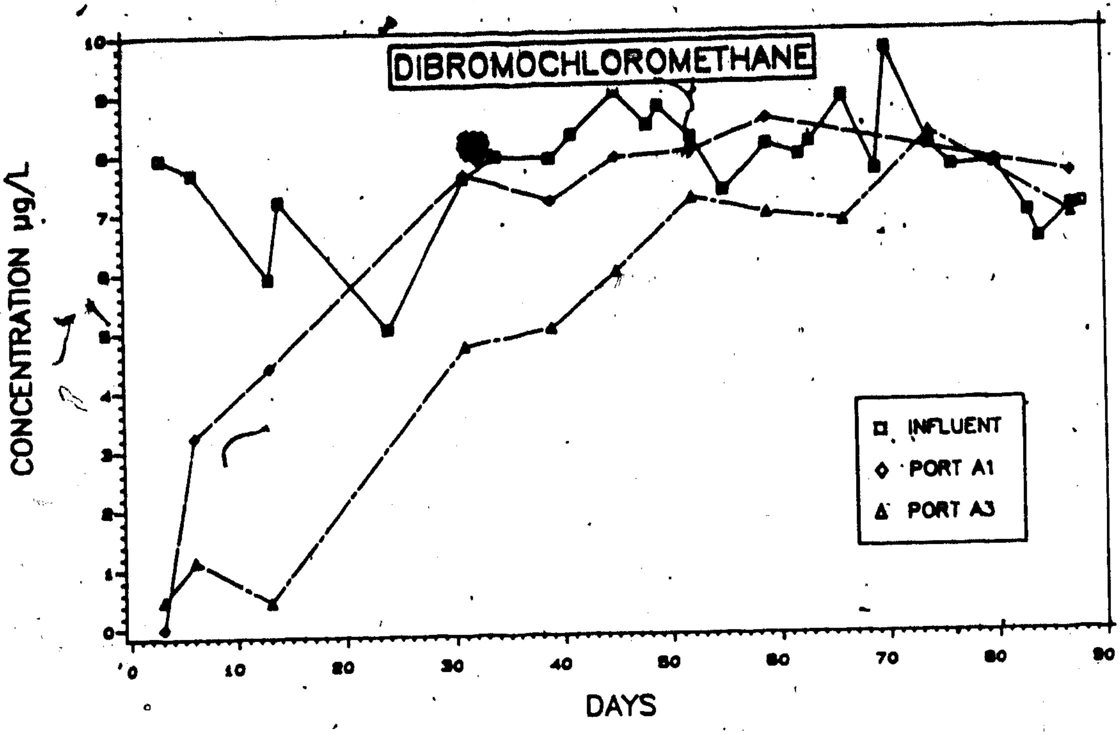

Figure D4 Dibromochloromethane in Finished Water and Removal by 10 and 31 cm GAC (Column B)

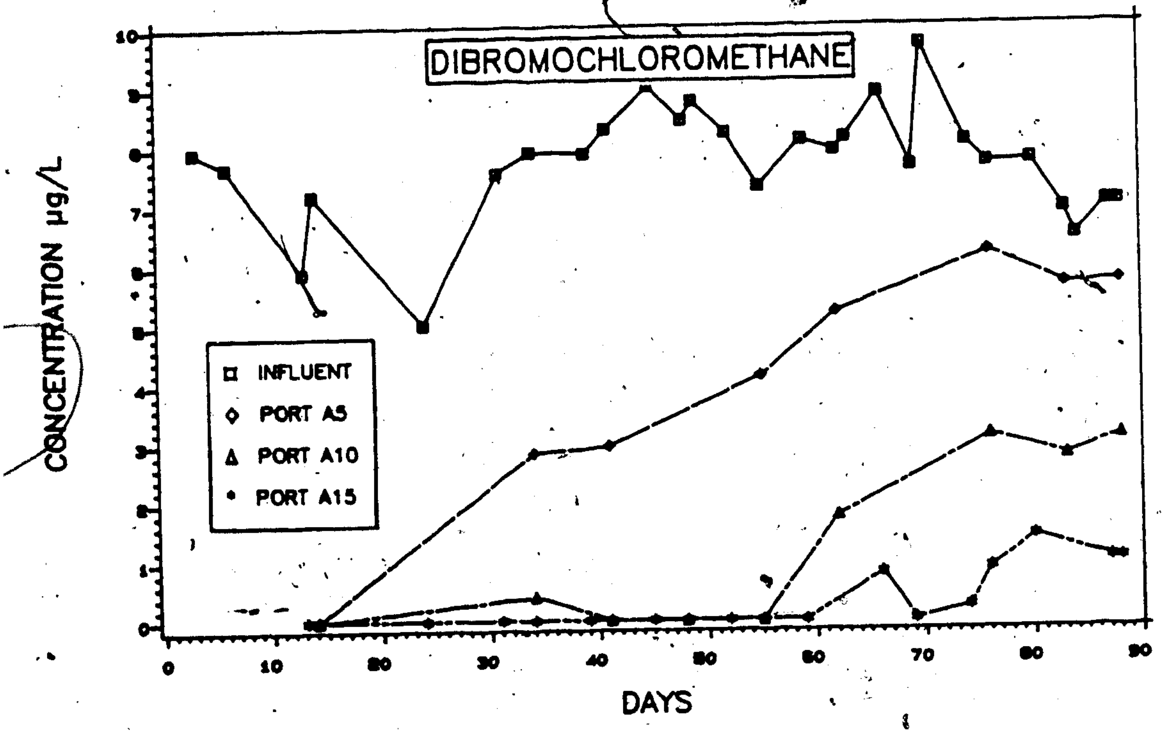

Figure D5 Dibromochloromethane in Finished Water and Removal by 51, 102, and 153 cm GAC (Column B)

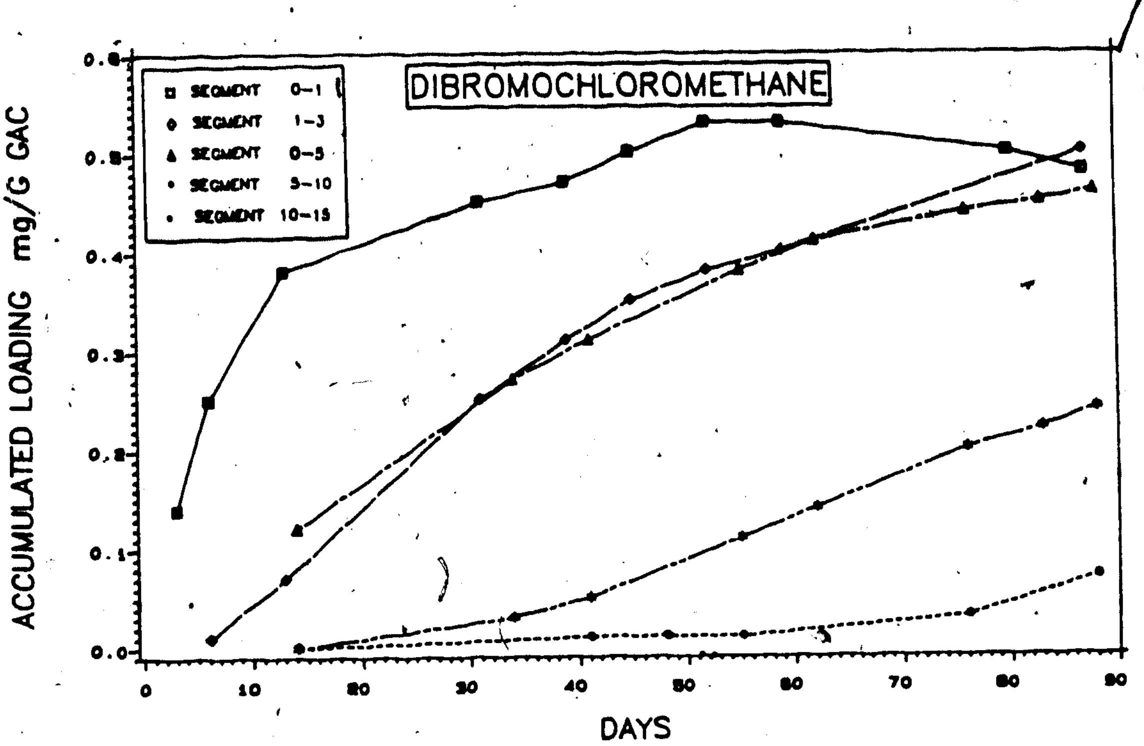

Figure D6 Dibromochloromethane Accumulated in Column B

APPENDIX E

TABLE E1 Trihalomethane segment loadings (mg/g GAC) Columns A, B, CA, CB, and S (Days 0-55)

TTHM:

	Column				
Segment	A	B	CA	CB	S
0-1	3.13	3.93	4.29	-	3.03
1-3	1.64	2.34	2.27	-	1.35
0-5	1.62	2.50	2.29	-	-
5-10	1.95	1.71	0.80	-	-
10-15	1.16	0.73	0.85	-	-
0-15	1.63	1.76	1.36	-	-
0-13	-	-	-	0.66	-

Chloroform:

	Column				
Segment	A	B	CA	CB	S
0-1	1.33	1.55	1.88	-	1.64
1-3	0.83	0.71	0.96	-	0.47
0-5	0.73	0.97	0.96	-	-
5-10	0.85	0.98	0.45	-	-
10-15	0.66	0.56	0.46	-	-
0-15	0.77	0.82	0.66	-	-
0-13	-	-	-	0.48	-

Bromodichloromethane:

	Column				
Segment	A	B	CA	CB	S
0-1	1.14	2.64	1.97	-	1.19
1-3	0.62	1.12	1.12	-	0.71
0-5	0.72	1.37	1.08	-	-
5-10	0.83	0.42	0.33	-	-
10-15	0.40	0.16	0.32	-	-
0-15	0.67	0.65	0.56	-	-
0-13	-	-	-	0.17	-

Dibromochloromethane:

	Column				
Segment	A	B	CA	CB	S
0-1	0.25	0.62	0.30	-	0.18
1-3	0.15	0.43	0.45	-	0.17
0-5	0.27	0.44	0.36	-	-
5-10	0.24	0.13	0.13	-	-
10-15	0.09	0.01	0.01	-	-
0-15	0.19	0.19	0.16	-	-
0-13	-	-	-	0.04	-

APPENDIX F

Table F1 . Isotherm Data

Norit® Row 0.8

Carbon added (g/L)	Chloroform C_f (μg/L)	Bromodichlormethane C_f (μg/L)	Dibromochloromethane C_f (μg/L)
0.00	54.0	28.1	7.4
0.01	48.4	23.5	5.5
0.02	41.1	18.1	3.7
0.05	31.2	10.2	1.9
0.10	21.1	4.8	1.0
0.20	9.6	3.1	LD
0.50	7.2	1.2	LD

LD - less than detection limit

Witco® 950

Carbon added (g/L)	Chloroform C_f (μg/L)	Bromodichlormethane C_f (μg/L)	Dibromochloromethane C_f (μg/L)
0.00	53.4	29.6	8.0
0.01	48.8	21.8	5.6
0.02	43.4	17.3	3.7
0.05	29.5	8.0	1.2
0.10	17.6	3.6	0.5
0.20	9.5	1.3	LD
0.50	8.1	1.4	LD

LD - less than detection limit

Filtrasorb® 300

Carbon added (g/L)	Chloroform C_f (μg/L)	Bromodichlormethane C_f (μg/L)	Dibromochloromethane C_f (μg/L)
0.00	51.9	26.7	8.7
0.01	41.7	15.6	5.0
0.02	40.4	16.5	4.3
0.05	33.7	11.0	LD
0.10	24.3	6.5	2.1
0.20	14.9	3.1	LD
0.50	8.1	2.4	LD

LD - less than detection limit

APPENDIX G

Table G1 Comparison of Isotherm and Column Loadings[1]

Column A

	Loading (µg/g)[2]						
		Column Segment					
Compound	Isotherm	0-1	1-3	0-5	5-10	10-15	0-15
Chloroform	734	ND	780	720	850	670	740
Bromodichloromethane	726	1060	610	770	1100	620	830
Dibromochloromethane	267	260	160	270	350	190	270
TTHM	1722	2970	1700	1720	2230	1420	1780
	Loading (mg/g)						
TOC	56.3	140.0	88.1	89.9	39.9	26.9	52.0

[1] At average column influent level: 54.1 µg/L for chloroform
30.8 µg/L for bromodichloromethane
7.5 µg/L for dibromochloromethane
92.2 µg/L for TTHM
3.6 mg/L for TOC

[2] At observed or calculated exhaustion

ND - Not determined

Table G2 Comparison of Isotherm and Column Loadings[1]

Column B

	Loading (μg/g)[2]						
		Column Segment					
Compound	Isotherm	0-1	1-3	0-5	5-10	10-15	0-15
Chloroform	632	1619	792	909	1200	1165	1083
Bromodichloromethane	1065	2307	1165	1561	1223	2260	1678
Dibromochloromethane	285	524	443	536	454	315	443
TTHM	1733	3891	2330	2598	2784	3076	2808
	Loading (mg/g)						
TOC	21.0	ND	41.1	54.6	3.7	0.0	19.3

[1] At average column influent level: 54.1 μg/L for chloroform
30.8 μg/L for bromodichloromethane
7.5 μg/L for dibromochloromethane
92.2 μg/L for TTHM
3.6 mg/L for TOC

[2] At observed or calculated exhaustion

ND - Not determined

Table G3 Comparison of Isotherm and Column Loadings[1]

Column CA

	Loading (µg/g)[2]						
		Column Segment					
Compound	Isotherm	0-1	1-3	0-5	5-10	10-15	0-15
Chloroform	903	1590	840	800	430	420	660
Bromodichloromethane	1533	1570	720	--	--	--	--
Dibromochloromethane	685	330	440	360	--	--	--
TTHM	2910	3530	2040	--	--	--	--
	Loading (mg/g)						
TOC	29.2	177.3	63.8	84.0	28.1	18.0	46.8

[1] At average column influent level: 54.1 µg/L for chloroform
30.8 µg/L for bromodichloromethane
7.5 µg/L for dibromochloromethane
92.2 µg/L for TTHM
3.6 mg/L for TOC

[2] At observed or calculated exhaustion

(--) Indicates that apparent exhaustion was not reached prior to carbon changeout at day 59

APPENDIX H

POLANYI-MAYNES ADSORPTION THEORY

The Polanyi-Manes adsorption potential theory was used in this study to predict adsorption from pure water for trihalomethanes. Observed loadings were compared to predicted values and provided an indication of the extent of competition. Only qualitative comparisons were made, because of the difficulty of extrapolating pure solution capacities to mixed solutions (without experimental verification).

The Polanyi theory has previously been applied to adsorption of organic substances from solutions by activated carbon (Arbuckle, 1982). Manes and Hofer (1969) describe a method by which relative adsorptive potentials may be predicted from the refractive index of a substance. This theory has been expanded by Wohleber and Manes (1971a, 1971b) to encompass partially miscible and miscible organic liquids. A complete discussion outlining limitations of this theory and its application to compounds of interest in drinking water may be found elsewhere (Manes, 1980; USEPA 1980). Important advantages and limitations are noted below:

Advantages:

- The Polanyi-based approach to characterization of carbons for individual applications is more powerful in predicting individual and competitive isotherms than customary methods including surface area, pore size distribution, and iodine number.

- The Polanyi model would be expected to be more stable to variation in experimental conditions than the Langmuir-based model because it does not assume uniform adsorptive energy over the entire carbon surface.
- Interactions between solute and solvent and between different solutes in solution are reflected in the efforts of solubilities which are included in calculations.

Limitations:

- The assumption that all carbon pores are accessible to the adsorbate may not be completely true due to the influence of molecular sieving.
- The model is essentially limited to London-force dispersion, however adsorption of a wide variety of solutes from water solution has been described without reference to any action of surface groups.

In the present context, the Polanyi theory will be used to predict the theoretical adsorption capacity of GAC for chloroform, bromodichloromethane, and dibromochloromethane.

To determine the theoretical value for adsorption of a substance on GAC a curve must be prepared by modifying an adsorption isotherm for butane on GAC. The butane isotherm used in this study was supplied by the Calgon Corporation (USEPA, 1980) and applies to Filtrasorb® 400. The GAC used in this investigation was Filtrasorb® 300; indications were obtained that adsorption on Filtrasorb® 300 would be approximately 15 percent less than on Filtrasorb® 400 (Rosene, 1983).

The theoretical adsorption isotherm for a gaseous substance other than butane is obtained by multiplying the butane isotherm by a scale factor, γ_s. This factor is defined as the ratio of polarizability of the substance, p^s, to the polarizability of butane, p^b, i.e.

$$\gamma_s = \frac{p^s}{p^b}$$

The scale factor for a liquid substance adsorbed from another liquid may be defined as γ_{sl} where:

$$\gamma_{sl} = \frac{p^s}{p^b} - 0.206$$

The factor 0.206 represents a constant for adsorption from water.

For example, the calculated scale factor, γ_{sl}, for chloroform adsorbed from water is 0.93. By multiplying the points defining the adsorption isotherm for butane gas by this value a new curve is obtained (Figure H1). This curve indicates the cc of chloroform that will be absorbed from pure water per 100 grams of Filtrasorb® 400.

The abscissa of Figure H1 is defined as follows:

$$\frac{\varepsilon}{4.6V} = \frac{T}{V} \text{Log} \frac{C_s}{C}$$

where: ε = the driving force

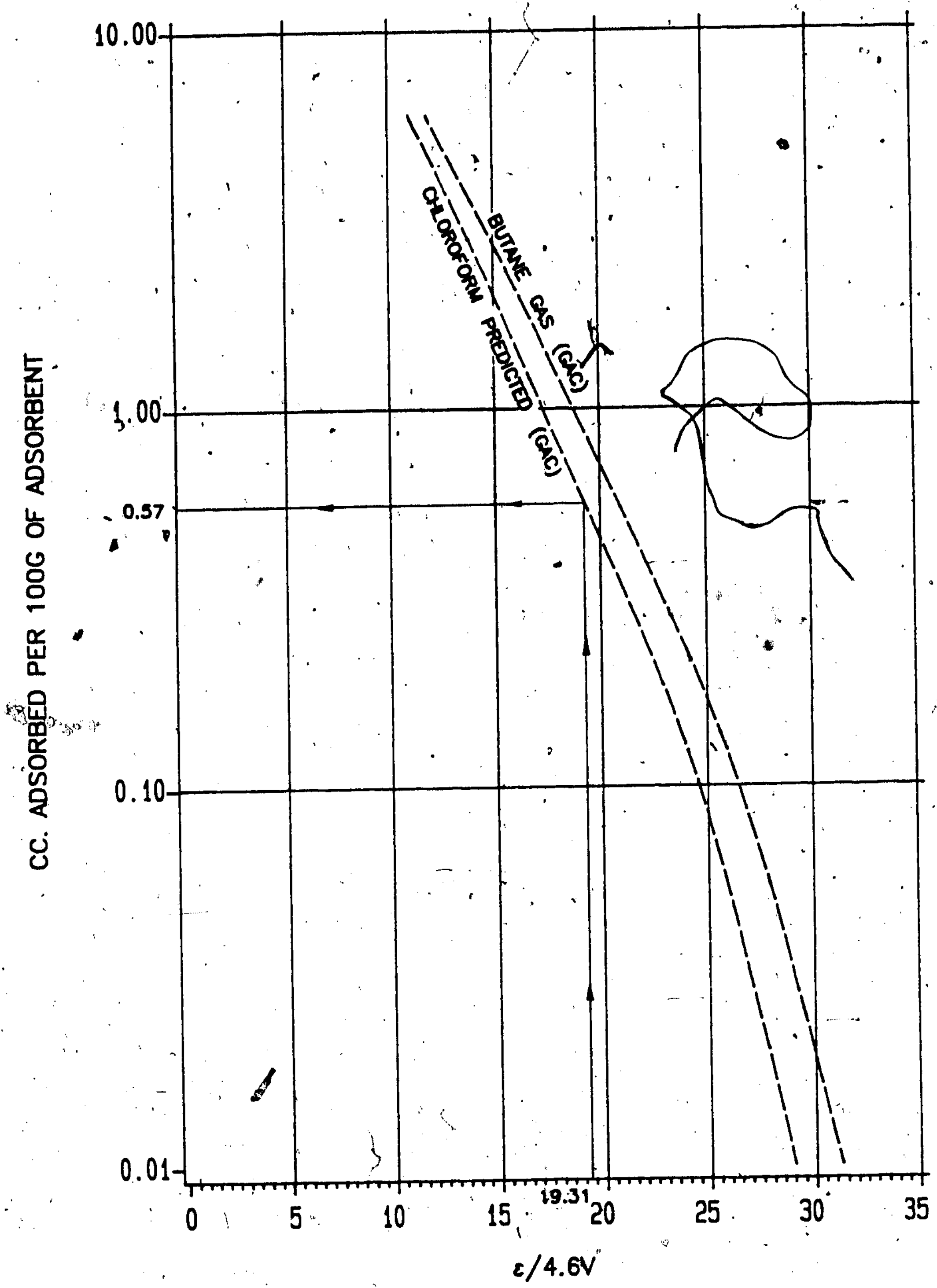

Figure H1 Polanyi-Manes Theory - Chloroform Adsorption by GAC

V = molar volume, cc/mole (80.0 for chloroform)

T = absolute temperature (295° for this study)

C_s = solubility of the substance in water, g/100 cc (0.82 for chloroform)

C = concentration of the substance in the column influent water, g/100 cc

To predict the loading of chloroform on Filtrasorb® 400 in pure water at a given equilibrium concentration, the abscissa is calculated, and the ordinate read off the curve. For example, for an equilibrium concentration of 47.7 μg/L, the abscissa in Figure H1 is 19.31 and the predicted loading in pure water is 0.57 cc/100 g carbon.

APPENDIX I

Table I1 Observed and Predicted (Pure Water) Isotherm Results

Carbon Added (g/l)	Loadings								
	Chloroform			Bromodichloromethane			Dibromochloromethane		
	Actual (cc/100g)	Predicted (cc/100g)	Actual ÷ Predicted (%)	Actual (cc/100g)	Predicted (cc/100g)	Actual ÷ Predicted (%)	Actual (cc/100g)	Predicted (cc/100g)	Actual ÷ Predicted (%)
0.01	0.0684	0.543	12.6	0.0554	0.760	7.3	0.00149	1.10	0.1
0.02	0.0387	0.541	7.2	0.0254	0.810	3.1	0.0088	0.97	0.9
0.05	0.0244	0.485	5.0	0.0156	0.700	2.2	LD	--	--
0.10	0.0185	0.415	4.5	0.0101	0.455	2.2	0.00027	0.77	0.03
0.20	0.0124	0.317	3.9	0.0059	0.408	1.4	LD	--	--
0.50	0.0059	0.230	2.6	0.0024	0.290	0.8	LD	--	--

LD - Equilibrium concentration (C_f) was below detection limit

APPENDIX J

Table J1 Observed and Predicted (Pure Water) Column Results

	Loadings					
	Chloroform		Bromodichloromethane		Dibromochloromethane	
Segment	Actual (cc/100g)	Actual ÷ Predicted (%)	Actual (cc/100g)	Actual ÷ Predicted (%)	Actual (cc/100g)	Actual ÷ Predicted (%)
0-1	0.107	17.3	0.078	7.8	0.013	3.3
1-3	0.056	9.0	0.036	3.6	0.018	4.5
0-5	0.054	8.7	(1)	--	0.015	3.8
5-10	0.029	4.6	(1)	--	(1)	--
10-15	0.028	4.5	(1)	--	(1)	--
0-15	0.044	7.1	(1)	--	(1)	--

Average chloroform influent conc. : 54.1 μg/L
ε/4.6V : 19.10
Predicted adsorption from pure water : 0.62 cc/100g
Average bromodichloromethane influent conc.: 30.8 μg/L
ε/4.6V : 19.15
Predicted adsorption from pure water : 1.00 cc/100g
Average dibromochloromethane influent conc.: 7.5 μg/L
ε/4.6V : 20.50
Predicted adsorption from pure water : 0.40 cc/100g

(1) Exhaustion of segment not reached before carbon replacement

APPENDIX K

HEADLOSS AND CHLORINE ADSORPTION RESULTS

As part of a separate study by Andrews (1984), headloss and both free and combined chlorine were monitored for Columns A, B, and CA.

K1 HEADLOSS

Following initial startup headloss measurements were taken 2-3 times weekly. Backwashing was conducted at approximately 7 day intervals. During the first 55 days of the study period Column CA developed the highest headloss between backwash cycles (Figure K1). For the period of 55 to 70 days headlosses remained similar for the 3 columns with Column CA exhibiting decreasing values. As the end of the test period approached there was a reversing of the trend seen during the first half with both Columns A and B now exhibiting headloss values greater than CA, while Column CA continued a decreasing trend.

Excluding initial startup values, maximum headlosses encountered during the study period were 2.7 psi, 2.3 psi and 2.7 psi for Columns A, B and CA respectively.

Backwashing provided an effective means for decreasing headloss with values obtained immediately after backwashing

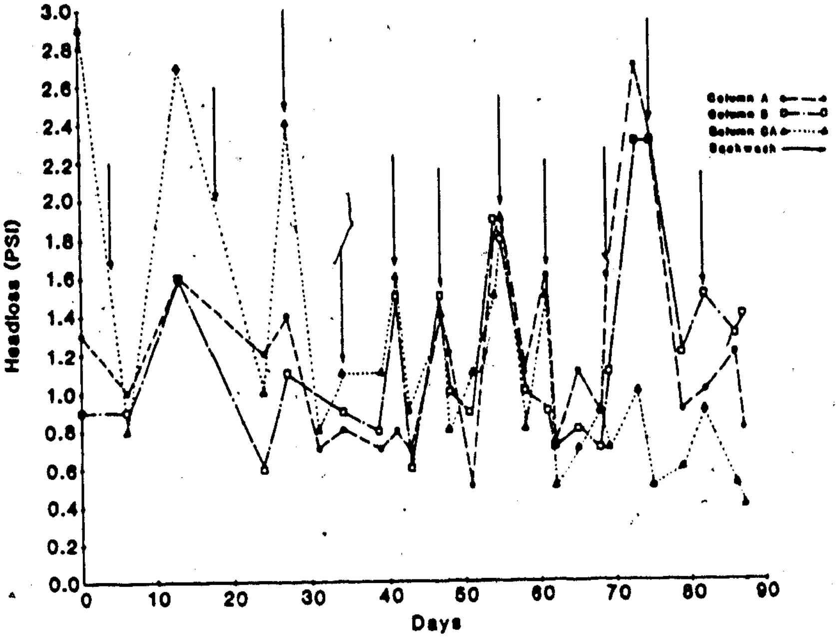

Figure K1 Headloss as a Function of Time averaging 0.7 psi, 0.7 psi and 0.5 psi for Columns A, B, and CA respectively.

A large amount of fines were present in the Column A backwash water from the point of initial startup to a period extending approximately 50 days into the study.

Except for a small amount of fines noted in Column CA backwash water after an operation period of 68 days, no appreciable amount of fines were present in either Column B or CA backwash water. As noted in previous studies by Forsyth et al. (1982) operational difficulties were not expected with runs extending up to 4 weeks between backwashes. This may be attributed to the warm summer temperatures which do not cause problems such as air binding and alum post-flocculation, commonly experienced during fall and winter.

K2 FREE AND COMBINED CHLORINE

All three of the carbon columns were found to be effective in the removal of free chlorine. Concentrations measured at Port 1 (10 cm bed depth) are shown in Figure K2. Even at this shallow bed depth removals exceeded 80% until the very end of the study period. Chlorine levels measured at Port 3 (31 cm bed depth) did not exceed the detection limit of 0.05 mg/L. None of the columns displayed removals that were significantly different from the others. Column CA achieved slightly better removals during the first 61

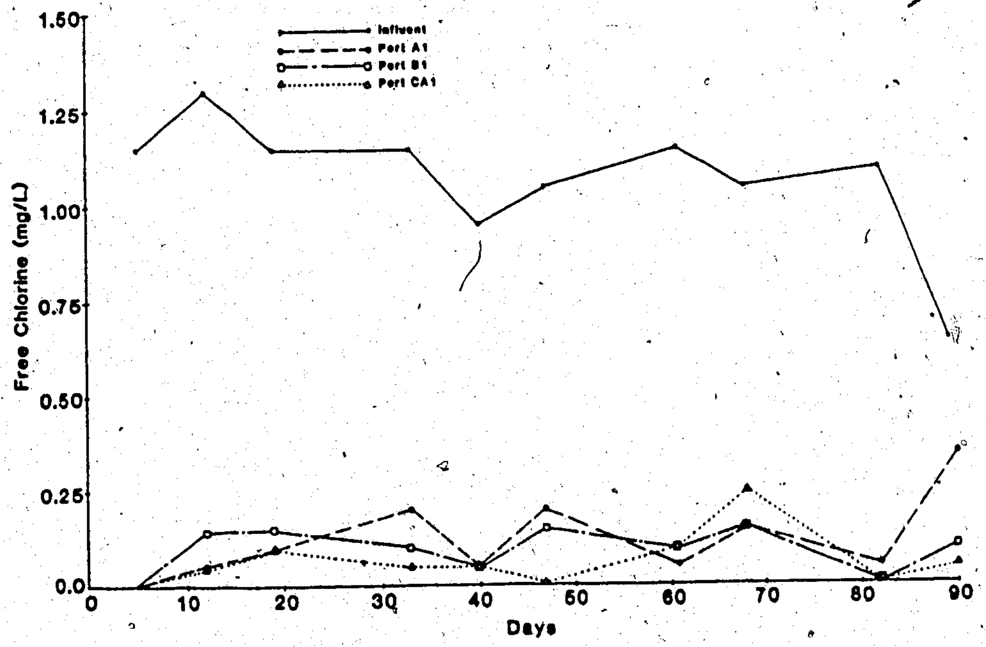

Figure K2 Free Chlorine Concentration in Columns A, B, and CA as a Function of Time days of the study period, with Column B showing the best removals from this point to the end of the study period. Influent free chlorine levels averaged approximately 1.10 mg/L, with a slight decreasing trend apparent during the latter part of the study period.

Combined chlorine was not as effectively removed as the free chlorine in any of the three columns. The influent concentration averaged 0.28 mg/L during the study period displaying no significant trend. With the exception of one data point, Column CA achieved the highest removal at Port 1 throughout the study (Figure K3). No measurable penetration of combined chlorine was noted at depths below Port 3 until the final week of the study. Up to this point, erratic levels were noted at Port 3, bordering on the detection limit.

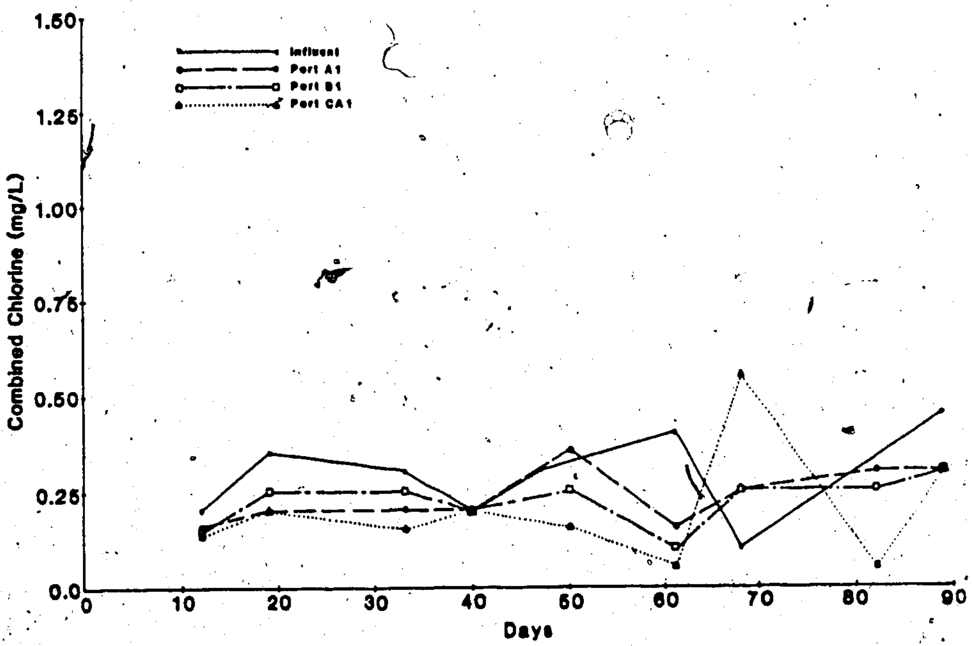

Figure K3 Combined Chlorine Concentration in Columns A, B, and CA as a Function of Time