

FINAL REPORT

EVALUATION OF THE EFFECTIVENESS OF FOUR POINT-OF-USE
DOMESTIC ACTIVATED CARBON FILTRATION DEVICES FOR THE
REMOVAL OF FOUR VOLATILE ORGANIC CONTAMINANTS FROM
DRINKING WATER

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SUMMARY

Mixtures of four VOCs in New Brunswick tap water at a total concentration of approximately 250. ug/l were applied to four point-of-use activated carbon filters at a flowrate of 1.0 GPM. These test solutions were permitted to run until a volumetric capacity of 200% for each filter was reached. The filters were: Culligan(C), Advanced Filtration Technology(AFT), Amway(AW), and Pollenex(P). The challenge compounds were chloroform, 1,1,1-trichloroethane, trichloroethylene, and tetrachloroethylene.

Competitive adsorption was evident for all four compounds on all four filters when the amounts adsorbed per gram of carbon from mixed systems were compared to those from single systems. For example, chloroform was adsorbed to the extent of .85 mg/g from a mixed solute system on the Culligan filter. From a single solute system, chloroform was adsorbed to the extent of 2.09 mg/g on the same filter. Similar results were obtained for the other compounds on all four filters.

Only chloroform was desorbed to any extent from all four filters. Percentages of desorption ranged from a low of 9.1 for the C filter to a high of 46, for the AW filter. 1,1,1-Trichloroethane was desorbed only from the AW (8.6%) and AFT (12.2%) filters. None of this compound was desorbed from the C and P filters. Tri and tetrachloroethylenes were not desorbed in any detectable quantities from all four filters.

When adsorption efficiency is expressed as the average

percentage removal over the entire filter run, greater than 96% of all compounds were removed by the C and AW filters. Removals ranged from 63% for chloroform to 97% for trichloroethylene on the AFT filter. These percentages for mixed solutes were slightly less than those observed in single systems for the Aft filter. Average removals were extremely poor for the Pollenex filter. They ranged from 5.4% for tetrachloroethylene to 10.1% for 1,1,1-trichloroethane and were considerably less than those observed for single solute systems.

Competitive adsorption was evident also for all four compounds on all four filters at 0.5 GPM when the amounts adsorbed per gram of carbon from mixed systems were compared to those from single systems. For example, chloroform was adsorbed to the extent of .93 mg/g from a mixed solute system on the Culligan system at 0.5 GPM. From a single solute system, chloroform was adsorbed to the extent of 2.09 mg/g on the same filter at 0.5 GPM. Similar results were obtained for the other compounds on three of the four filters. For some reason, the Pollenex filter did not show any significant adsorption of the four VOCs at 0.5 GPM.

Flow rate does not appear to be a factor in the adsorption of the four VOCs by the Culligan and Amway filters. This is observed when adsorption is expressed either as the total amount adsorbed at 200% of filter capacity or as the amount adsorbed per gram of carbon. Only the AFT filter exhibited greater adsorption at the lower flow rate of 0.5 GPM.

When adsorption efficiency is expressed as the average percentage removal over the entire filter run, greater than 92% of

all compounds were removed by the C and AW filters at 0.5 GPM. There was no significant difference between these % removals on C and AW filters than at 1.0 GPM. On the other hand, the AFT filter gave significantly higher % removals of all four VOCs at 0.5 GPM than at 1.0 GPM. These removals ranged from 72% for chloroform to 100% for tetrachloroethylene. The Pollenex filter showed % removals that ranged from 0.5 to 1.9% that may not be statistically significant.

Mixtures of four VOCs in New Brunswick tap water at a total concentration of approximately 250. ug/l were run at a flow rate of 1.0 GPM in systems buffered at pH values of 5.0 and 9.0. A summary of the average percentage removals of each compound on each filter at pH values of 5.0 and 9.0 when the flow rate was 1.0 GPM is given in Table 16. Also, included in this table are the average removals at the unbuffered pH value of New Brunswick tap water in the 6.5 to 7.5 range when the flow rates were 0.5 and 1.0 GPM. That $[H^+]$ concentration may be factor affecting adsorption was given only by chloroform on the four filters. For example, at a flow rate of 1.0 GPM, the average removal of chloroform was: at pH 5.0, 65.6%, at pH 6.5 - 7.5, 96.4%, and at pH 9.0, 88.9% on the Culligan filter. Similar observations can be made for chloroform on the other three filters.

The factors of $[H^+]$ and flow rate apparently do not influence the adsorption of 1,1,1-trichloroethane, trichloroethylene, and tetrachloroethylene on the four carbon filters. Average percentage removals are approximately the same for these three compounds at the pH values of 5.0, 6.5 - 7.5, and 9.0 at a flow rate of 1.0 GPM.

Overall, the efficiency of filter performance remains: Culligan/Amway > AFT > Pollenex regardless of pH and flow rate. This observations applied to all four VOCs in a competitive matrix.

INTRODUCTION

Many studies about groundwater quality throughout the United States (Westrick, 1984; McGuire, 1978; Tucker, 1981; and Roux, 1980) have found that a number of water supplies are contaminated by a variety of organic compounds. Some of those compounds in trace amounts are potentially dangerous to human health. Several factors contribute to this increased detection that include newly developed and highly sophisticated analytical techniques, increased awareness of chemical contamination resulting in more frequent testing, and better identification of pollution sources. More than seven hundred specific organic compounds have been identified in drinking water supplies. At least eighty three contaminants, including eight volatile organic chemicals, must comply with the 1986 amendments to the Safe Drinking Water Act (SDWA). As of now, more than ninety five percent of all available freshwater in the United States, including the Great Lakes, is groundwater. Approximately eighty percent of all public water supplies and about ninety six percent of all water used for rural domestic purposes in US depend on groundwater for potable water sources. This creates public concern about water quality and its effects on human health.

When a water supply contains contaminants in concentrations exceeding the US Environmental Protection Agency (USEPA) maximum contaminant level (MCLs), the community and/or the individual have

two possible solutions: (1) obtain a new source of water, or (2) treat the existing water source to remove the contaminant. In a large community, or where sufficient money is available, a small treatment plant can generally be built. However, in a small community (fewer than 500 people) or for a private well system, the cost of a full scale treatment plant is commonly not feasible to the water users. In this case, installing point-of-use treatment devices in each home or building in the small community or home using a private well system would be a possible economic solution.

Point-of-use treatment devices, although not officially recommended by government agencies, have become more popular as health concerns have increased in recent years. A single-tap unit is often sufficient in reducing organic contaminants if health effects develop when water is consumed. Public interest in point-in-use treatment devices is usually based on a desire to remove potential carcinogenic and toxic chemicals, or to improve the aesthetic quality of the drinking water by removing tastes, odors, turbidity, particulates, or other undesirable materials. One of the most available commercial devices is the activated carbon filter. The units can remove potentially dangerous contaminants from water by adsorption of activated carbon, but the performance and duration of these filters is difficult to determine and to compare.

One objective of this study was to analyze the performance of a range of point-of-use devices by challenging them with a groundwater spiked with VOCs. A laboratory study was designed to subject point-of-use devices to uniform, experimental conditions.

Comparisons of the effectiveness of the removal of volatile organic compounds by point-of-use devices, and identification of the most efficient devices, were made possible by this process.

NEW JERSEY'S A280 PROGRAM

This research on point-of-use activated carbon filter systems was made possible by a grant from the New Jersey Department of Environmental Protection and Energy's (NJDEPE) Division of Science and Research. This kind of research has become part of New Jersey's "A280" program to monitor the concentration of carcinogenic and noncarcinogenic chemicals in drinking water and to produce information on treatment technologies of the removal of these compounds from water. The A280 program refers to the amendments of New Jersey's State Safe Drinking Water Act (P.L. 1983, C. 443) made in 1984. This amendment resulted in a list of twenty-two organic (primarily volatile) and chlorinated compounds that should be routinely monitored in public drinking water supplies. These chemicals are among those most commonly detected organic contaminants in drinking water (New Jersey Drinking Water Quality Institute, 1987). In addition to monitoring these contaminants in drinking water supplies, the A280 program also mandates the following for specific compounds: establishing maximum contaminant levels (MCLs), developing the necessary techniques for the analysis of these contaminants, reviewing all NJDEPE activities in connection with the Safe Drinking Water Act, and considering appropriate water treatment technologies for removal of hazardous compounds from water.

The owners of private domestic wells, especially those not

covered by the monitoring of the A280 program, are the most likely candidates for point-of-use devices. These systems are one of the alternatives for treatment of drinking water contaminated by A280 compounds. Two lists of potentially hazardous compounds are provided in the A280 program: 2a and 2b. The 2a list is the original list of twenty-two compounds written by the A280 amendment, and 2b is an additional list for future adoption which includes pesticides, other synthetic organics, and metals. 2a is given in the Appendix of this report and from which four compounds were selected for this study. The selection procedure involved personnel from the NJDEPE with input from the Department of Environmental Sciences at Rutgers University.

RESEARCH OBJECTIVES

The intent of this study was to investigate the remediation potential of point-of-use activated carbon filters for removal of volatile organic contaminants from water. Four locally accessible line by-pass filters were selected in accord with the claims of the manufacturer for removal of various organic compounds, different types and weights of carbon, volume to total rated capacity, and capacity of throughput (Table 1). Four volatile contaminants, commonly detected in groundwater throughout the United States and New Jersey, were selected from the 2a list of New Jersey's A280 program. This incorporated a range of challenge contaminants varying broadly in their affinities for adsorption and other physical properties (Table 2). Filters were tested against these compounds singly (part I) (Cotton, et al, 1989) and in mixtures (part II) (this report).

The objective of the first study was to evaluate the efficiencies of the filters by removing these compounds from a single contaminant spiked into pretreated tap water. This study was to provide information about how each filter operates in comparison with other types of units. In the second study, the research was designed to investigate how the sample matrix would affect the efficiencies of these filters. Study on multi-contaminant spiked water was to show how adsorption would be affected by the presence of other compounds, i.e. competitive adsorption. Other issues were to discover whether or not adsorbed substances would be released from a heavily dosed filter if the level of contamination in the water source decreased. Two buffer solutions were used to test how the adsorption would be affected by $[H^+]$ of the spiked water.

These issues are important to address because of the changeable quality of groundwater. The knowledge of filter performances could assist governmental agencies in recommending specific filters as a temporary alternative water treatment for homeowners with contamination problems for volatile organic compounds.

REVIEW OF LITERATURE

Granular activated carbon (GAC) has been used for taste and odor control in potable water supplies since 1883 (McCreary, 1980). Studies have been conducted to assess the removal capabilities of GAC by adsorption of a wide range of organic compounds (Dobbs and Cohen, 1980; Faust and Aly, 1983; Hyde, 1980; Lykins and Baier,

1989; Suffet and McGuire, 1980; Taylor and Allen, 1979). However, studies on the performance of numerous point-of-use devices are not available for most consumers.

One of the most complete studies of point-of-use commercial filters was by the Gulf South Research Institute (GSRI) under funding from USEPA that was published by Perry, et al. in 1980 and 1981 and summarized by Bell, et al. in 1984. In this study, the removal efficiency of trihalomethanes (THMs) and seven halogenated organics were tested on thirty one commercial filters. The types of units used in this study included faucet mount, countertop, pour-through, cold tap, and line bypass. Flow rates were adjusted in accordance with the specifications provided by the manufacturers. In most cases, actual residence times were much greater than the empty bed contact time (EBCT) that existed under constant flow conditions. The duration of a filter run was based on the total volumetric capacity of the filter given by the manufacturers.

Other GSRI studies concentrated on the reduction of trihalomethanes (THMs) using unspiked New Orleans, La. tap water (feeding concentration from 110 to 239 mg/l). The average reductions for THMs obtained with commercial GAC units ranged from 76% to 99%. The line bypass units exhibited the highest removal efficiencies--up to 99%. Among this type of filter, the highest reduction percentages were observed for those units with the greatest weight of carbon combined with the longest residence time. However, overall design was also important, because in a few cases even though the preceding conditions were the same, low THMs

reductions were obtained. This part of the GSRI study on New Orleans tap water showed that most of the devices could not remove nonpurgeable total organic carbon (NPTOC) effectively. Only two of them reduced NPTOC by more than 50%. The others reduced NPTOC between 2% to 41%.

In the same GSRI research, tests were conducted also to reduce four halogenated organics: 1,1,1-trichloroethane, carbon tetrachloride, trichloroethylene, and tetrachloroethylene. These compounds are contaminants mostly from industrial sources. These organics were spiked into groundwater and their removal was evaluated with 10 commercial filters. The reduction percentages were given by the initial (higher) value and the ending (lower) value based on the duration of each unit. Again, line bypass devices consistently showed the best performance since initial reductions were excellent for every unit (as high as 99%). Generally, the units with the greatest weight of carbon and the longest residence times performed better at the end of the filter run.

The GSRI study also considered the reduction of the combination of three specific halogenated organics (p-dichlorobenzene, hexachlorobenzene, and chlordane) spiked into surface water. The initial reductions were excellent (as high as 99%), but the filter runs seemed too long, and the contaminant's effluent concentrations increased significantly. In this test, the adsorption capacities of the units (chlordane > hexachlorobenzene) were not consistent with the order of adsorption capacity (hexachlorobenzene > chlordane) determined by Dobbs and Cohen

(1980) whose studies were based on single compounds. The inconsistent results were probably due to differences in concentrations and use of single vs. a mixture of compounds.

In the Taylor and Allen study (1970), four kinds of carbon filters were evaluated by chloroform removal efficiency from drinking water in Cincinnati, Ohio. The carbon weight contained by the filters ranged from 266 to 596 grams. For simulating water conditions consumed in the home, flow rates were regulated as 1.5 gpm with intermittent flows. By using a timer, flow through the filter was limited to 10 hours during the daytime "on" with cycles varying from 30 seconds to 3 minutes and 14 hours "down" time in the evening. Chloroform concentrations of influent within the testing period (20 weeks) were between 20 and 50 ug/l. The initial removal efficiencies of the four filters were 100%, 82%, 58%, and 55%, respectively. Only one filter showed 20% removal of chloroform during of the 20-week testing period whereas the removal efficiency of the other filers dropped to 0% within 10 to 18 weeks.

In part I of this study (Cotton, et al, 1989), ten commercial activated carbon filters were used to evaluate their reduction percentages of four volatile organic compounds (VOCs): 1,1,1-trichloroethane, chloroform, tetrachloroethylene, and trans-1,1-dichloroethylene. These compounds were spiked into New Brunswick, New Jersey tap water. Only one chemical at a time was spiked into the tap water to obtain influent concentrations of approximately 250. ug/l. Water pressure was maintained at 60 psi and the flow rate was maintained between 0.8 and 1.0 gpm. Flow through the filter was controlled by a timer using approximately 30 minutes

"on" and 30 minutes "off" cycles for durations of 20-22 hours per day with an on to off ratio of 45:55. Effluent was sampled at every 25% of the volumetric capacity of the filter. The sampling procedure was terminated either at an effluent concentration of 100 ug/l or at 200% capacity of the filter. Of these ten filters, three performed quite well compared to the manufacturer's rated life; four performed on the average; and the last three performed poorly. The initial reduction percentages for each of the four compounds for all the filters were as high as 99%, with the exception of one filter with a percentage of 77% for chloroform. The removal efficiency gradually decreased in the order of tetrachloroethylene > trichloroethylene > 1,1,1-trichloroethane > chloroform.

Several studies are still in progress or have just been completed in several small communities for a period of time (one year or more). The following results summarize those studies that are based on accessible information.

A National Sanitation Foundation study funded by the USEPA, tested several commercial GAC filters (line bypass units) at locations in New Jersey and Pennsylvania that have VOCs in their groundwater (Bellen, et al., 1985). The wells in Rockaway Township, New Jersey, contained 1,1,1-trichloroethane and trichloroethylene, with concentrations up to 240 ug/l, 1,1-dichloroethylene up to 21 ug/l, tetrachloroethylene up to 12 ug/l, and 1,1-dichloroethane up to 10 ug/l. After 24 months of operation, the removal results of twelve GAC devices were good. Essentially, no VOCs were observed in the effluent (<1 ug/l).

Wells in Silverdale, Pennsylvania contained concentrations of trichloroethylene up to 84. ug/l and tetrachloroethylene up to 21. ug/l. Five models and forty seven GAC units were tested for 14 months. Again, no VOCs were observed in the effluent (< 1 ug/l).

There have been many studies performed over the decades to determine what factors are responsible for the adsorption process of GAC. In general, the adsorption process is affected by the physical-chemical characteristics of the adsorbent, the adsorbate, and the experimental system (McQuire and Suffet, 1978, Benedict, 1982, and Zogorski, 1975). Since adsorption is a dynamic process with all of the factors interrelated, it is easier to discuss them separately.

The characteristics of GAC mostly result from the types of starting materials and the activation process used to activate them. Because contaminants are adsorbed on the surface of GAC, the greater the available surface area on or inside the carbon particle, the higher is the capacity for contaminant removal. As a result of the fact that most of the adsorption occurs within the internal pore structure of GAC, the smaller particles have more pores exposed to the adsorbate solution for a given mass of carbons. High surface to volume ratio allows for a more rapid diffusion of the contaminants from the carbon's external surface to the internal pore structure. But as the particle size gets too small, the head loss causes the pressure to increase to the point where the cost exceeds the benefits.

The nature of the adsorbates (contaminants), their concentrations, and the effects of competition also affect the

removal efficiencies of GAC. Belfort (1979) noted that "large" molecules are generally more sorbed than "small" ones of the same structural group until they become too large to diffuse into the internal pore space of the carbon. At that point, the majority of the GAC surface area is not available for adsorption and results in a lower removal efficiency of the GAC. Branched-chain compounds are less adsorbable than their straight-chain counterparts because of the branched configurations strictly inhibit the adsorbates from entering the internal space of the granular GAC (Zogorski, 1975). Functional groups can change the dissociation constants, electron densities, and solubilities for a given molecular structure: they also can react with functional groups found on the surface of GAC. Thus the amounts of molecules with similar structures but different functional groups may be adsorbed on GAC surface quite differently.

Weber and Morris (1964) found that, as the initial concentration of the adsorbate solution increases, the rate of adsorption also increases as the diffusion pressure drives the adsorbate into the inner pore space. This results in an increase of total adsorption capacity of the GAC. Also, the solubility of a compound in water also appears to be a factor in determining whether or not the compound can be adsorbed easily by GAC. Generally, the more polar the compound is, the more soluble it is in water, so it is less likely to be adsorbed by GAC and removed from water (Zogorski, 1975; Belfort, 1979). Since organic compounds are rarely found singly in natural groundwaters but occur in mixtures, competition between compounds must be taken into consideration. Studies (Zogorski, 1975; Weber and Morris 1964)

have shown that, as in a single solute system, the higher the initial concentration of the multi-solute system, the higher is the capacity of the GAC for a mixture of contaminants. But at the same time, the capacity of GAC for an individual contaminant is lower than those in single - solute system. Another effect of competition is the "displacement" process where the weakly adsorbed compounds are likely to be displaced or washed out by the more strongly adsorbed compounds.

The pH ($[H^+]$) of the system can affect the adsorption of organics on GAC by determining whether or not the adsorbate in an associated or disassociated form in solution (McQuire and Suffet 1978; and Zogorski, 1975). The pH value may also alter the electrokinetic and chemical characteristics of the GAC during adsorption process. At lower pH values: organic acids are strongly adsorbed whereas at higher pH values the organic bases are adsorbed. For the neutral organics, the pH may not significantly affect the adsorption.

The contact time between compound and carbon is determined by the linear velocity through the GAC bed. Therefore, comparisons can only be made between the systems with the same contact time. The rate-limiting step for the ability of GAC to remove the contaminant is the diffusion rate of the adsorbate into the internal pore space of GAC (Zogorski, 1975). In this case, filter performance is a function of the linear velocity but beyond the critical contact time there is not an additional increase in removal efficiency.

MATERIALS AND METHODS

There were two parts in this study: single-solute systems and multi-solute systems. In the first part, ten filters and seven compounds were used where the removal efficiency of each filter for each of the contaminants was evaluated (Cotton, et al, 1989). The second part was a multi-solute system. This investigation was designed to study the competitive effects of other compounds, flow rate, and pH value on performance of the filters, and whether or not desorption from a heavily loaded filter would occur. From the results of the first study, four filters and four commonly found contaminants were selected to run the multi-solute system studies under two difference flow rates (1.0 & 0.5 gpm) and two pH values (5.0 & 9.0). After the flow rate 1.0. gpm adsorption test was finished, the desorption test followed.

POINT-OF-USE FILTERS

Four commercially available point-of-use domestic activated carbon devices were chosen in this study (three granular activated carbon and a powdered activated carbon block) with various rated capacities, sizes, and recommended flow rates (Table 1). These filters were: Advanced Filtration Technology UTC-1 (AFT), Amway (AW), and Pollenex WP-52 (P).

Trace amounts (<1 ug/l) of chloroform and methylene chloride were found in the blank runs (unspiked reagent water) of the filters. This condition was more severe in the Pollenex filter (P) where the methylene chloride concentrations measured in blank and spike runs were as high as 40 ug/l. Because this compound did not co-elute with the challenge compounds on the GC, its removal was

Table 1. Specifications of point-of-use domestic activated carbon filters.

<u>Filter name</u>	<u>Filter Code</u>	<u>Dimensions (inches)</u>	<u>Rated Capacity (Gallons)</u>
Pollenex WP-52	P	3.5 * 3.5 * 9.5	2400
Culligan Super-Gard THM	C	4 * 4 * 13	2000
Advanced Filtration Technology UTC-I	AFT	3 * 3 * 9.5	1000
Amway WTS (AW)	AW	5 * 5	1 year (used 1500)
<u>Filter name</u>	<u>Flow Rate (gpm)</u>	<u>Filter Carbon Wt (qr)</u>	<u>Carbon Type</u>
Pollenex WP-52	1.0	283	GAC a
Culligan Super-Gard THM	0.5	863 b	GAC a
Advanced Filtration Technology UTC-I	1.0	399 b	GAC a
Amway WTS	0.75-0.95	1002 b	Carbon Block

- a Specific information on carbon source and sieve size of particles was not available from manufacturers
- b Information on amount of carbon used in filter device was not available from the manufacturer, but was measured in this study.

unnecessary.

CHALLENGE CONTAMINANTS

Four compounds were selected for this study: chloroform, 1,1,1-trichloroethane, trichloroethylene, and tetrachloroethylene (Table 2). All except chloroform were chosen from the A-280 2a list of drinking water contaminants (see Appendix). Chloroform was selected because it is commonly found as a chlorination by-product in drinking water. Aliphatic compounds with different degrees of halogenation were included to cover a range of their ability to be adsorbed by activated carbon. The total initial concentration of those compounds in spiked water was 250 ug/l that was selected simply because it was higher than the maximum value that may be encountered in N.J. groundwaters (Tucker, 1981) and was a mass that would challenge the test units.

One of the adsorptive properties of these challenge contaminants listed in Table 2 is the Freundlich K constant. This constant is derived from the Freundlich Isotherm equation:

$$x/m = K C_e \exp (1/n)$$

where x = the amount of solute adsorbed, usually mg

m = the weight of adsorbent, usually grams

C_e = the solute equilibrium concentration, usually mg/l

$K, 1/n$ = constants, characteristic of the system (Faust and Aly, 1983).

There are two constants in this equation: K and $1/n$ that describe two factors: the total amount of adsorbate (contaminant) that can be removed by a given amount of adsorbent (activated

Table 2. Selected Properties of the Four Challenge Contaminants.

Compound	b.p. ^a (C)	Solubility (mg/l) (C) ^a	Vapor Pressure Torr (C) ^a	Freudlich K	
				PAC ^b	GAC ^c mg/g
Tetrachloroethylene	121	150 - 200 (20)	14 (20)	51	57.7
Chloroform	61	8200 (2)	150.5 (20)	2.6	.016
1,1,1-Trichloroethane	75	480 - 4400 (20)	96 (20)	2.5	42.7
Trichloroethylene	87	1000 (20)	77 (25)	28.0	32.0

- a. degrees centigrade .
- b. from Dobbs, 1980.
- c. from Faust and Aly, 1983 .

carbon) from water (K) when $C_e = 1.0 \text{ mg/l}$ and the rapidity of adsorption ($1/n$). Larger K values indicate a greater capacity of the carbon for the contaminant. In other words, it may take a longer time for a contaminant to breakthrough from a carbon column. For example, in Table 2, tetrachloroethylene with the largest K constant and the lowest solubility of all selected compounds, has the highest adsorptive capacity on carbon. To the contrary, chloroform with a lower K value and higher solubility shows a lower adsorptive capacity.

TEST APPARATUS

The National Sanitation Foundation's Standard No. 53, Drinking Water Treatment Units Health Effects (1982) was used, and the design of apparatus for point-of-use testing was established by Cotton, et al. (1989). The composition of the system included a 1200 gallon stainless steel water tank, two large capacity GAC prefilters, a low power recirculating pump, a high power water supply pump, pressure tank solenoids and timers, pressure gauges, and sampling ports (Figure 1).

Since no groundwater was available on site, New Brunswick tap water was used that was passed through two large capacity GAC prefilters to remove any residual chlorine and organic compounds. This reagent water was then delivered into the large stainless steel water storage tank. After the tank was filled, the reagent water was automatically shut off by a solenoid/mercury switch. A recirculating pump was used to mix the volatile contaminant with the reagent water. A high powered pump draws water, via a separate water line just above tank bottom, and pushes water into a water

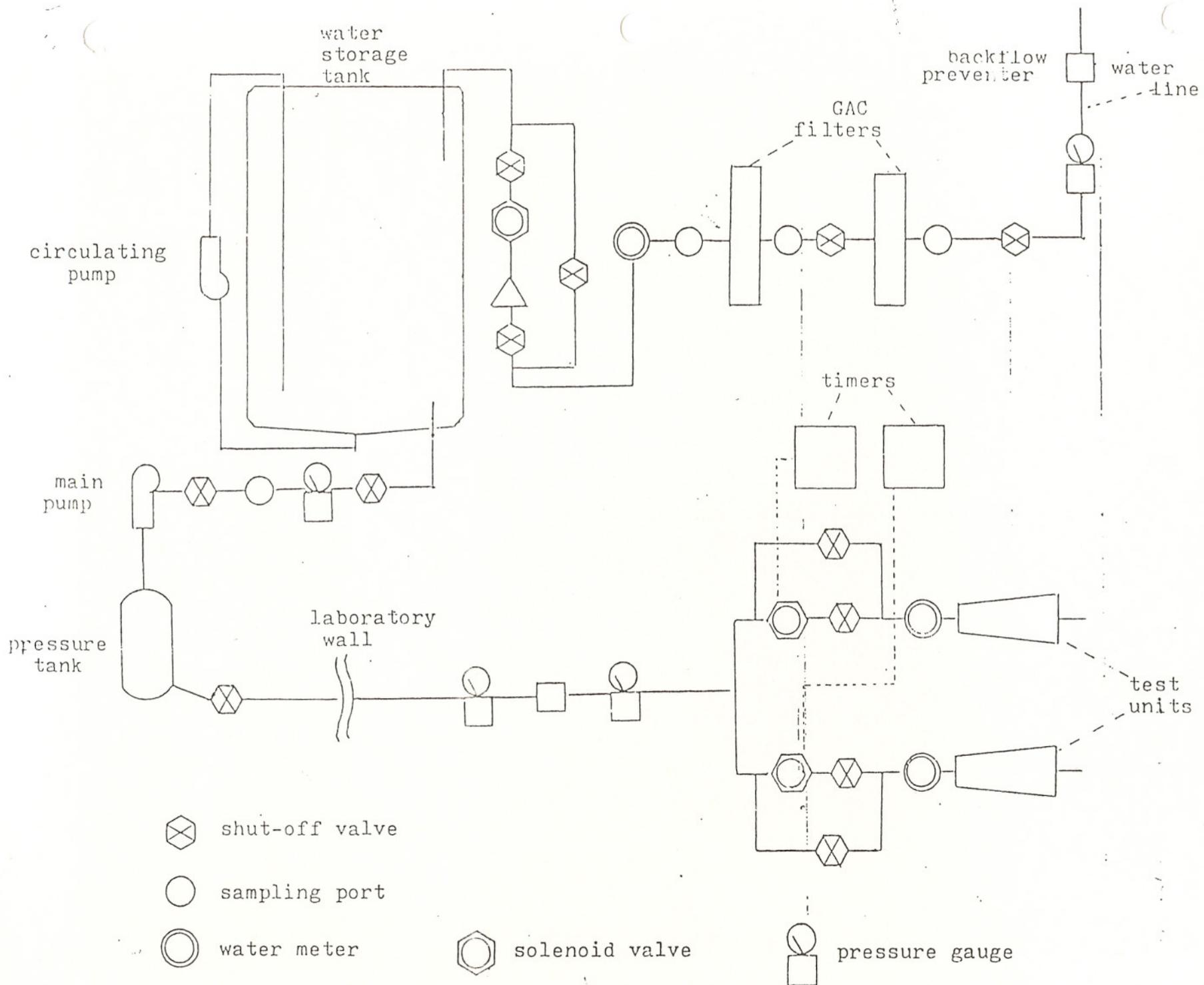


Figure 1. System Schematic

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pressure tank to set the pressure (70 psi). The average water pressure in the tank was, consequently, 61 psi, but the range was 52 psi to 70 psi. The above apparatus was located in the storage room in the Operating Training Center (OTC) on College Farm Road, Cook Campus of Rutgers University.

Water was delivered by pipe from the pressure tank and sent into the laboratory adjacent to the storage room. After being regulated by two pressure gauges, the water was divided into two lines and was sent through meters that finally was connected to the test units. There were several sampling ports located at various places within this test apparatus: before and after the large GAC prefilters, at the bottom of the storage tank, at the pressure tank, and at the point of test unit attachment. Pressure gauges appear before the prefilters, at the bottom of storage tank, and at the point after passing through the laboratory wall. Water meters are located under the storage tank for measuring storage tank volume and before the test units attachment for regulating flow rate.

MIXED SOLUTE SYSTEMS

All mixed solute adsorption tests were conducted at flow rates of 0.5 and 1.0 GPM and were run to 200% of filters rated capacities. Four point-of-use activated carbon filters were evaluated by their ability to remove VOCs from prespiked water. This was accomplished in the following steps:

1. Fill the stainless steel tank with carbon-filtered reagent water (about 1200 gallons).
2. Place a plastic cover on top of the water inside the

- tank to minimize the loss of the spiked compounds by evaporation.
3. Start the recirculating pump.
 4. Weigh an appropriate amounts of the chemicals into a 30 ml glass syringe and fill the syringe with reagent water and then inject its content into the recirculating line.
 5. Fill the syringe with reagent water and inject the content into the recirculating line to wash out any residue compound. Repeat. Wait 30 minutes for complete mixing. This will give a spiked water with a total concentration of appromixately 250 ug/l in the tank.
 6. Activate the main pump to fill the pressure tank with spiked water up to a pressure of 70 psi. Due to the pressure loss from the pipeline and valves, the average pressure for the system was 61 psi.
 7. Set timer with 30 minutes "on" and 30 minutes "off" alternately. Estimate the time, when the tank will be empty, and stop the timer to avoid pump burn-out.
 8. Open the line valves and adjust the flow rate to a desired value with time "on".
 9. Set time "off" to connect the test units to the end of the apparatus and reset the time "on" to start the test run.
 10. Take influent and effluent samples at intervals of 25% of rated capacity of each filter.
 11. Run the filter until time shuts off the flow or until the tank is nearly empty.
 12. When the tank is nearly empty, shut off the timer and drain off any residual water from reservoir tank and pressure tank.

13. Refill the reservoir tank with reagent water and repeat steps from 1 to 12 unless the termination point of the filter run is reached or a challenge compound is changed.
14. Turn off the timer before disconnecting the finished filter from the apparatus. Check flow rate after a new filter is connected and start a new test run from step 7 again.
15. Before a new compound is used, empty the reservoir and pressure tanks first. Then refill with reagent water. Turn on recirculating and main pumps at least one hour to remove any previous residue from the system. Repeat this process again to minimize contamination. Go back to step 1 and continue.

SAMPLING PROTOCOL

To imitate residential water usage, the flow was controlled by solenoids and timers to create an intermittent flow. Spiked water was set to flows through the filters with the interval of 30 minutes "on" and 30 minutes "off". Both influent and effluent samples were taken and analyzed for the VOCs at every 25% of the filter rated capacity until either 200% of total rated capacity or until an 100 ug/l effluent concentration was reached. This provided information about how the filters functioned through its rated lifetime and beyond. Multiple samples were collected, chilled, and stored at 4°C. until analysis. Sample bottles were filled with water until overflow to avoid passing or trapping air bubbles into the bottles during filling or sealing.

It was found that to maintain a constant concentration of spiked volatile contaminants through the testing period was very

difficult. Influent concentrations decreased with time due to volatilization of challenge VOCs from batch solution. Because there was no way to keep the storage tank from contacting the atmosphere to prevent volatilization, concentrations of the challenge contaminants in effluent samples were highly dependent on influent concentrations. As the influent concentrations declined, effluent concentrations also declined, therefore comparison of effluent values was not possible. It is more meaningful to use a ratio of effluent (C) to influent (C_i) concentration, C/C_i , for comparison within and between filter runs.

ANALYTICAL EQUIPMENT

USEPA Methods for the Determination of Organic Compounds in Finished Drinking Water and Raw Source Water (USEPA, 1985) were used to analyze the water samples. The four compounds were analyzed with method 502.1, Volatile Halogenated Organic Compounds in Water by Purge and Trap Gas Chromatography. A Valco Trace Organics Concentrator, connected to a Varian Gas Chromatograph (GC), model 3700, that was, in turn, connected to a Tracor 700 Hall Electrolytic Conductivity Detector were used in this procedure. A 25 ml purge vessel was used for a 25 ml water sample. A 2.5 meter x 0.1 inch diameter stainless steel column packed with 1% SP-1000 on carbonpack-B (60/80 mesh) was used in the Varian 3700 GC. The column temperature was programmed to provide a better separation of the compounds. The flow rates of purge gas (N_2), carrier gas (He), and reaction gas (H_2) were 40ml/min., 30ml/min., and 40ml/min., respectively. The minimum detectable levels of the VOCs used in this study were: tetrachloroethylene, 0.62 ± 0.05 , chloroform,

0.30 ± 0.03, 1,1,1-trichloroethane, 0.43 ± 0.01, and trichloroethylene, 0.42 ± 0.06 ug/l.

QUALITY CONTROL

Quality Control (QC) was maintained through all of the analytical procedure by following the latest USEPA requirements that are provided in method 502.1 (USEPA, 1985). There were several measurements included in QC: inject an aliquot amount of a surrogate compound into every sample to indicate the performance of the method and inclusion of a standard every 10 samples to indicate the accuracy of analysis. Bromochloromethane (BCM), with a short retention time and no interference with challenge compounds, was chosen as the surrogate compound. Data of surrogates quality control for test run samples are presented in Table 3.

Additionally, at least 10% duplicate water samples were taken to assess precision in sampling and 20% duplicates of test units were run to check the accuracy of the test protocol and testing system. Filter duplicates were first run side by side, started at the same time, and samples at same percentage of capacity, then were run parallel with another filter to check the variation between every run. The sample duplicates were also taken at the same sampling time during each filter test run and were analyzed by the GC procedure. The performance of GC operation also passed a blind PCE test provided by DSR before the experiments began.

Method detection limits (MCLs) for each compound were determined to express the sensitivity of the analytical method. The method detection limits were calculated as the standard

Table 3. Quality Control Data for Test Run Sampling Surrogates.

Treatment	Filter	SC (ug/l)	Recovery %
0.5 gpm Adsorption	AW	12.2 ± 0.3	97.6
	AFT	13.8 ± 0.5	99.0
	C	12.5 ± 0.7	99.6
	P	14.0 ± 0.6	100.8
1.0 gpm Adsorption	AW	11.9 ± 0.4	101.1
	AFT	13.7 ± 0.4	100.6
	C	12.8 ± 0.5	101.2
	P	12.8 ± 0.4	101.2
1.0 gpm Desorption	AW	19.5 ± 0.6	101.2
	AFT	18.5 ± 0.6	100.2
	C	18.1 ± 0.6	98.4
	P	19.1 ± 0.5	98.9
pH 5.0	AW	11.7 ± 0.5	106.4
	AFT	10.7 ± 0.3	97.3
	C	11.8 ± 0.4	106.3
	P	10.2 ± 0.6	92.7
pH 9.0	AW	11.7 ± 0.3	101.7
	AFT	11.3 ± 0.6	98.3
	C	11.7 ± 0.5	101.3
	P	11.3 ± 0.9	98.3
<u>Duplicate Sample Run</u>			
1.0 gpm Adsorption	AW	14.4 ± 0.3	99.3
	AFT	14.0 ± 0.7	96.6
0.5 gpm Adsorption	P	14.7 ± 1.0	101.4

deviation of the four lowest detectable concentrations determined by trial and error on the GC. Data for quality control analysis of filter duplicates and method detection limits were given above.

ANALYSIS OF REAGENT WATER

The quality of reagent water was analyzed frequently to make certain it remained relatively constant throughout the whole study period. Water quality tests were conducted with HACH water analysis kit and its methods including alkalinity, calcium, chloride, chlorine residual, iron, magnesium, nitrate, phosphate, potassium, sulfate, sodium, and total hardness. Water pH values were measured by a standard pH electrode. Total dissolved solids (TDS) and standard plate counts of bacteria were done separately by following the methods 209B and 907 of Standard Methods for the Examination of Water and Wastewater (16th edition, 1985). These water quality tests were conducted more frequently as the variations become more prominent. Concentrations of VOCs in tap water and reagent water were checked on a monthly basis. Results from these analyses were reported in the final report of part 1 of this study (Cotton, et al., 1989) and are given also in the Appendix of this report.

EXPERIMENTAL CONDITIONS

1. Flow rate effect study

Flow rates of 0.5 and 1.0 GPM were employed in accord with the manufacturer's recommendations.

2. Desorption study

In order to investigate whether or not adsorbed substances would be released from heavily loaded filters, non-spiked reagent

water was run through the filters at 1.0 gpm flow rates.

3. Effect of pH study

Phosphate and borax buffer solutions were used to provide pH 5.0 and pH 9.0 of the test systems. pH values were continuously monitored throughout the filtration runs.

- a. For the pH 5 system, approximately 23 liters of 0.1M KH_2PO_4 were added to the storage tank during refilling. When the tank was filled, the recirculating pump was turned on and, after 30 min., the pH value of the water was measured. 0.1M HCl or 0.1M NaCl was used to adjust the water pH to 5.0 ± 0.5 . Wait 30 min. to measure water pH after every HCl or NaCl addition.
- b. For the pH 9 system, approximately 30 liters of 0.025M $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ was added into the storage tank during refilling. When the tank was filled, the recirculating pump was turned on and, after 30 min., the pH value of the water was measured. 0.1M HCl or 0.1M NaOH was used to adjust the water pH to 9.0 ± 0.5 . Wait 30 min to measure water pH after every HCl or NaOH addition.

EXPERIMENTAL RESULTS

A. Single Compounds

The detailed results and discussions of the removal of the four compounds in this study as single solutes are given in the MS thesis of Cotton (1988) and the final report of part 1 (1989). A brief description of these results is given here.

1. Breakthrough Runs with Tetrachloroethylene

Tetrachloroethylene (PCE) was chosen as one of the challenge contaminants with which to perform filter breakthrough tests. Of the four compounds used in testing, PCE has the highest Freundlich K constant (see Table 2). This is an indication that, of these four compounds, PCE is adsorbed the greatest by activated carbon (ground, powdered activated carbon- see Dobbs and Cohen, 1980). In estimating real capacities for the test filters, then, tetrachloroethylene will give an estimate of the longest time to breakthrough for the challenge contaminants. The remaining three compounds will be expected to breakthrough before PCE, as indicated by their lower K constants.

Table 4 shows each filter's response to the 250 ug/l of PCE. Note that three of the devices tested showed no detectable breakthrough of PCE. These were C, AW, and AF. The C device was tested to 288% of its rated capacity, the filter AW to 229% of capacity, and AF to 350% of its rated capacity. One other filter, the AM filter, plugged at 154% of total capacity before any concentration of PCE could be detected.

Five other point-of-use devices showed breakthrough of PCE before 200% of capacity. Graphs of breakthrough (not shown) showed the rate and extent to which breakthrough occurred for each filter. The I filter exhibited breakthrough at 90% of its capacity. Effluent concentrations after 90% were increased from 0.62 to 1.57 ug/l at 110% of capacity. The AFT device allowed breakthrough of PCE at 145% of capacity and showed an increase from 0.72 ug/l to 1.39 ug/l in 166% of capacity. The E filter showed a breakthrough at 25% with a concentration of 6.81 ug/l. At 184% the

Table 4. Tetrachloroethylene Concentrations in Effluent Filter Samples.

<u>Filter</u>	<u>% of Capacity</u>	<u>Volume(Gal.) Throughput</u>	<u>Effluent Conc. Sampled (ug/l)</u>	<u>C/Ci</u>
I (AK) a	90	1350	0.62	0.003
	95	1425	2.10	0.008
	100	1500	1.40	0.006
	105	1575	1.96	0.008
	110	1650	1.57	0.006
AM	154	770	Filter Plugged	
AFT	145	1450	0.72	0.003
	157	1570	0.46	0.002
	166	1660	1.39	0.002
	172	1720	0.20	0.001
C	288	5750	ND *	ND
AF	350	1750	ND	ND
E	25	250	6.81	0.027
	46	460	-	-
	84	840	5.11	0.020
	154	1540	13.58	0.054
	184	1840	23.07	0.092
P	20	465	3.65	0.015
	45	1075	3.12	0.012
	71	1715	3.88	0.016
	98	2353	10.89	0.044
AW	229	3430	ND	ND
AP	37	740	3.02	0.015
	62	1240	4.29	0.021
	91	1820	11.13	0.031
	103	2055	48.40	0.134

ND * no concentration detected
a I and AK filters are identical.

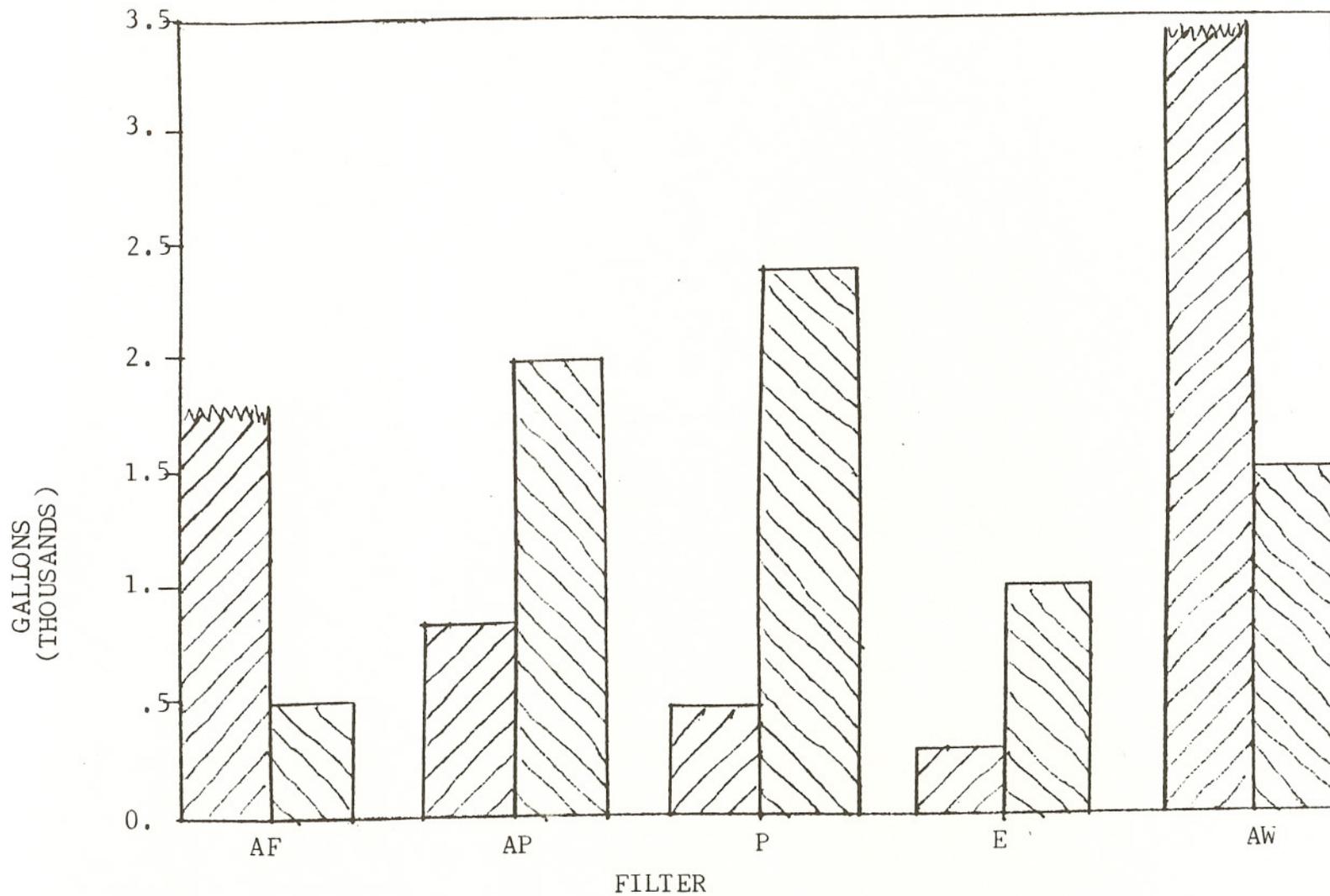
concentration had risen to 23.07 ug/l. Breakthrough for the P filter occurred at 20% of the device's capacity. An increase from 3.65 ug/l to 10.89 ug/l occurred over an additional 78% of capacity. For the AP device, breakthrough occurred at 37% of capacity, with the concentration increasing in effluent samples from 3.02 ug/l to 48.4 ug/l at 103%; after an additional 66% in filter capacity.

Figure 2 presents bar graphs of volume throughput for breakthrough of PCE from the filters and volume to 100% of the filter's rated capacity. This figure allows the evaluation of the filter's performance by juxtaposition of graphs of the filter's capacity to graphs of the volume throughputs achieved to breakthrough by the filters. Three of these filters exhibited breakthrough of PCE before their full rated capacities. These were AP, P, and E. Three of the devices, AFT, I and AK, showed breakthrough after their capacities were reached, but before 200% of rated capacity. The AM filter, though plugging, also showed no breakthrough before 200%. Three filters showed no breakthrough of PCE at all. These were: C, AW, and AF.

2. Breakthrough Runs with Chloroform

Chloroform was chosen as the second volatile organic with which to challenge the 10 point-of-use devices. This compound has the lowest Freundlich K value on GAC of the compounds tested initially. In as much as tests with tetrachloroethylene gave indications of breakthrough for a compound well adsorbed by activated carbon, tests with chloroform were expected to indicate filter performance with a compound not well adsorbed by activated

FIGURE 2 a. VOLUME TO BREAKTHROUGH FOR TETRACHLOROETHYLENE.



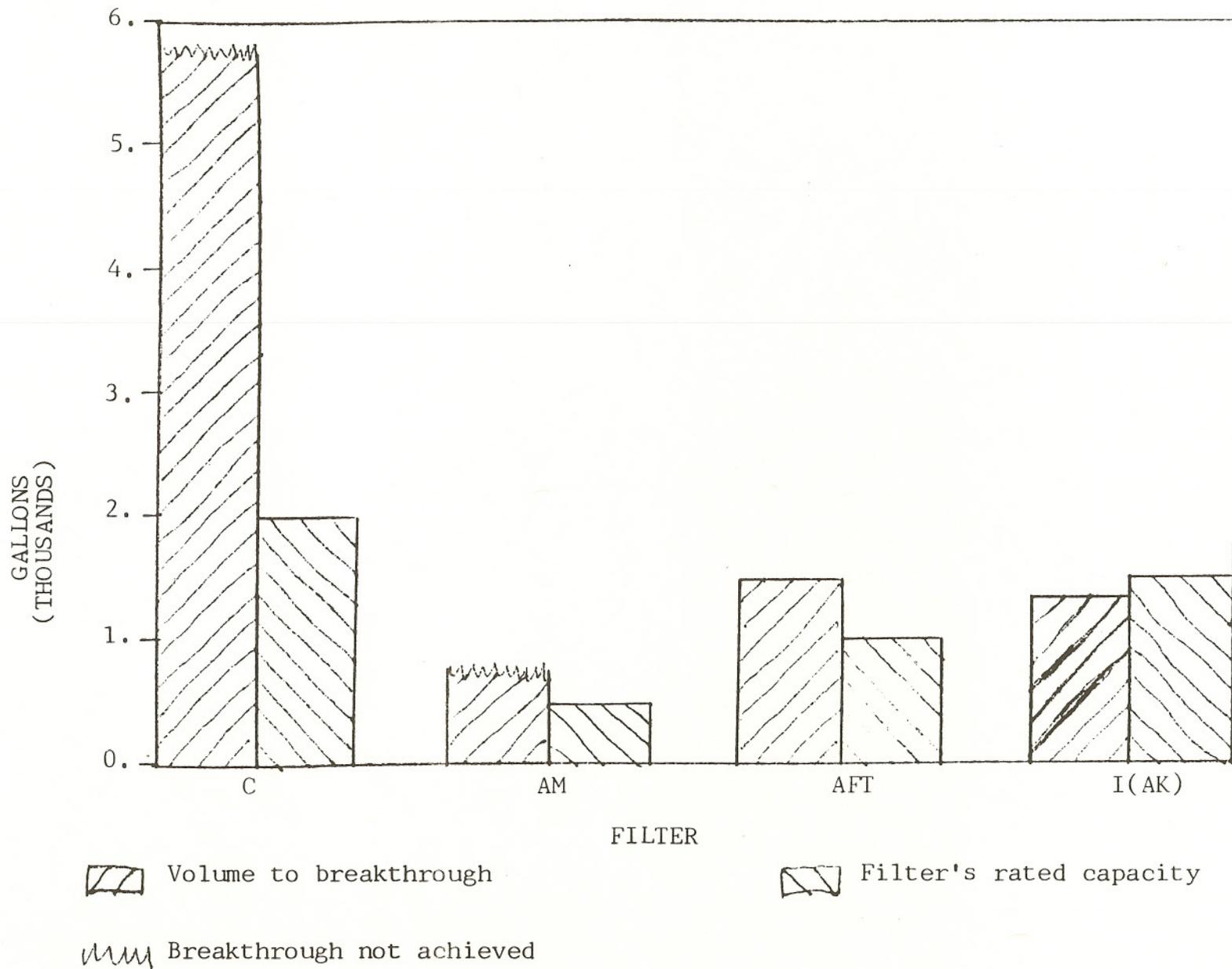
 Volume to breakthrough.

 Filter capacity

 Breakthrough not achieved

34

FIGURE 2b. VOLUME TO BREAKTHROUGH FOR TETRACHLOROETHYLENE.



carbon. The lower extreme of filter performance, in adsorbing contaminants from drinking water, then, was tested with chloroform.

Table 5 gives the effluent chloroform concentrations at first appearance and at termination of the filter run. Concentrations of chloroform are given along with the percentage capacity of the filter from which it was sampled and in terms of column throughput. Concentration is expressed both as ug/l and as the dimensionless C/Ci ratio.

Three filters performed distinctly from the other seven. C, AW, and E filter devices showed the longest time to breakthrough of chloroform. These filters also exhibited the lowest rise in effluent chloroform concentration over the period tested. None of these filters reached a C/Ci of 0.4. In fact, two of the filters barely reached a C/Ci of 0.1, while one, E, reached a C/Ci of only 0.044 at 200% of capacity.

The filters P, AP, and AF responded quite differently from those in the above tests. These showed an almost immediate (appearance came in the first sample) breakthrough of chloroform; Pond AF devices showed breakthrough at 25% whereas AP broke through at 35% P and AP filters had significant concentrations in first samples of 51.7 and 13.2 ug/l, respectively, while the AF filter had a concentration of 0.55 ug/l at breakthrough. The rate of increase in concentration, for all three filters, was quite rapid. P samples increased from 51.7 ug/l at 25% of capacity to 183.9 ug/l at 78% of its rated capacity. AP samples rose from 13.2 ug/l at 35% capacity to 131.7 ug/l at 74% of capacity. The AF samples climbed to 190 ug/l at 100% capacity from approximately 0.55 ug/l

Table 5. Chloroform Concentration in Effluent Filter Samples.

<u>Filter</u>	<u>Occurrence of Compound</u>	<u>% Filter Capacity</u>	<u>Volume(Gal.) Throughput</u>	<u>Conc.(ug/l) sampled</u>	<u>C/Ci</u>
C	F *	50	1000	0.5	0.003
	PT @	200	4000	22.7	0.160
I (AK)	F	30	225	22.2	0.099
	PT	150	1125	96.8	0.407
AFT	F	25	250	23.6	0.105
	PT	204	2040	93.7	0.358
AM	F	25	125	10.5	0.044
	PT	150	750	120.5	0.535
AF	F	25	125	0.8	0.004
	PT	100	500	190.4	0.841
duplicate	F	25	125	0.3	0.002
	PT	75	375	158.2	0.700
P	F	25	600	51.7	0.230
	PT	78	1870	183.9	0.770
AP	F	35	700	13.2	0.088
	PT	74	1480	131.7	0.520
AW	F	15	220	0.3	0.002
	PT	184	2755	17.1	0.103
E	F	60	600	0.7	0.003
	PT	198	1980	7.3	0.044

F* First appearance of compound.
 PT@ Appearance of compound at point of termination of the test run.

at 25% of capacity. A C/Ci of 0.4 was reached before 75% of total capacity with all three filters.

The other four filters tested showed responses between those of the first and second groups discussed. I, AM, and AFT filters all had breakthroughs of chloroform at, or, around 25% of capacity. The rate of the rise in effluent concentration was slower than with P, AP, and AF filters and faster than with C, AW, and E filters. Three of the filters came to a 0.4 C/Ci before 200% of their rated capacity. The AFT filter, however, met this criteria at just about 200%. All four filters reached 0.4 C/Ci after 100% of their rated capacities.

Figure 3 gives a comparison of volumes of throughput achieved by filters and the volume to each filter's rated capacity. Three filters attained a 0.4 C/Ci before reaching their rated capacities (AF, AP, and P). One filter (AM) reached this criterion at 100% of its capacity. The remainder of the filters surpassed their capacities before reaching 0.4 C/Ci.

3. Breakthrough Runs with 1,1,1-Trichloroethane

1,1,1-Trichloroethane was the third compound used in tests with the ten filters. Table 6 presents trichloroethane concentrations in the effluent at first appearance and at the end of the run. Again, three filters performed distinctly better than the others. E, C, and AW filters had the greatest length of time to breakthrough of the challenge contaminant and showed the lowest increase in concentration during the test period. All three filters reached approximately 200% of their rated capacities at a C/Ci under 0.03. The AW filter showed very low levels of

FIGURE 3 a. VOLUME THROUGHPUT TO 0.4 C/Ci FOR CHLOROFORM

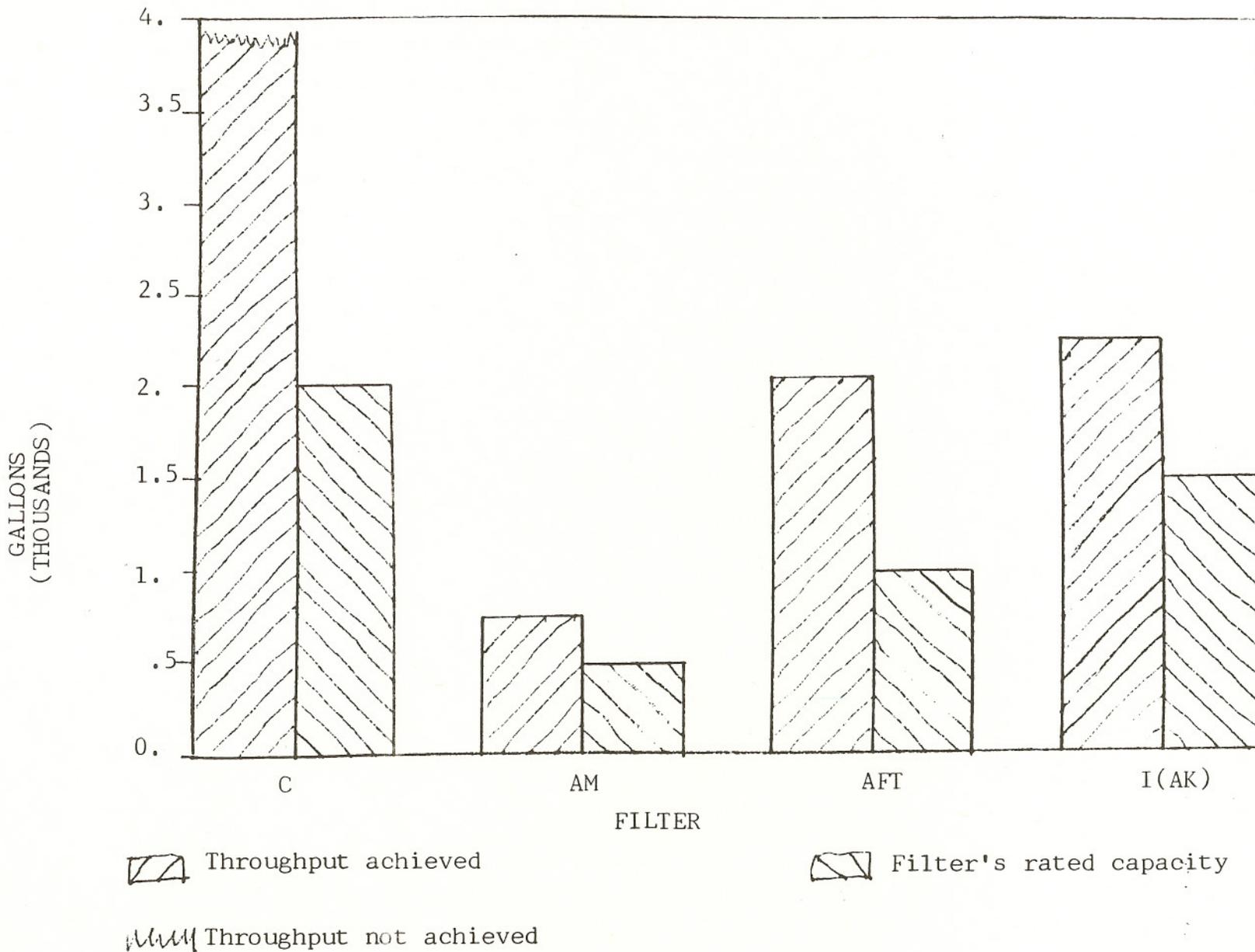
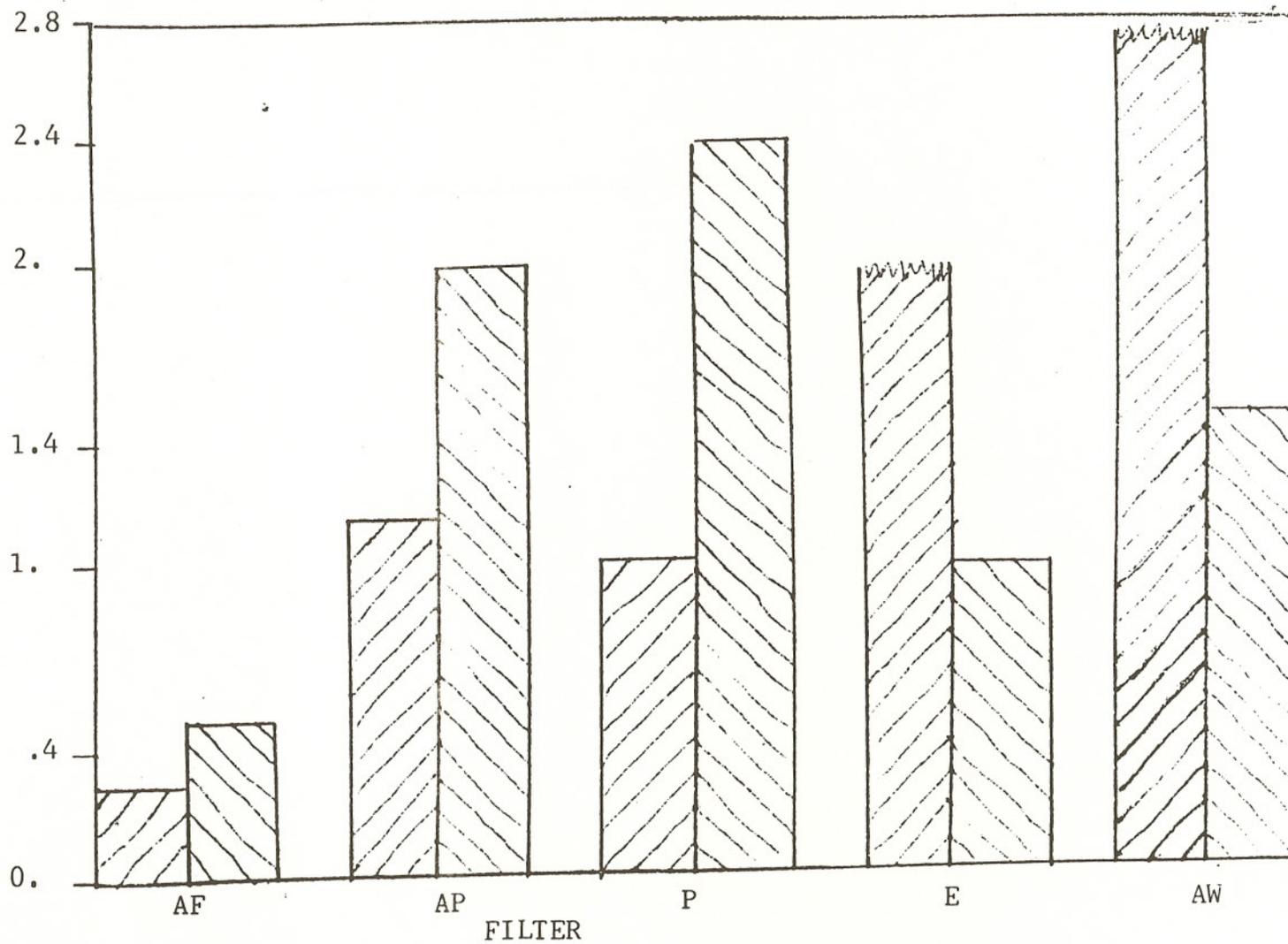


Figure 3b. Volume Throughput to 0.4 C/Ci for Chloroform

40
GALLONS
(THOUSANDS)



 Throughput achieved

 Filter's rated capacity

 Throughput not achieved

Table 6 . 1,1,1-Trichloroethane Concentrations in Effluent Filter Samples.

<u>Filter</u>	<u>Occurrence of Compound</u>	<u>% of Capacity</u>	<u>Volume(Gal) Throughput</u>	<u>Conc. (ug/l)</u>	<u>C/Ci</u>
C duplicate	F a	68	1350	0.4	0.002
	PT b	190	3800	11.6	0.046
	F	68	1350	0.4	0.002
	PT	190	3800	7.9	0.032
I (AK)	F	25	188	9.2	0.037
	PT	224	1680	48.6	0.265
AFT	F	19	190	4.6	0.019
	PT	186	1860	54.8	0.300
AM	F	25	125	6.4	0.016
	PT	150	750	180.1	0.734
AW	F	50	125	0.8	0.001
	PT	199	2980	2.1	0.008
P	F	25	600	42.7	0.139
	PT	87	2090	102.6	0.540
AP	F	27	540	39.9	0.220
	PT	75	1500	95.6	0.510
E	F	25	250	1.1	0.005
	PT	200	2000	10.9	0.038
AF	F	50	125	0.8	0.001
	PT	111	555	151.3	0.616

Fa First appearance of compound
 PTb Appearance of compound at point of termination of the test run

trichloroethane up to about 190% of its capacity. The AW run ended with a C/Ci of 0.008 at 200% of capacity at a concentration of about 2.1 ug/l. The E and C filters performed similarly with trichloroethane. Both devices gave an effluent concentration of approximately 10. ug/l or a C/Ci of 0.04 at 200% of their capacities. P, AP, and AF filters again had the shortest times to breakthrough. The P and AP devices showed an immediate appearance of trichloroethane in effluent samples, P with a concentration of 42.7 ug/l (C/Ci of 0.139) and AP with a concentration of 39.9 ug/l (C/Ci of 0.22). The AF filter didn't show breakthrough until 50% of its capacity. Subsequent rises in effluent concentrations with AF were the most rapid of the filters tested. AF produced a rise of 0.4 C/Ci within 50% of its capacity after breakthrough was achieved at 97% of total capacity. P and AP filters both reached a C/Ci of 0.4 at about 56% of their capacities. All three filters came to a 0.4 C/Ci below 100% of their rated capacities. Subsequent concentrations of 1,1,1-trichloroethane were, then, detected well before life expectancy of the filter was reached.

Again intermediate between extremes of performance were the I, AM, and AFT filters. These filters allowed breakthrough of trichloroethane to occur before 100% of rated capacities. However, concentrations detected at or before 100% were all below C/Ci of 0.18 (a concentration of about 45 ug/l). Additionally, each filter showed a detectable level of the compound in the first samples taken during filter runs. Filter I showed a concentration of 9.2 ug/l at 25% of capacity, AM showed a 6.4 ug/l level at 25%, and AFT gave 4.6 ug/l at 19% of its capacity. After 100% of capacity, AM

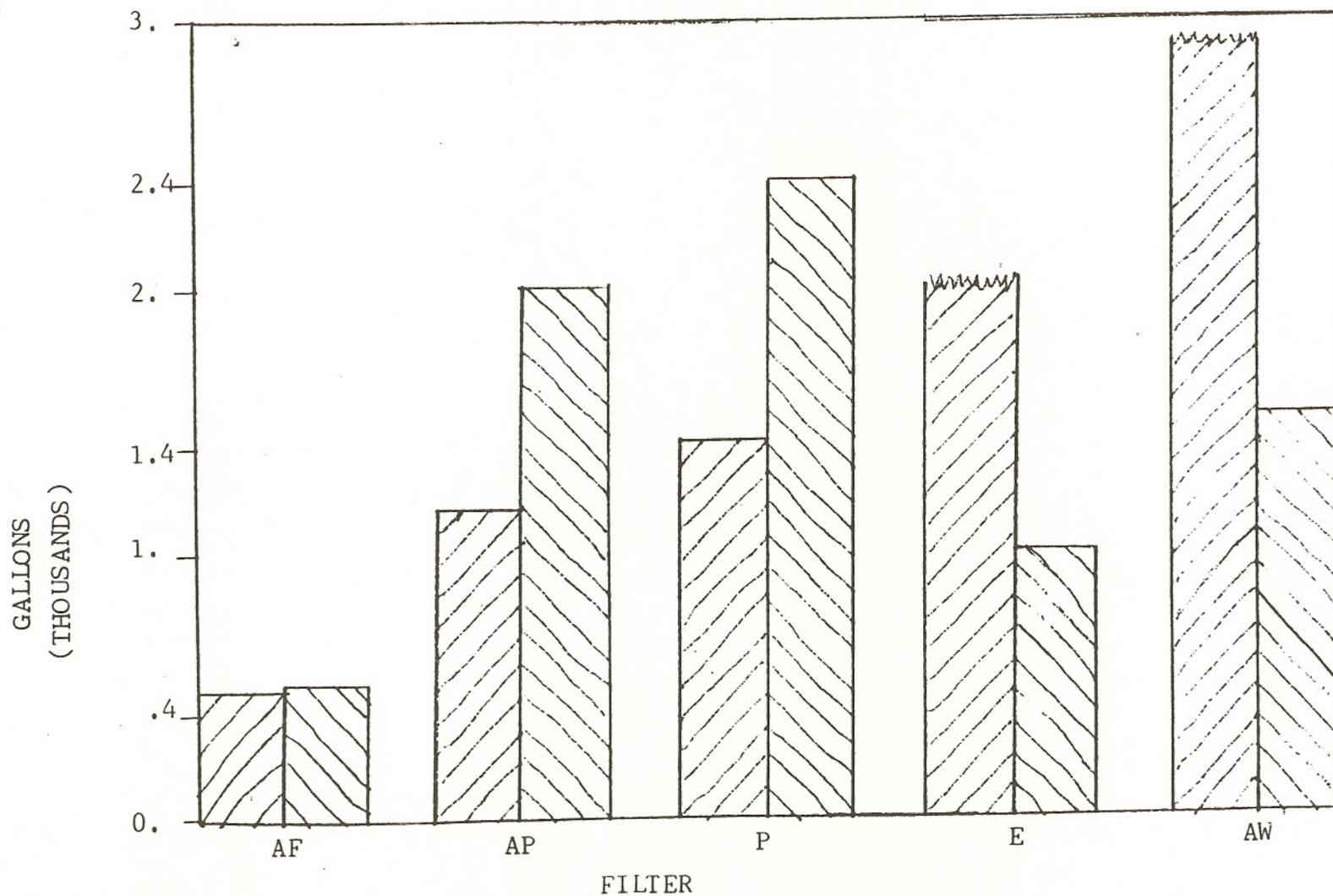
gave a dramatic increase in effluent concentrations. A 0.4 C/Ci was reached at about 130% of capacity; an increase of 0.28 C/Ci (70 ug/l) in only 30% of capacity. After 100% of their capacities, I and AFT filter samples showed a more gradual rise in concentrations. Filter I effluent samples eventually reached 0.4 C/Ci at about 183% of the filter's capacity whereas AFT reached this value after 186% of its rated capacity.

Figure 4 shows the comparison of throughput achieved at 0.4 C/Ci to filter rating in volume where 1,1,1-trichloroethane was used as challenge contaminant. The same general pattern is seen here as was seen for chloroform. Three filters failed to reach their rated capacities before 0.4 C/Ci was met and six other filters surpassed 100% of capacity before 0.4 C/Ci was reached. The three filters were: AF, AP, and P. The six were: E, AW, C, AFT, I, and AM. The AM filter, this time, exceeded its capacity before 0.4 C/Ci was reached.

4. Breakthrough Runs with Trichloroethene

The fourth compound used as a challenge contaminant with the carbon filters was trichloroethene. Table 7 gives the concentrations of trichloroethene at first appearance of the compound in the effluent samples and at termination of the filter run. Filters C, AFT, and AW performed exceptionally well with less than 1 ug/l at first appearance with removals continuing to 200% of filter capacity. However, filters I, AM, AF, P, AP, and E were considerably less efficient with significant quantities of trichloroethene breaking through at filter capacities less than 100%. Continuation of these filters to capacities greater than

FIGURE 4a. VOLUME THROUGHPUT TO 0.4 C/Ci FOR 1,1,1-TRICHLOROETHANE



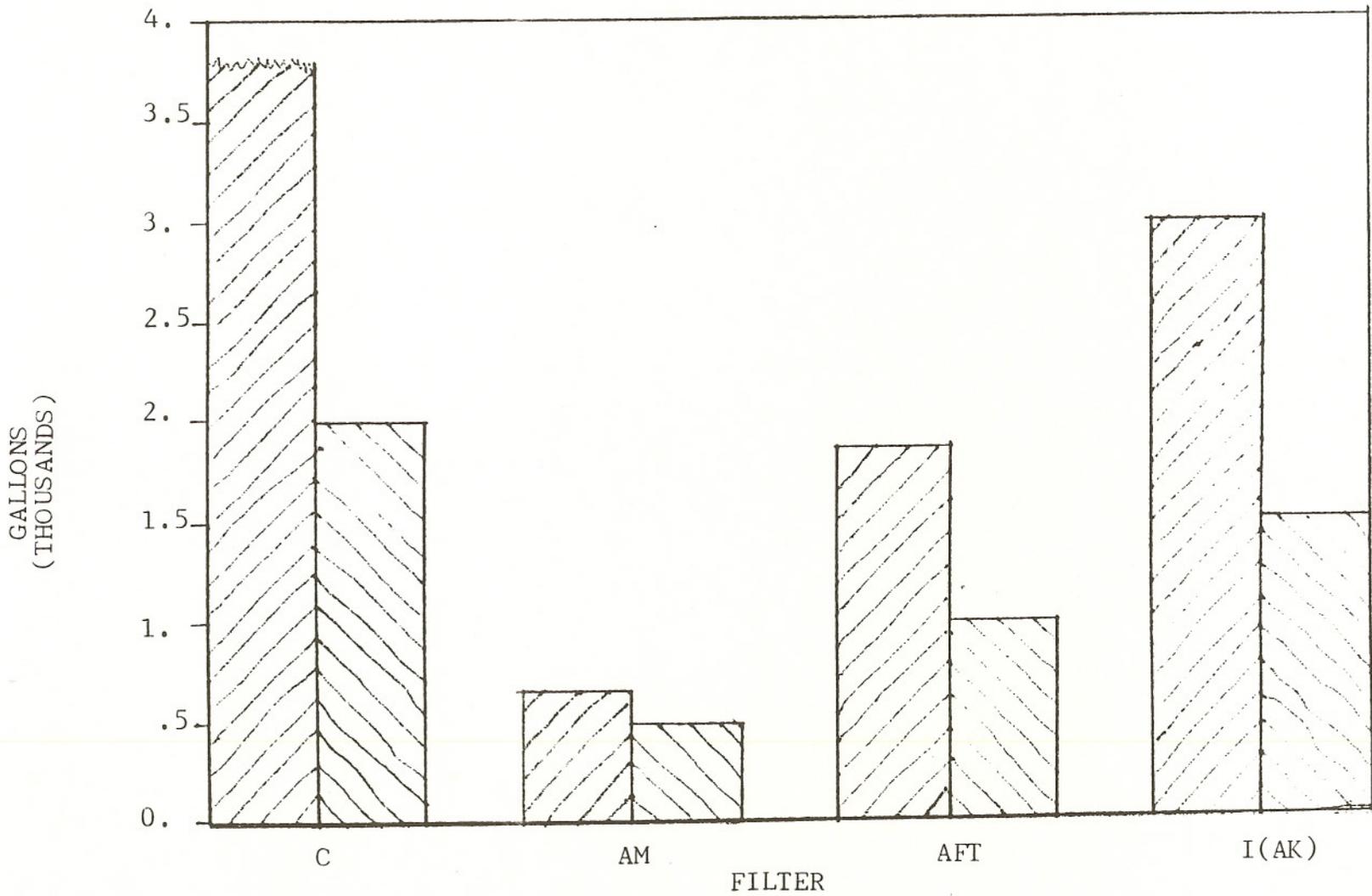
 Throughput achieved

 Filter's rated capacity

 Throughput not achieved

FIGURE 4 b. VOLUME THROUGHPUT TO 0.4 C/Ci FOR 1,1,1-TRICHLOROETHANE

47



 Throughput achieved

 Filter's rated capacity

 Throughput not achieved

Table 7. Trichloroethene Concentrations in Effluent Filter Samples.

<u>Filter</u>	<u>Occurrence of Compound</u>	<u>% Filter Capacity</u>	<u>Volume of Throughput gal.</u>	<u>Conc. ug/l</u>	<u>C/Ci</u>
C	F ^a	-	-	ND ^c	ND
	PT ^b -plugged	125	2500	ND	ND
I	F	50	750	3.28	.016
	PT	200	3000	16.15	.069
AFT	F	25	250	.50	.002
	PT	200	2000	6.08	.026
Duplic.	F	25	250	.49	.004
	PT	200	2000	5.94	.028
AM	F	25	125	7.22	.029
	PT	100	500	95.42	.419
AF	F	100	500	3.56	.014
	PT	175	875	114.94	.710
P	F	25	600	5.78	.030
	PT	200	4800	113.37	.641
AP	F	25	500	6.34	.027
	PT	200	4000	93.14	.383
AW	F	-	-	ND	ND
	PT	200	3000	ND	ND
E	F	25	500	30.88	.149
	PT	75	1500	104.31	.567

a. First appearance of compound.

b. Appearance of compound at point of termination of test run.

c. Not Detected.

100% showed significant quantities of trichloroethene in the effluent samples.

Figures 5 a and b show the bar graphs of volume throughput for each filter when the ratio of 0.4 C/Ci was achieved for trichloroethene. In turn, this volume is compared to the manufacturer's rated capacity. This comparison is another measure of filter efficiency as well as an evaluation of the manufacturer's claim. Filters AF, AP, P, AW, C, AFT, and I exceeded the volumetric capacity whereas filters E and AM essentially met their rated capacities. This is more an evaluation of the filter's hydraulic characteristics than their adsorptive properties.

Average Percentage Removals

Tables 8 through 11 list the average removal efficiencies of each of the four test compounds for the ten filters. These tables show the average percentage of challenge contaminant removed by the point-of-use devices, the range of percentage removals detected in that run, and the length, in percentage of filter capacity, of the test run. The average percentage removal is calculated for an entire filter run, using samples of effluent and batch concentration from that run. Because removal efficiencies are usually higher at the start of a test run than at the end, ranges of removal efficiencies are given showing highest and lowest values that occurred during the run. Removal efficiencies are given for all ten filter devices for all seven compounds used.

Best removal efficiencies occurred when tetrachloroethylene was used as the challenge contaminant (Table 8). Four of the filters tested showed no detectable concentrations of the compound

FIGURE 5 a. VOLUME THROUGHPUT TO 0.4 C/ci FOR TRICHLOROETHENE.

bh

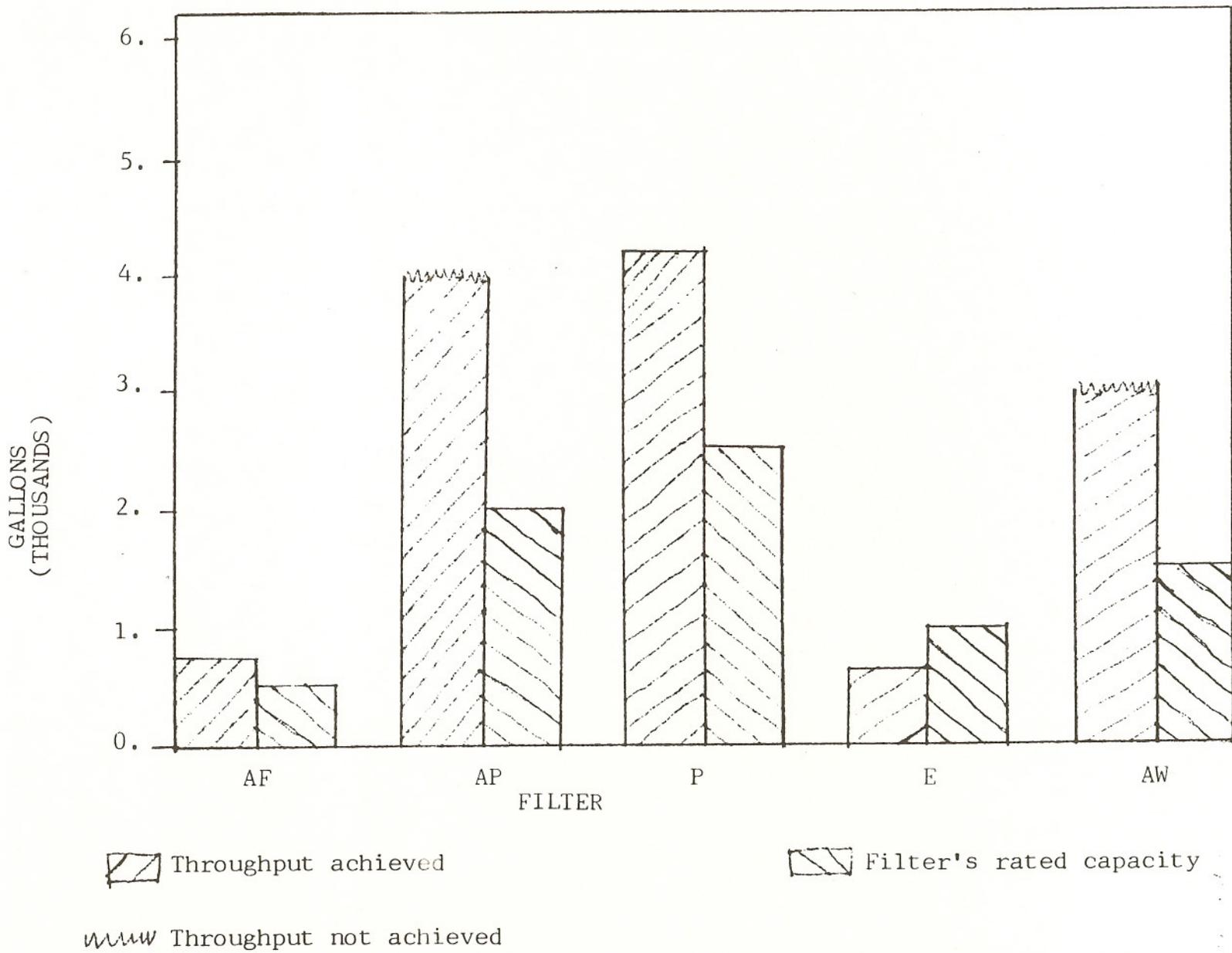
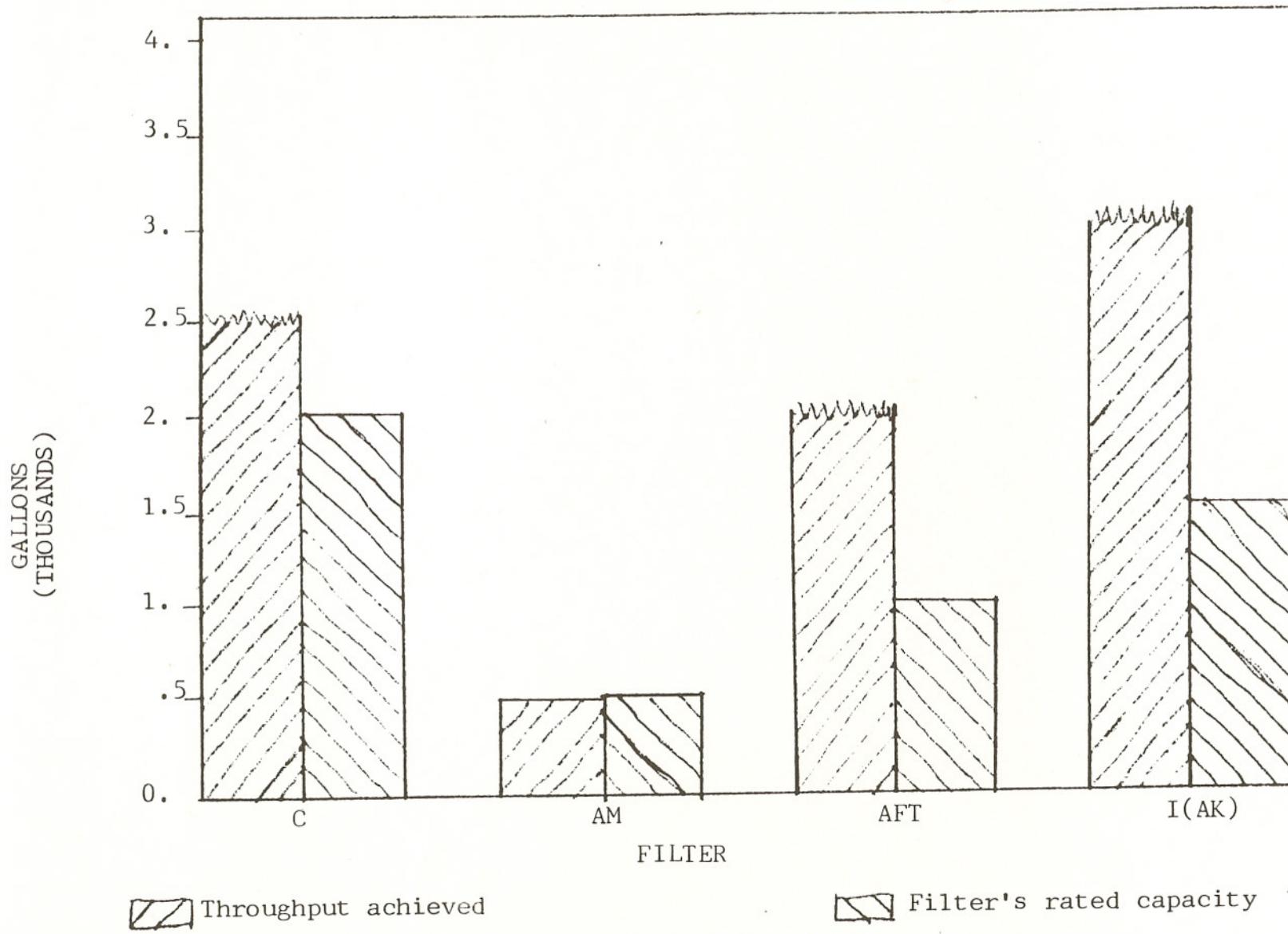


FIGURE 5 b. VOLUME THROUGHPUT TO 0.4 C/Ci FOR TRICHLOROETHENE.

bh



Throughput not achieved

Table 8. Average Percentage Removal of Tetrachloroethylene by Filter Devices.

<u>Filter</u>	<u>Average Removal %</u>	<u>Range of Removal %</u>	<u>Capacity at termination (%)</u>
C	99.9	--	288
I (AK)	99.4	99.7-99.2	220
AFT	99.8	99.9-99.7	172
AM	99.9 (plugged)	--	154
AF	99.9	--	350
P	97.6	98.5-95.8	98
AP	95.0	98.5-86.7	103
AW	99.9	--	229
E	94.6	97.7-91.2	184

Table 9. Average Percentage Removal of Chloroform by Filter Devices.

<u>Filter</u>	<u>Average Removal %</u>	<u>Range of Removal %</u>	<u>Capacity at Termination (%)</u>
C	96.5	99.9-89.4	200
I (AK)	79.2	90.1-59.3	150
AFT	76.2	89.5-64.0	200
AM	74.8	95.6-46.5	150
AF	66.6	99.7-23.0	100
P	50.8	77.0-23.0	77
AP	65.0	91.9-48.0	74
AW	98.2	99.8-89.7	185
E	98.0	99.9-93.6	200

Table 10. Average Percentage Removal of 1,1,1-Trichloroethane by Filter Devices.

<u>Filter</u>	<u>Average Removal %</u>	<u>Range of Removal %</u>	<u>Capacity at Termination (%)</u>
C	99.0	99.9-96.2	190
I (AK)	79.1	96.3-45.9	224
AFT	82.0	98.1-58.4	186
AM	81.8	98.4-26.6	150
AF	80.2	99.9-38.4	111
P	55.9	86.1-46.0	87
AP	58.8	78.0-49.0	75
AW	99.8	99.7-99.2	199
E	97.4	99.5-96.2	200

Table 11 . Average Percentage Removal of Trichloroethene
by the Filter Devices.

<u>Filter</u>	<u>Average Removal</u>	<u>Range of Removal</u>	<u>Capacity at Termination</u>
	%	%	%
C	99.9 plugged	-	127
I	96.1	99.9-91.81	198
AM	82.1	97.4-56.0	98
AFT	99.4	99.9-98.0	201
Duplicate	99.0	99.9-98.4	199
AF	83.4	99.9-26.13	174
P	79.6	98.8-34.15	202
AP	81.0	98.8-60.1	198
AW	99.9	-	202
E	64.5	85.1-41.3	74

throughout the test runs. C, AM, AF, and AW filters provide average removals of 99.9% of PCE. The six remaining filters all give removal efficiencies above 95%. Lows in the range of removal efficiency, however, dropped below 90% for one filter, the AP device. Other filters, I (and AK), AFT, P and E, all maintained efficiencies above 90% with ranges between 91 to 99.9%.

Removal efficiencies changed dramatically when chloroform was used as the challenge contaminant (Table 9). All filters showed detectable concentrations of this compound at some point during test runs. Average percentage removals for the filters with chloroform varied from a high efficiency, for AW, of 98.2%, to a low of 50.8% for P. Lows in ranges of percentage removal values dropped to 23.0% for two of the filters, AF and P. Other low bottom ranges were witnessed with several of the devices; 59.3% for I, 64% for AFT, 46.5% for AM, and 48% for AP.

Removal efficiencies improved somewhat with 1,1,1-trichloroethane as the challenge contaminant (Table 10). Average percentage removal values are as high as 99.8% for AW and as low as 55.9% for P. C and E filters also register high percentage removals with 99.0% and 97.4%, respectively. The low range of percentage removal values is also somewhat higher with trichloroethane. The lowest occurred with AM, at 150% of its rated capacity, for a 26.6% removal. Other lower bottom ranges are found with I, at 45.9%, AF, at 38.4%, P, at 46.0%, and AP, at 49% removal.

The average percentage removals in Table 11 for trichloroethene ranged from 64.5 (Filter E) to 99.9 (Filter C).

The most efficient removals of trichloroethene were exhibited by filters AFT and AW that continued to the 200% volume capacity at termination. Removals of greater than 99% were observed for these two filters. Filter I was also reasonably effective with an average of 96.1% removal throughout the experimental run. Filters AM, AF, P, AP, and E were considerably less efficient in their removal of trichloroethene. This observation can be explained by the lesser amounts of carbon in each filter (as seen in Table 2b of the final report - part 1). These five filters have the smallest quantities of carbon of the ten experimental carbons.

B. Mixtures of Compounds

It is well known that the adsorption of organic compounds on activated carbon is inhibited or suppressed by the presence of other similarly structured compounds. This is presumably due to competition among the molecules for adsorption sites on the surface of activated carbon. Evaluation of competitive effects can be made by comparing the adsorption of an equal mass of a given compound under identical test conditions from mixed solute and from single solute solutions.

Four filters were selected from the previous study (part 1) to cover a range of performances: excellent (AW and C), moderate (AFT) and poor (P). Four compounds, tetrachloroethane, chloroform, 1,1,1-trichloroethane, and trichloroethene from the previous study were selected for the mixed solute study. These four compounds, 50-75 ug/l of each, were added to the reagent water in order to achieve a mixed competitive solution with a total concentration of approximately 250 ug/l.

1. Effect of Flow Rate

The recommended flow rates of the filters range from 0.5 gpm to 1.0 gpm (Table 1). In order to emphasize the effect of contact time between adsorbate and adsorbent, the two flow rates of 0.5 gpm and 1.0 gpm were selected.

a. Tests at 1.0 gpm

Table 12 shows the adsorption data for each volatile contaminant on filter C (Culligan), AW (Amway), AFT (Advanced Filtration Technology) and P (Pollenex), respectively. The concentrations and rated capacities at the first appearance of the compounds were given in the first row for each filter marked as F. The concentrations of compounds at the point of termination were also given in the second row marked as PT for each filter. Whenever there was no detectable breakthrough of a given compound at F or PT, the concentration was reported as ND (not detected).

Similar to the single-solute systems, filters C and AW show little or no breakthrough of all four compounds from a multi-solute system. There were no breakthroughs of 1,1,1-trichloroethane and trichloroethene for filter C to 200% of rated capacity (Figure 6). The breakthrough of tetrachloroethene appeared relatively early at 50% of capacity as 1.19 ug/l (C/Ci of 0.03) that was increased to 1.42 ug/l (C/Ci of 0.05) at 200% of capacity, the termination point. Filter C shows breakthrough of chloroform relatively late at 100% of capacity with 1.61 ug/l (C/Ci of 0.05) that quickly was increased to 5.46 ug/l with similar C/Ci values, 0.1 for single and 0.13 for the mixed solution at the point of termination.

Except chloroform, there were no breakthroughs of the other

Table 12. Compound Concentrations in Effluent Filter Samples at 1.0 gpm

Compound	Occurrence	Filter Capacity%	Throughput Volume - gal.	Concentration ug/l	C/D
<u>Culligan</u>					
Chloroform	F a	100	2000	1.61	0.05
	PT b	200	4000	5.46	0.15
1,1,1-Trichloroethane	F	-	-	ND c	ND
	PT	200	4000	ND	ND
Trichloroethylene	F	-	-	ND	ND
	PT	200	4000	ND	ND
Tetrachloroethylene	F	25	500	1.19	0.03
	PT	200	4000	1.42	0.05
<u>Amway</u>					
Chloroform	F	125	1875	1.61	0.03
	PT	200	3000	10.51	0.15
1,1,1-Trichloroethane	F	-	-	ND	ND
	PT	200	3000	ND	ND
Trichloroethylene	F	-	-	ND	ND
	PT	200	3000	ND	ND
Tetrachloroethylene	F	-	-	ND	ND
	PT	200	3000	ND	ND
<u>Amway - Duplicate</u>					
Chloroform	F	25	375	2.47	0.03
	PT	200	3000	27.87	0.36
1,1,1-Trichloroethane	F	125	1875	0.81	0.01
	PT	200	3000	2.7	0.06
Trichloroethylene	F	-	-	ND	ND
	PT	200	3000	ND	ND
Tetrachloroethylene	F	-	-	ND	ND
	PT	200	3000	ND	ND

a: First detectable concentration.
 b: Point of termination of run.
 c: Not detected.

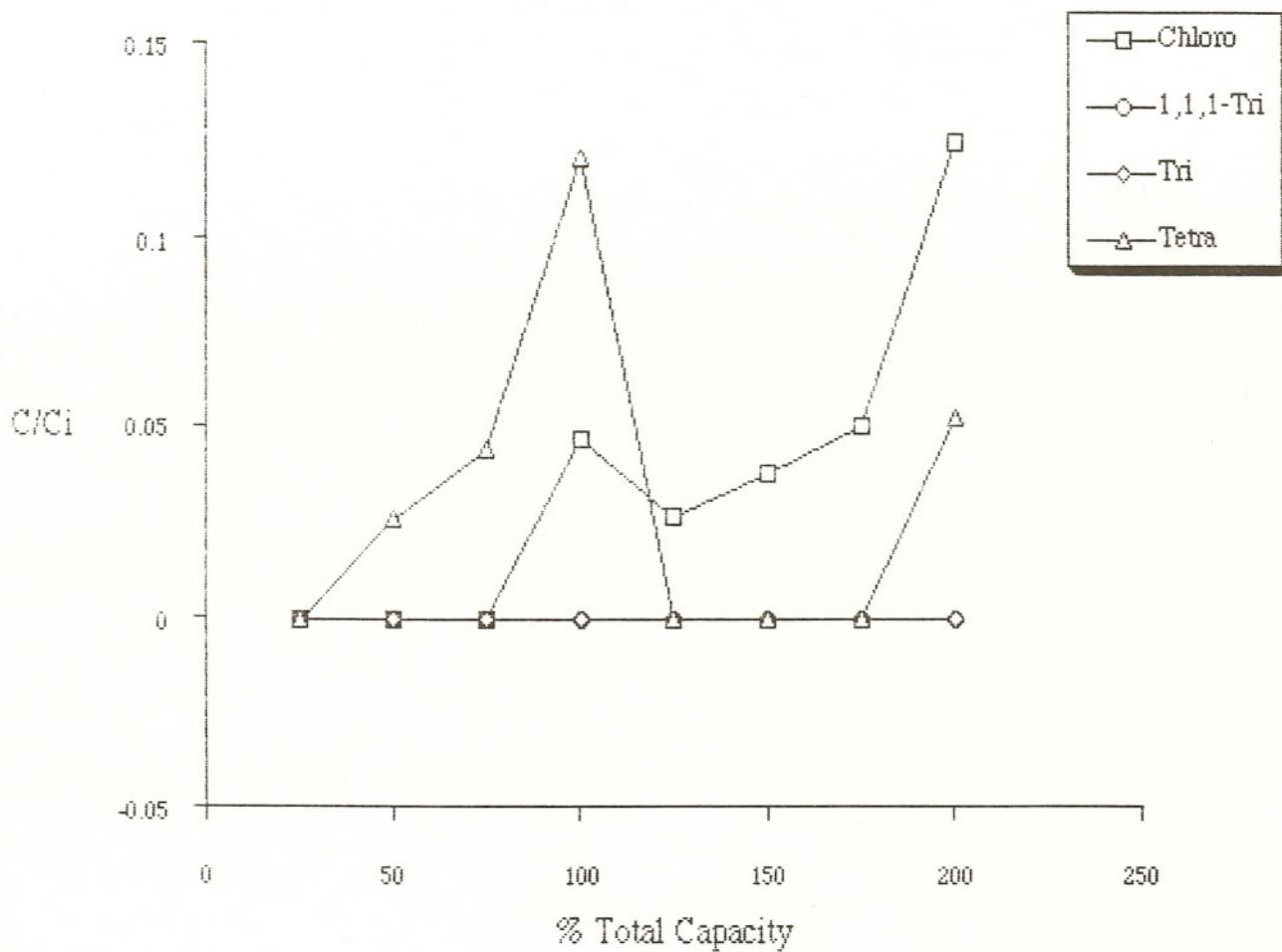
Table 12 (co) Compound Concentrations in Effluent Filter Samples at 1.0 gpm

Compound	Occurrence	Filter Capacity%	Throughput Volume - gal.	Concentration ug/l	C/Ci
<u>A E I</u>					
Chloroform	F	25	250	3.78	0.06
	PT	200	2000	38.49	1.22
1,1,1-Trichloroethane	F	25	250	2.77	0.05
	PT	200	2000	18.44	0.74
Trichloroethylene	F	75	750	0.67	0.02
	PT	200	2000	1.99	0.09
Tetrachloroethylene	F	75	750	1.15	0.03
	PT	200	2000	1.98	0.09
<u>A E I - Duplicate</u>					
Chloroform	F	25	250	2.98	0.02
	PT	200	2000	48.06	0.69
1,1,1-Trichloroethane	F	25	250	1.68	0.02
	PT	200	2000	15.8	0.16
Trichloroethylene	F	200	2000	0.34	0.005
	PT	200	2000	0.34	0.005
Tetrachloroethylene	F	-	-	ND	ND
	PT	200	2000	ND	ND
<u>Pollux</u>					
Chloroform	F	25	600	37.26	0.85
	PT	200	4800	46.06	0.91
1,1,1-Trichloroethane	F	25	600	38.22	0.88
	PT	200	4800	55.25	0.98
Trichloroethylene	F	25	600	37	0.9
	PT	200	4800	45.63	0.98
Tetrachloroethylene	F	25	600	22.88	0.94
	PT	200	4800	43.65	0.99

a : First detectable concentration.
 b : Point of termination of run.
 c : Not detected.

Figure 6. Adsorption Curves for the Culligan Filter.

1.0 gpm Multi-Solute System



three compounds for filter AW before the termination point (Figure 7). This result is a little better than the single-solute system. The breakthrough of chloroform at 125% capacity with 1.61 ug/l at a C/Ci of 0.03 is relatively later than in single-solute system at 15% capacity with 0.3 ug/l at a C/Ci of 0.002. However, it is difficult to compare the termination point for both systems at different capacities, different concentrations and C/Ci values. In Figure 7, the duplicate filter of AW (dark symbols) shows a little decline of removal efficiencies for chloroform and 1,1,1-trichloroethane.

From Table 12 and Figure 8, it is easy to find that the contaminant removals were greatly improved in the duplicate filter (AFT). Chloroform and 1,1,1-trichloroethane at 200% capacity, C/Ci values were significantly reduced from 1.22 to 0.69 and from 0.74 to 0.16, respectively. Also, there was no breakthrough for tetrachloroethene of AFT to 200% capacity. But the improvement was not so evident for trichloroethene of AFT (dark symbols, Figure 8). After the breakthrough of chloroform at 25% capacity, both filters (AFT and AFT-D) reached 0.4 C/Ci value before 200% capacity. Compared to the single-solute system that never reached the 0.4 C/Ci value, it seems that the presence of other compounds inhibited the adsorption of chloroform by filter AFT. The results of single-solute system were between those of multi-solute system for AFT and its duplicate. However, from the past performances of filter AFT, the behavior of AFT-D should be more representative than that of AFT.

In Figure 9, filter P shows an early breakthrough and reached

Figure 7. Adsorption Curves for the Amway Filter

1.0 gpm Multi-Solute System

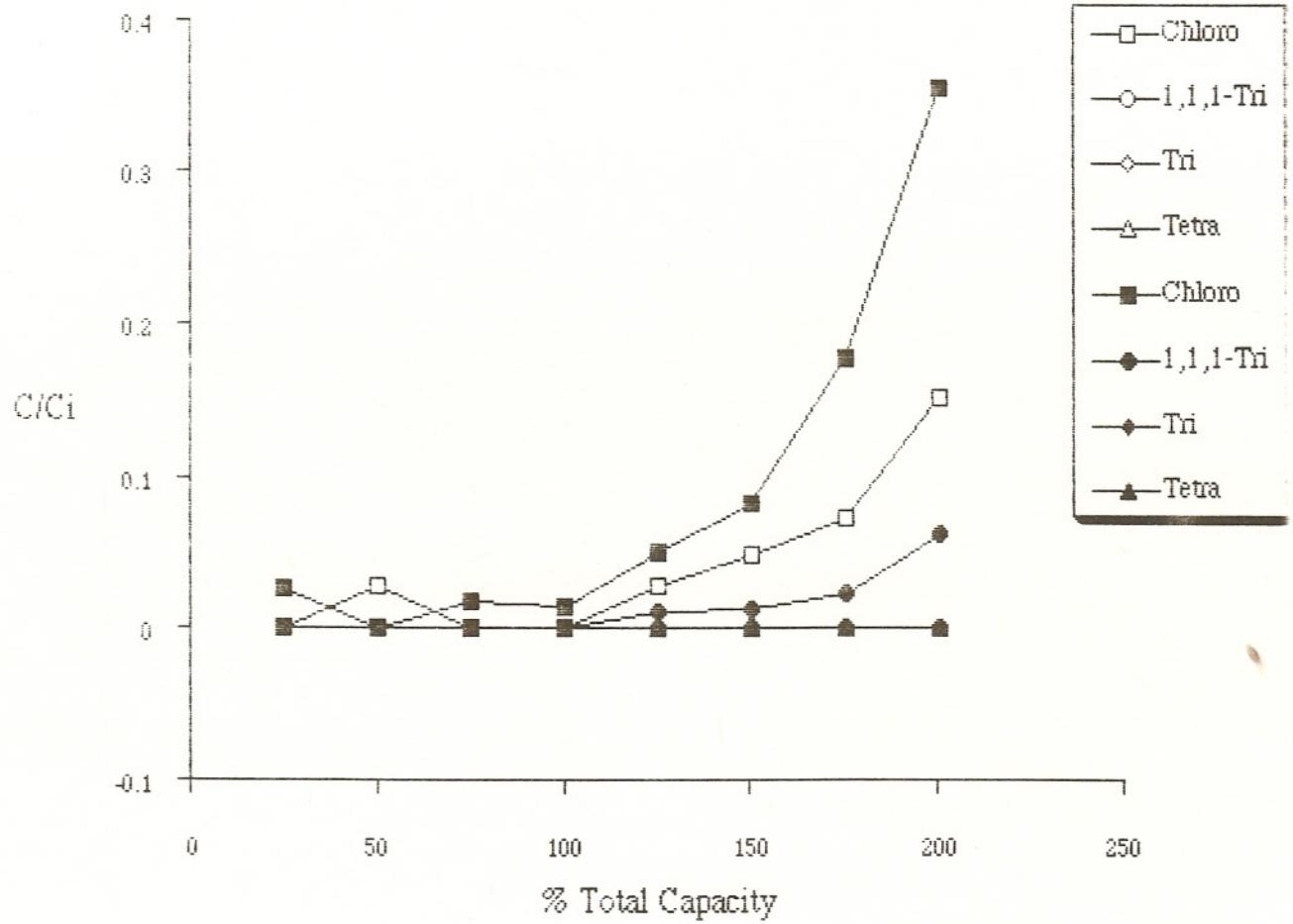


Figure 8. Adsorption Curves for the AFT Filter.

1.0 gpm Multi-Solute System

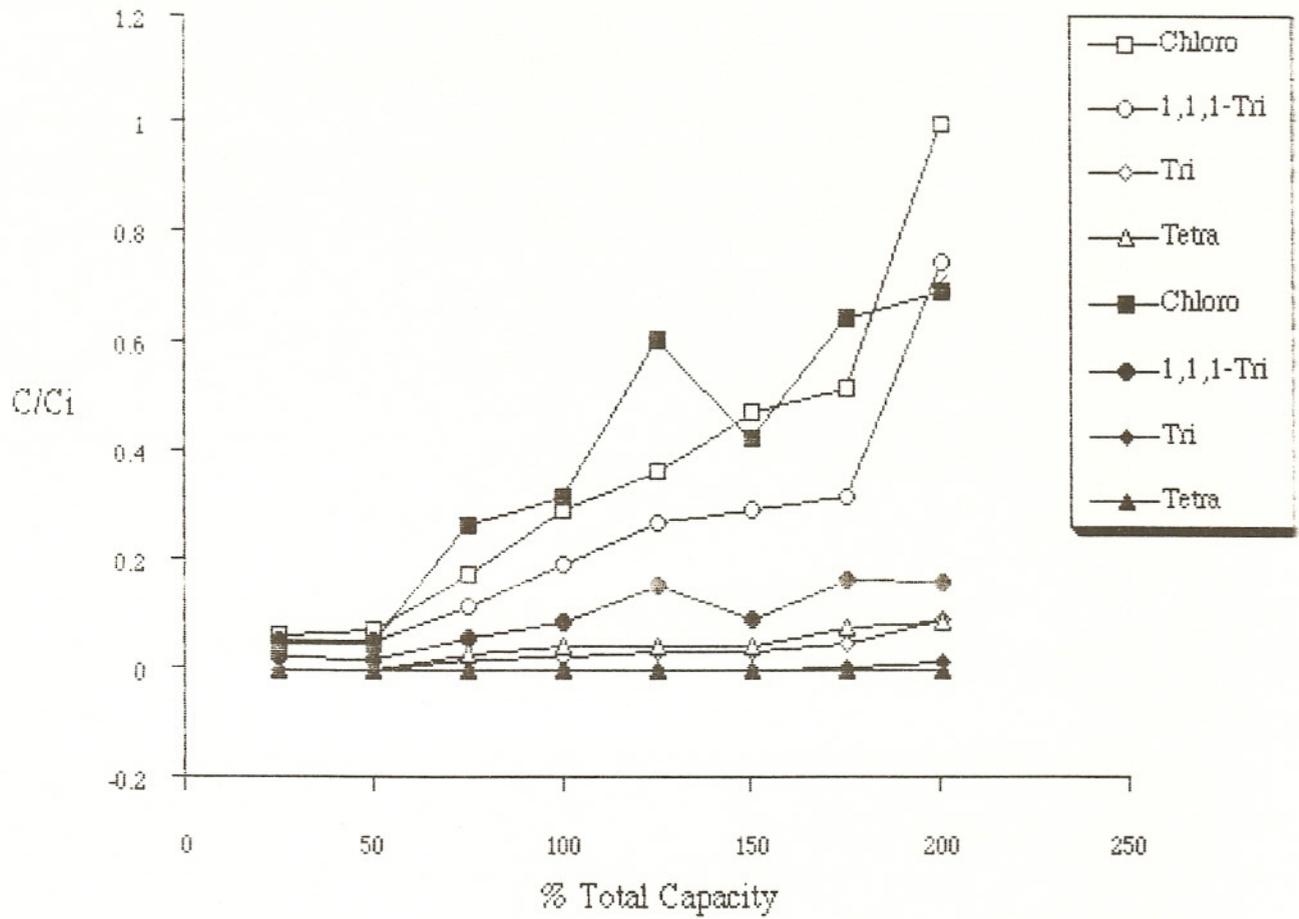
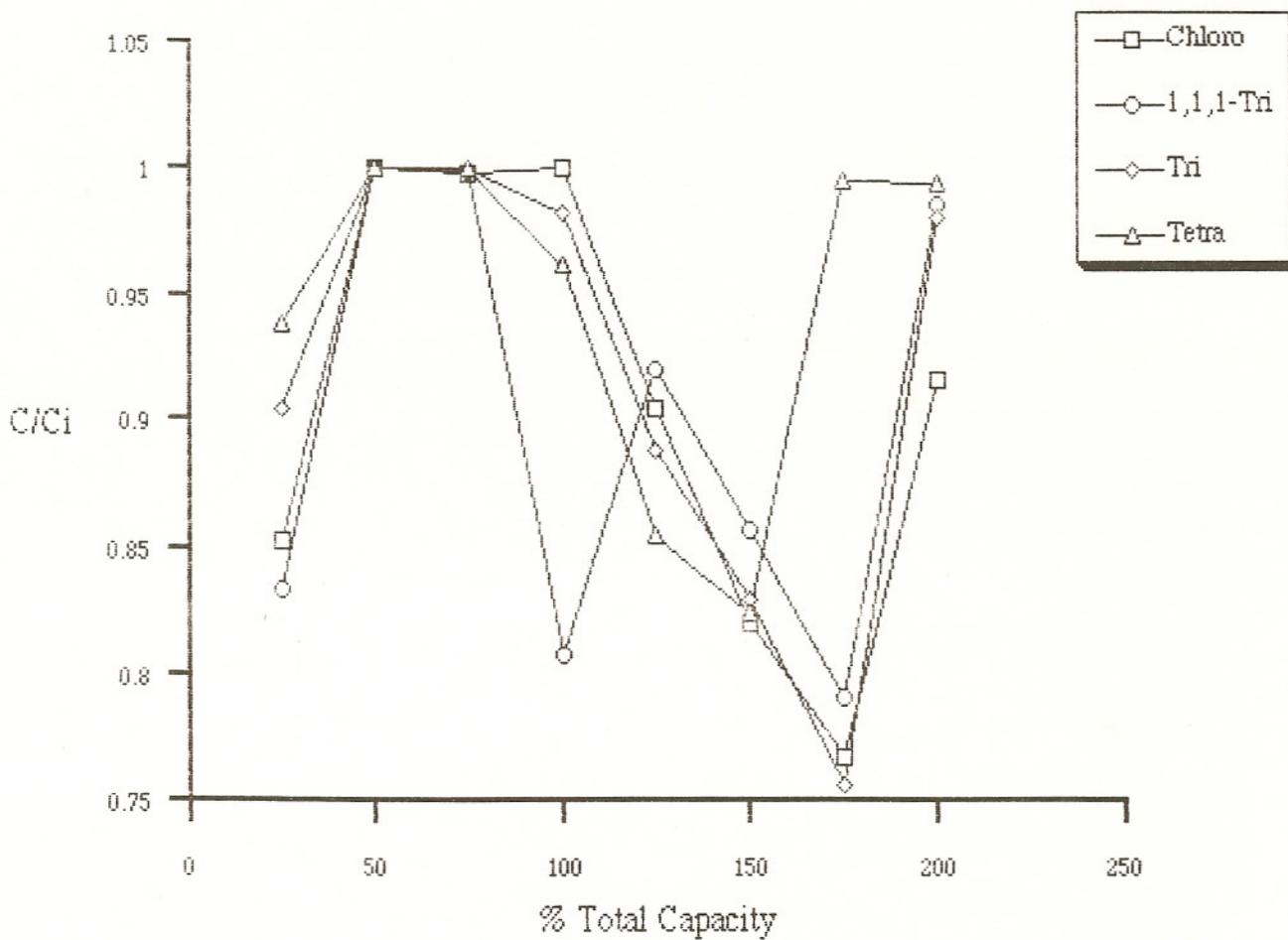


Figure 9. Adsorption Curves for the Pollenex Filter.

1.0gpm Multi-Solute System



the 0.4 C/Ci value both at 25% rated capacity for all four compounds. This result, almost no removal for the four contaminants, is much worse than those from the single-solute system.

b. Tests at 0.5 gpm.

Table 13 give the adsorption data for each volatile organic compound on filters C, AW, AFT, and P. Two sets of data are provided for each filter, the concentration and rated volumetric capacity of the first detectable sample and the concentration at the termination point (200% rated capacity). For each compound, filter performance follows the sequence : C > AW > AFT > P. This sequence is consistent with prior results.

In Figure 10, filter C shows no detectable concentration of 1,1,1-trichloroethane, tetrachloroethene, and trichloroethene throughout the entire runs. Filter C only shows a little breakthrough of chloroform at 25% capacity with a C/Ci of 0.03 (1.71 ug/l) and kept the C/Ci as low as 0.07 (2.94 ug/l) at the termination point. Comparing the results of 0.5 gpm and 1.0 gpm, it seems that more of the contaminants were removed by the filters at the lower flow rate. For example, the C/Ci of chloroform at 200% capacity dropped from 0.13 for 1.0 gpm to 0.07 for 0.5 gpm. No breakthrough of tetrachloroethene was observed before 200% capacity for 0.5 gpm vs. a C/Ci of 0.05 for 1.0 gpm.

For the AW filter, the removal performance of contaminants is also good (Figure 11). Except chloroform, AW filter shows little breakthrough around 175% capacity and with C/Ci values under 0.08 at the termination point for three of the contaminants.

Table 13. Compound Concentrations in Effluent Filter Samples at 0.5 gpm

Compound	Occurrence	Filter Capacity%	Throughput volume - gal.	Concentration ug/l	C/D
<u>Culligan</u>					
Chloroform	F ^a	25	500	1.71	0.030
	PT ^b	200	4000	2.94	0.070
1,1,1-Trichloroethane	F	-	-	ND ^c	ND
	PT	200	4000	ND	ND
Trichloroethylene	F	-	-	ND	ND
	PT	200	4000	ND	ND
Tetrachloroethylene	F	-	-	ND	ND
	PT	200	4000	ND	ND
<u>Culligan - Duplicate</u>					
Chloroform	F	125	2500	1.80	0.040
	PT	200	4000	5.45	0.110
1,1,1-Trichloroethane	F	175	3500	0.58	0.010
	PT	200	4000	0.74	0.010
Trichloroethylene	F	-	-	ND	ND
	PT	200	4000	ND	ND
Tetrachloroethylene	F	-	-	ND	ND
	PT	200	4000	ND	ND

a: First detectable concentration.
 b: Point of termination of run.
 c: Not detected.

Table 13 (con) Compound Concentrations in Effluent Filter Samples at 0.5 gpm

Compound	Occurrence	Filter Capacity%	Throughput Volume - gal.	Concentration ug/l	C/D
<u>Amway</u>					
Chloroform	F	50	750	1.60	0.040
	PT	200	3000	13.38	0.240
1,1,1-Trichloroethane	F	175	2625	1.37	0.030
	PT	200	3000	2.84	0.060
Trichloroethylene	F	200	3000	0.97	0.040
	PT	200	3000	0.97	0.040
Tetrachloroethylene	F	200	3000	1.38	0.060
	PT	200	3000	1.38	0.060
<u>A E I</u>					
Chloroform	F	25	250	1.91	0.030
	PT	200	2000	42.13	0.560
1,1,1-Trichloroethane	F	25	250	0.72	0.020
	PT	200	2000	18.27	0.280
Trichloroethylene	F	100	1000	0.63	0.020
	PT	200	2000	1.01	0.020
Tetrachloroethylene	F	-	-	ND	ND
	PT	200	2000	ND	ND

a : First detectable concentration.
 b : Point of termination of run.
 c : Not detected.

Table 13 (con) Compound Concentrations in Effluent Filter Samples at 0.5 gpm

Compound	Occurrence	Filter Capacity%	Throughput Volume -gal.	Concentration ug/l	C/Ci
<u>Pollenex</u>					
Chloroform	F	25	600	72.9	1.080
	PT	200	4800	59.76	1.020
1,1,1-Trichloroethane	F	25	600	62.17	0.970
	PT	200	4800	50.21	1.040
Trichloroethylene	F	25	600	51.32	1.060
	PT	200	4800	41.26	1.040
Tetrachloroethylene	F	25	600	48.54	1.040
	PT	200	4800	42.85	1.020
<u>Pollenex #1</u>					
Chloroform	F	25	600	13.33	0.300
	PT	200	4800	52.75	0.850
1,1,1-Trichloroethane	F	25	600	3.32	0.060
	PT	200	4800	53.47	0.850
Trichloroethylene	F	75	1800	0.67	0.010
	PT	200	4800	8.99	0.130
Tetrachloroethylene	F	150	3600	0.64	0.009
	PT	200	4800	1.25	0.020
<u>Pollenex #2</u>					
Chloroform	F	25	600	15.47	0.300
	PT	200	4800	59.28	1.040
1,1,1-Trichloroethane	F	25	600	6.69	0.010
	PT	200	4800	82.91	1.160
Trichloroethylene	F	50	1200	0.25	0.004
	PT	200	4800	14.78	0.220
Tetrachloroethylene	F	125	3000	0.99	0.020
	PT	200	4800	1.63	0.030

a: First detectable concentration.
 b: Point of termination of run.
 c: Not detected.

Figure 10. Adsorption Curves for the Culligan Filters.

0.5 gpm Multi-Solute System

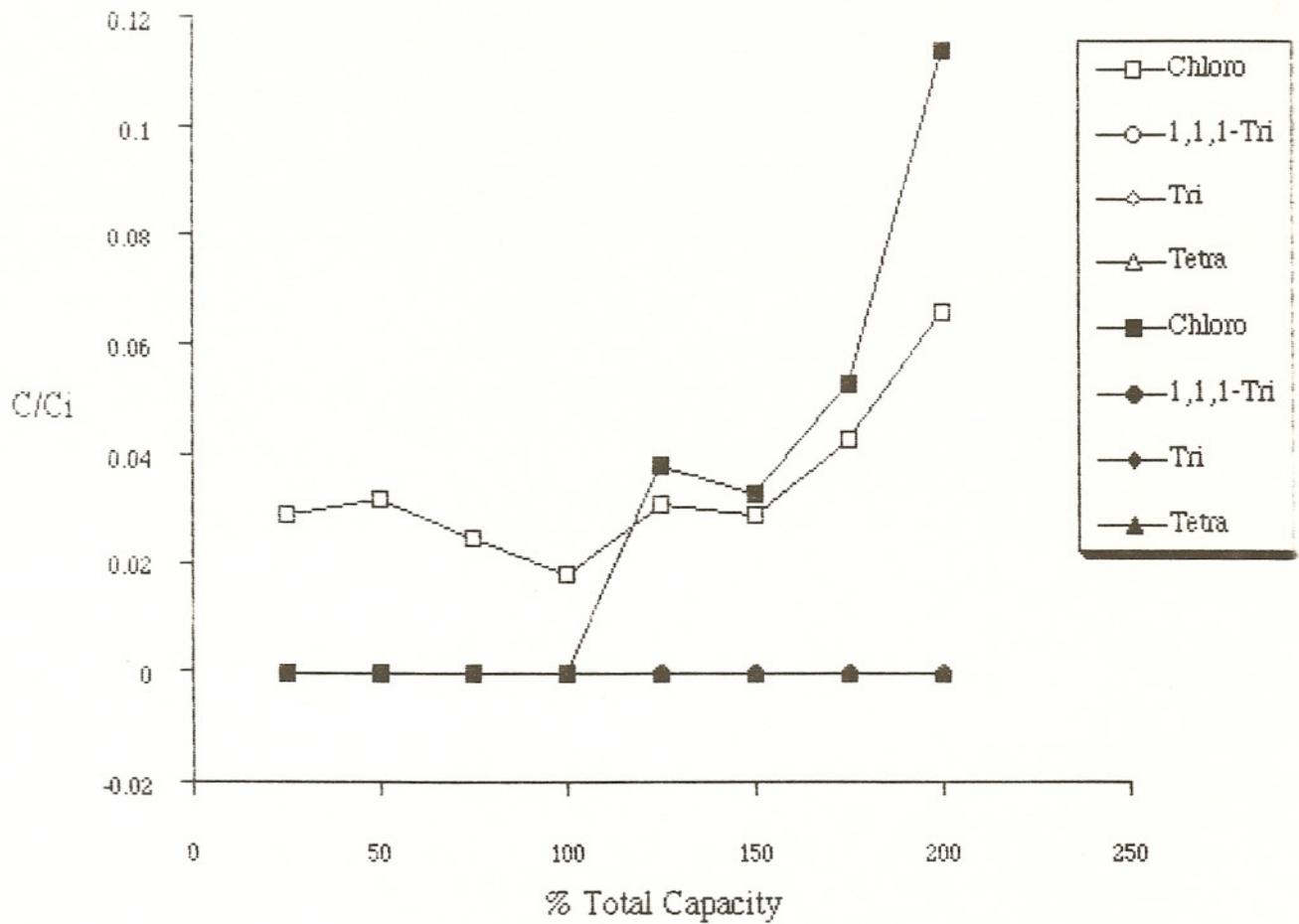
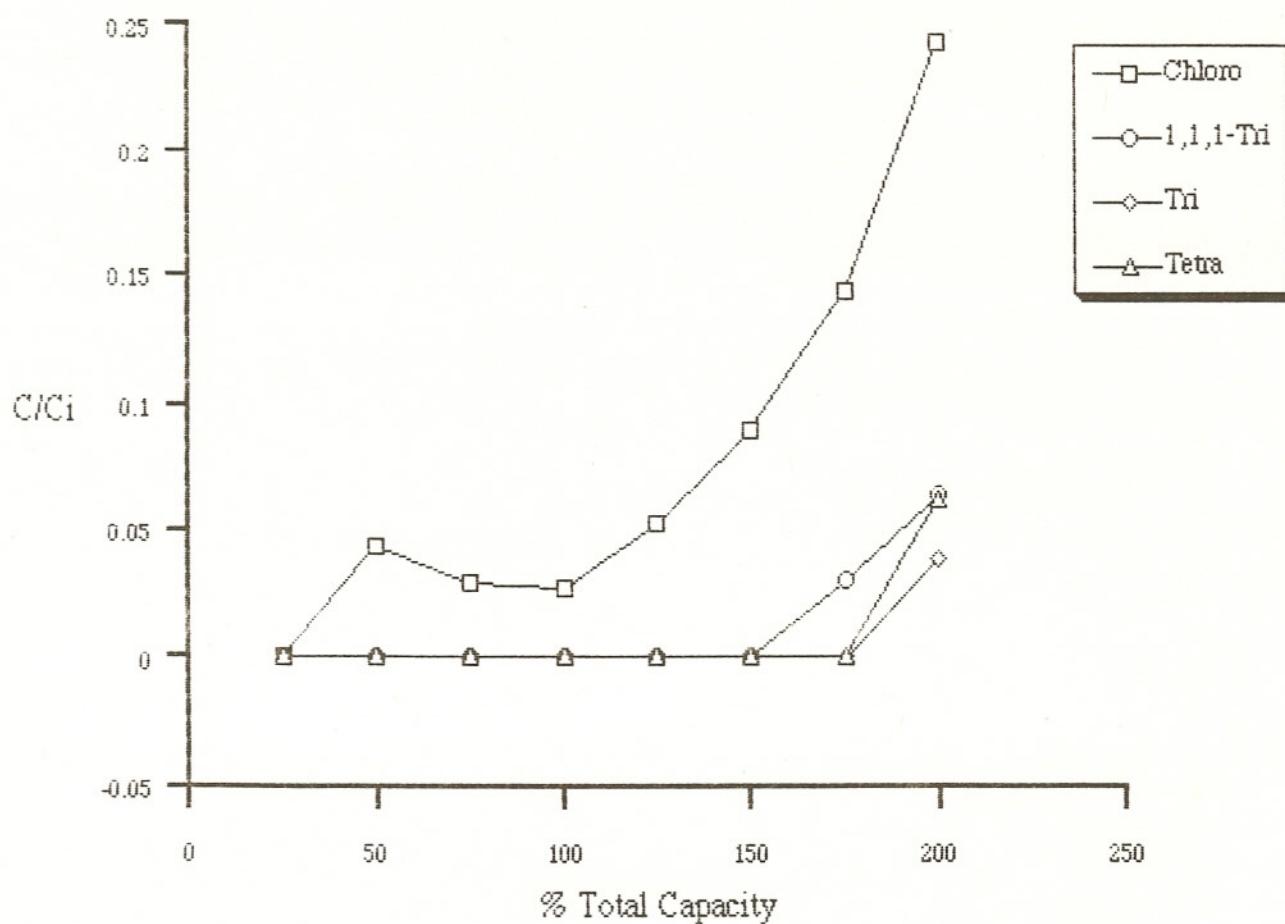


Figure 11 Adsorption Curves for the Amway Filter.

0.5 gpm Multi-Solute System



Chloroform was released from AW into the effluent at 50% capacity with a C/Ci of 0.04 but no higher than 0.25 at 200% capacity. There was no significant improvement for filter AW at the lower rate flow.

For the AFT filter, the removal performance of the four compounds follows the order: tetrachloroethane > trichloroethene > 1,1,1-trichloroethane > chloroform (Figure 12). Filter AFT shows a breakthrough of chloroform at the first effluent sample with C/Ci of 0.03 (1.91 ug/l). It reached a 0.55 C/Ci value at 200% of capacity. There is no breakthrough of tetrachloroethene for filter AFT up to 200% of rated capacity. Filter AFT shows breakthroughs for trichloroethene and 1,1,1-trichloroethane with a C/Ci of 0.02 (below 1 ug/l) at 100% and 25% rated capacity, respectively. However, trichloroethene is constantly removed from the influent by AFT to 200% of rated capacity at a C/Ci of 0.02 (1.01 ug/l). But the concentration of 1,1,1-trichloroethane was increased from 0.72 ug/l to 18.27 ug/l (C/Ci from 0.02 to 0.28) at 200% of capacity. Referring this result to the 1.0 gpm test, the lower flow rate of 0.5 GPM seems to facilitate the removal of contaminants from water by the AFT filter. This observation is revealed by the C/Ci values of the four compounds at 200% rated capacity. They are equal or lower than those from the 1.0 gpm test.

The performances of filter P are quite different in Table 13 and Figures 13 to 17. A distinct difference of effluent concentrations for all four compounds was found first between filter P and its duplicate P*1 (Figures 13 and 14). Another duplicate filter, P*2 was run (Figure 15). In Figure 16, it is

Figure 12. Adsorption Curves for the AFT Filter.

0.5 gpm Multi-Solute System

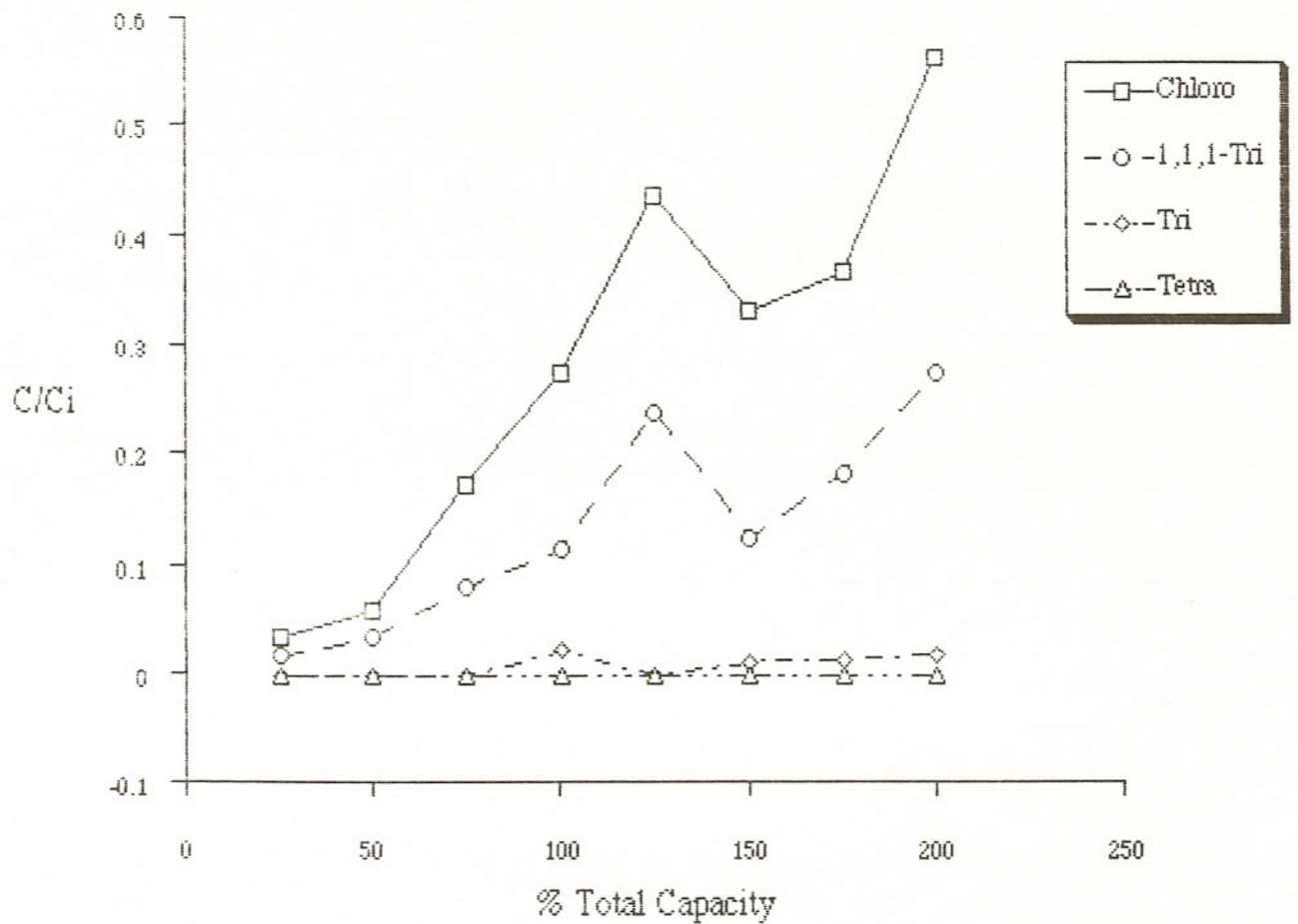


Figure 13. Adsorption Curves for the Pollenex Filter.

0.5 gpm Multi-Solute System

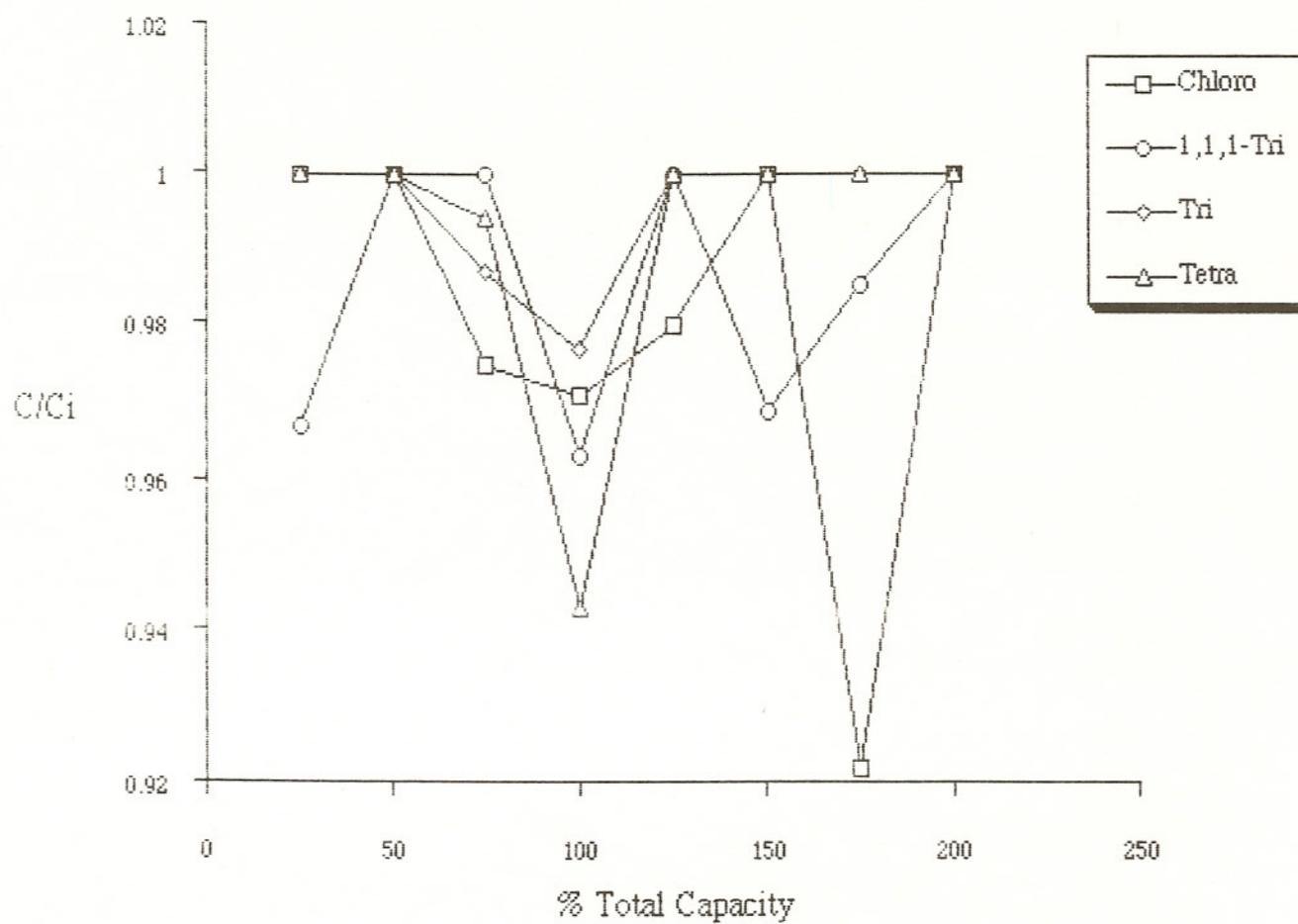


Figure 14. Adsorption Curves for the Pollenex Filter Duplicate 1.

0.5 gpm Multi-Solute System

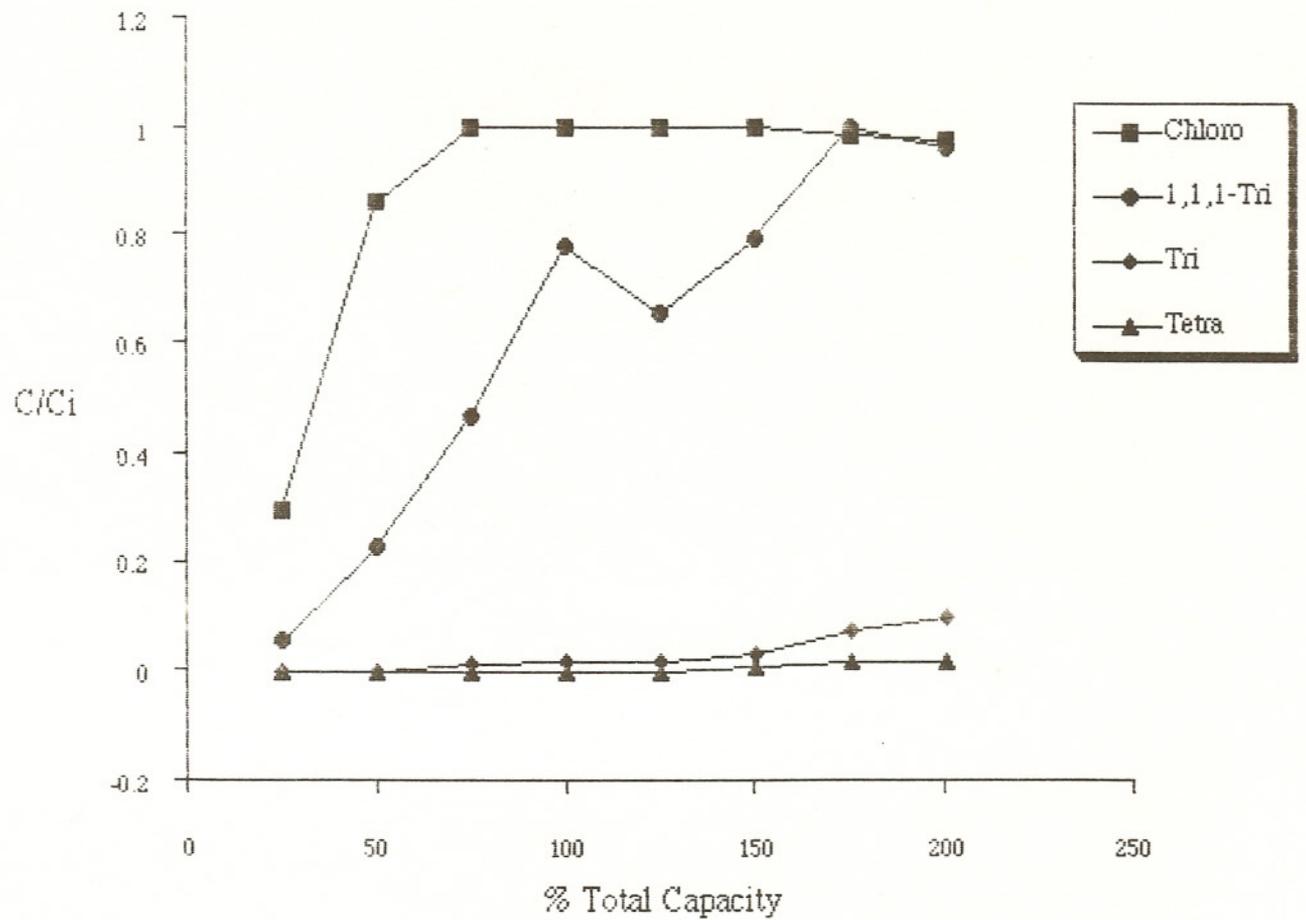


Figure 15 Adsorption Curves for the Pollenex Filter Duplicate 2.

0.5gpm Multi-Solute System

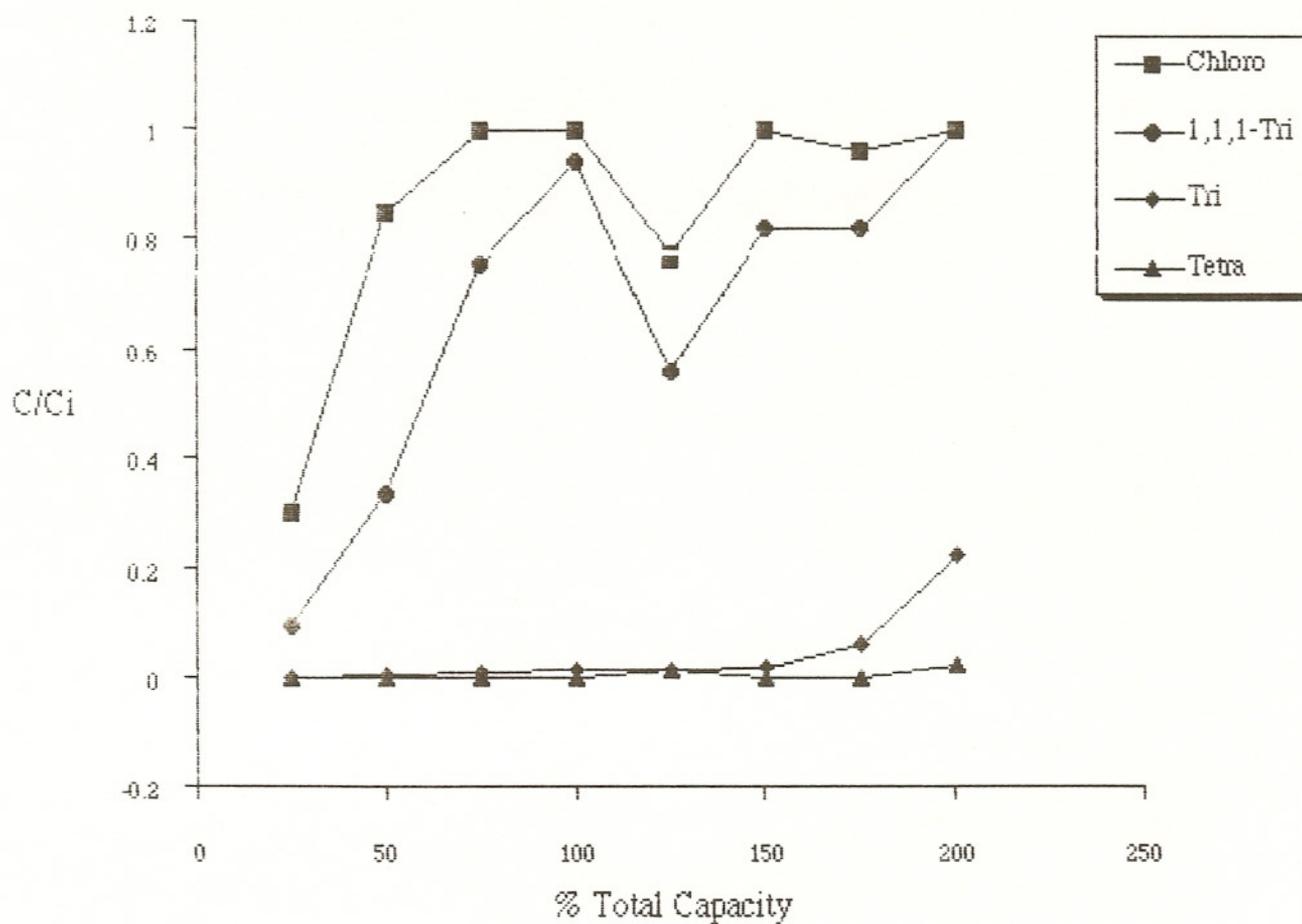


Figure 16. Adsorption Curves for the Pollenex Filters Duplicate 1 & 2.

0.5 gpm Multi-Solute System

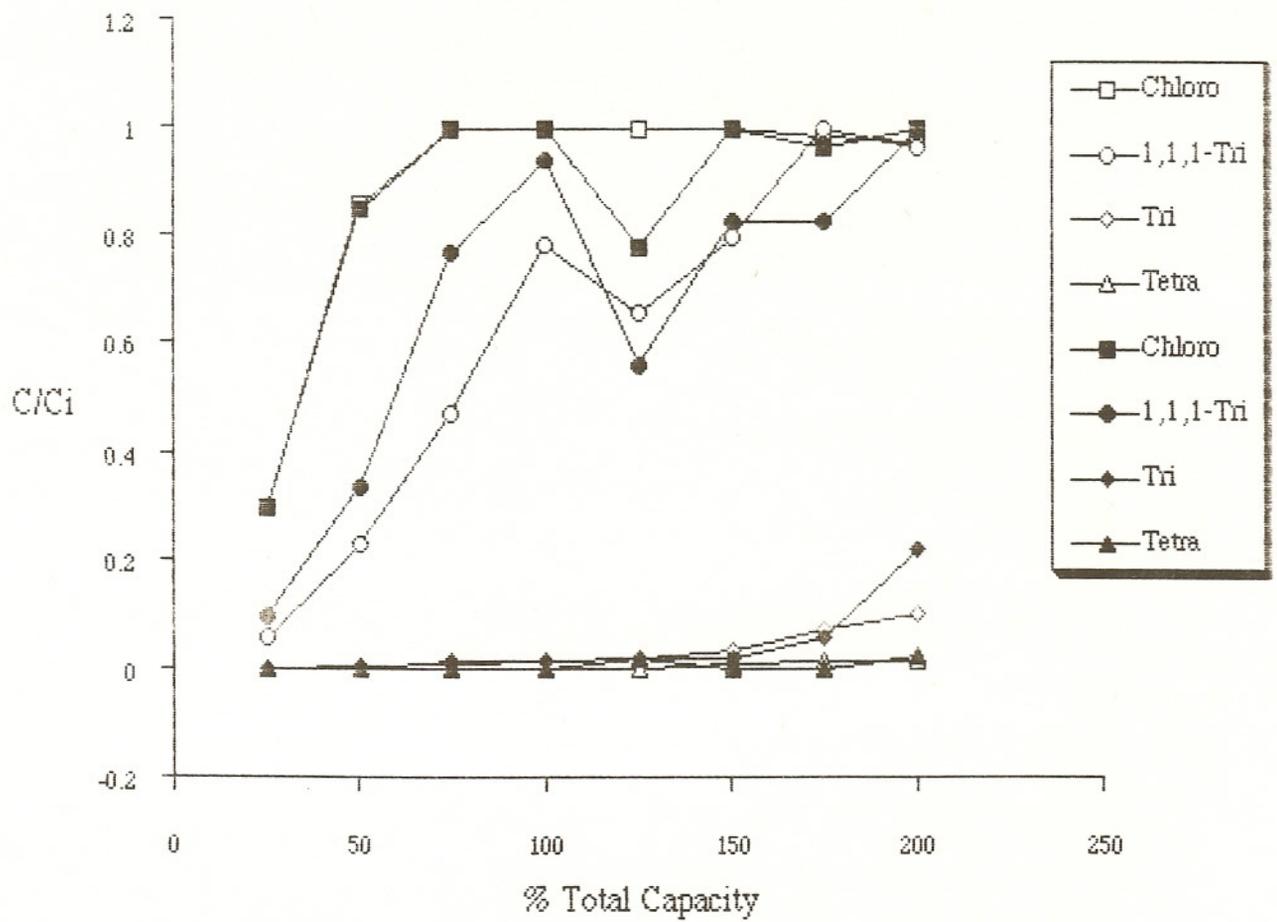
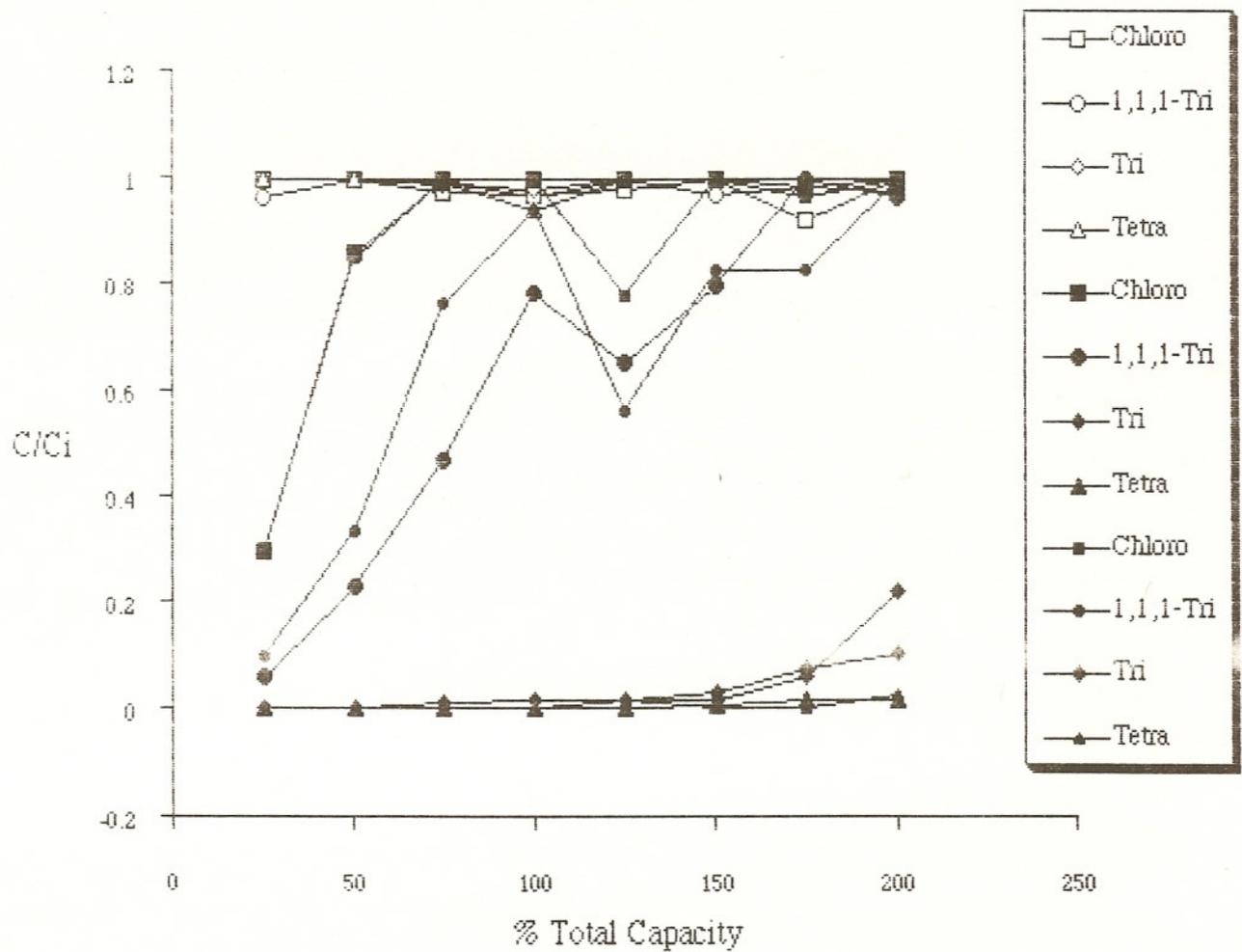


Figure 17 Adsorption Curves for the Pollenex Filters.

0.5 gpm Multi-Solute System - Summary.



obvious that the performances of filter P can be divided into two groups : one with normally poor removals (P) and the other with improved removals (P*1 and P*2).

In Figure 13, the removal of four contaminants are close to zero for P. Because the concentrations of the compounds in the effluents were close to the influents for filter P, the C/Ci values fluctuated up and down around 1.0. However, the removal of the four compounds for P*1 and P*2 were somewhat higher (Figures 14, 15, and 16). For chloroform (the least adsorbed compound) runs P*1 and P*2 showed a breakthrough at 25% of capacity (same as P) but with a C/Ci around 0.3 (lower than 1.08 for P). For 1,1,1-trichloroethane, runs P*1 and P*2 showed moderate removals at a breakthrough of 25% of capacity with a C/Ci below 0.1 (0.97 for P). Runs P*1 and P*2 showed an excellent removal for tetrachloroethene at a breakthrough around 125% capacity (25% for P) with a C/Ci below 0.02 (1.04 for P) and with a C/Ci below 0.03 at 200% of capacity. The removal efficiencies of P*1 and P*2 for trichloroethene are a little lower than those of tetrachloroethene. These filters exhibited breakthrough around 50% (25% for P) with a C/Ci below 0.010 (1.06 for P) and with a C/Ci below 0.3 at the termination point. It is unclear why filter P and its duplicates acted so differently.

It is difficult to decide how to compare the results from the 0.5 gpm test with those from the 1.0 gpm test. There is no major difference between filter P from 0.5 gpm and 1.0 gpm. They both did not perform well for all four contaminants. Filters P*1 and P*2 performed much better than P at 0.5 gpm and 1.0 gpm for all

four compounds.

2. Desorption Study

After completion of the adsorption tests at 1.0 GPM with the multisolute system for each filter, the 1200 gallon reservoir tank was washed and cleaned by reagent water several times to remove any residual contaminants. Upon refilling the tank, the unspiked reagent water was passed through each filter from the previous adsorption run to 200% capacity (termination point). In Table 14, the accumulated desorbed mass (mg) at PT of each compound is given for each filter. These quantities were also expressed as percentage of the total mass adsorbed.

It seems that only chloroform was desorbed from all four filters. The percentage of desorption ranged from the highest, 49% for AW to the lowest 11.4% for C. Filters AFT and P showed moderate desorption of chloroform at 25.3% and 20.9%, respectively. Only filter P showed no desorption of 1,1,1-trichloroethane. The percentage of desorption for 1,1,1-trichloroethane is 16.36% for AFT, 9.2% for AW, and 1.8% for C, respectively. There was no detectable desorption of tetrachloroethene and trichloroethene for filters C, AW, and P but there was little desorption (below 3%) for filter AFT.

In Table 14, filter P showed little or no desorption of adsorbed compounds. In as much as filter P adsorbed small quantities of the four compounds initially there was little mass to be desorbed. Filter C showed excellent resistance against desorption of these four compounds. Filter AW might work nicely with conditions of low chloroform and high concentrations of 1,1,1-

Table 14. Total Amounts Desorbed at Point of Termination
200% Filter Rated Capacity at 1.0 GPM.

Filter	<u>Chloroform</u>		<u>1,1,1-Trichloroethane</u>		<u>Trichloroethene</u>		<u>Tetrachloroethene</u>	
	Amt.-mg	% ^a	Amt.-mg	%	Amt.-mg	%	Amt.-mg	%
Culligan	82.0	11.4	14.0	1.8	Nil	-	Nil	-
Amway	272.6	46.0	50.0	9.2	Nil	-	Nil	-
AFT	67.0	22.2	45.1	16.4	7.0	2.5	1.6	0.6
Pollenex	19.4	20.9	Nil	-	Nil	-	Nil	-

a: Percent of total mass adsorbed from Table 12.

trichloroethane, tetrachloroethene, and trichloroethene. Filter AFT could be used under normal operating conditions with moderate desorption. Filter P might be not the proper choice under any conditions.

3. Effect of pH Study

Two systems, pH 5 and pH 9, were used in this research to study the effect of $[H^+]$. Because the normal pH value of tap water ranges from pH 5 to pH 9, it could be said there were three pH systems actually.

a. Tests at pH 5.

In Table 15, the adsorption data for each volatile organic compound (VOC) at a pH value of 5 on filters, C, AW, AFT and P are given. Two sets of data are provided for each filter, the concentration and rated volumetric capacity at the first detectable quantity and the concentration of 200% of rated capacity (termination point). Whenever there was no detectable breakthrough of a given compound at F or PT, the results was reported as ND (not detected). For each compound, filter performance follows the sequence : AW/ C > AFT > P.

The removal efficiencies of chloroform were dramatically decreased, especially for filters AW and C, at pH 5. In Figure 18 filter C exhibited breakthrough of chloroform at 50% of capacity with a C/Ci of 0.03 (1.75 ug/l) and reached 0.4 C/Ci at 150% of capacity. This change is quite significant because filter C never reached 0.4 C/Ci for chloroform before 200% of capacity in previous adsorption runs. Filter C showed a moderate breakthrough of 1,1,1-trichloroethane at 125% capacity with a C/Ci of 0.023 (1.67 ug/l).

Table 15. Compound Concentrations in Effluent Filter Samples at 1.0 gpm, pH5.0

Compound	Occurrence	Filter Capacity %	Throughput Volume - gal.	Concentration ug/l	C/Ci
<u>Culligan</u>					
Chloroform	F a	50	1000	1.75	0.030
	PT b	200	4000	74.46	1.100
1,1,1-Trichloroethane	F	125	2500	1.67	0.023
	PT	200	4000	8.44	0.108
Trichloroethylene	F	--	--	ND c	ND
	PT	200	4000	ND	ND
Tetrachloroethylene	F	--	--	ND	ND
	PT	200	4000	ND	ND
<u>Amway</u>					
Chloroform	F	75	1125	1.10	0.020
	PT	200	3000	45.95	0.875
1,1,1-Trichloroethane	F	150	2250	1.81	0.023
	PT	200	3000	4.99	0.092
Trichloroethylene	F	--	--	ND	ND
	PT	200	4000	ND	ND
Tetrachloroethylene	F	--	--	ND	ND
	PT	200	4000	ND	ND

a : First detectable concentration.

b : Point of termination of run.

c : Not detected.

Table 15 (con) Compound Concentrations in Effluent Filter Samples at 1.0 gpm, pH 5.0

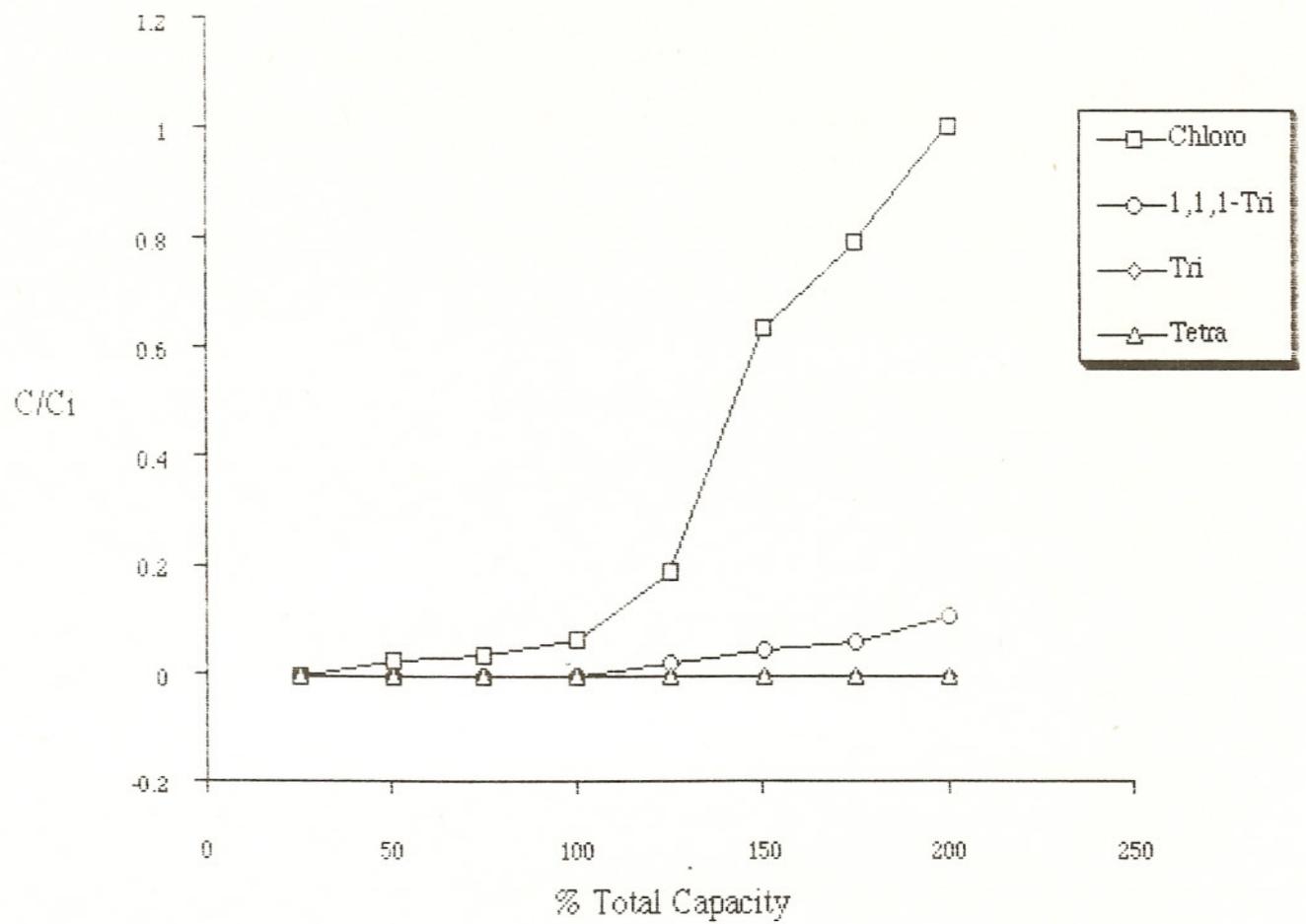
Compound	Occurrence	Filter Capacity %	Throughput Volume - gal.	Concentration ug/l	C/Ci
<u>AFT</u>					
Chloroform	F a	25	250	3.50	0.067
	PT b	200	2000	66.81	0.967
1,1,1-Trichloroethane	F	25	250	3.05	0.055
	PT	200	2000	24.07	0.321
Trichloroethylene	F	25	250	1.23	0.020
	PT	200	2000	4.60	0.075
Tetrachloroethylene	F	75	750	0.77	0.024
	PT	200	2000	5.29	0.069
<u>Pollenex</u>					
Chloroform	F	25	600	57.83	0.959
	PT	200	4800	50.18	0.822
1,1,1-Trichloroethane	F	25	600	54.05	0.897
	PT	200	4800	62.40	0.974
Trichloroethylene	F	25	600	50.51	0.967
	PT	200	4800	51.89	0.896
Tetrachloroethylene	F	25	600	36.01	0.981
	PT	200	4800	52.36	0.929

a : First detectable concentration.

b : Point of termination of run.

Figure 18. Adsorption Curves for the Culligan Filter.

1.0 gpm, pH5 Multi-Solute System



But the concentrations of 1,1,1-trichloroethane were never higher than 10 ug/l or a C/Ci higher than 0.15 toward the termination point. There were no detectable concentrations of trichloroethene and tetrachloroethene for filter C during this test run. Generally speaking the lower pH of 5.0 seems to hinder the adsorption of chloroform and 1,1,1-trichloroethane but promotes the adsorption of tetrachloroethene when compared with the results from 1.0 gpm runs (pH > 5).

Filter AW showed a breakthrough of chloroform at 75% of capacity with a C/Ci of 0.02 (1.10 ug/l). At 150% of capacity, the relative concentration (C/Ci value) of chloroform was significantly increased from 0.169 (10.85 ug/l) to 0.875 (45.95 ug/l) for the 200% capacity at the termination point (Figure 19). There was a little breakthrough of 1,1,1-trichloroethane for AW at 150% of capacity with a C/Ci of 0.023 (1.81 ug/l) and with a C/Ci of 0.092 (4.99 ug/l) at 200% of capacity. Filter AW did not show any detectable concentration of trichloroethene or tetrachloroethene during the entire run. Some effects of $[H^+]$ can be found with the results of filter AW. When the pH value was lowered to 5.0, the adsorption of chloroform and 1,1,1-trichloroethane were also decreased when compared to the 1.0 gpm results at nearly neutral conditions.

In Figure 20, for filter AFT, it seems that the lower pH value depressed the adsorption of chloroform and 1,1,1-trichloroethane. This effect is seen at the termination point with higher C/Ci values than the 1.0 gpm test as 0.967 (66.82 ug/l) to 0.69 (48.06 ug/l) for chloroform and 0.321 (24.07 ug/l) to 0.16 (15.80 ug/l)

Figure 9. Adsorption Curves for the AW Filter.

1.0 gpm, pH5 Multi-Solute System

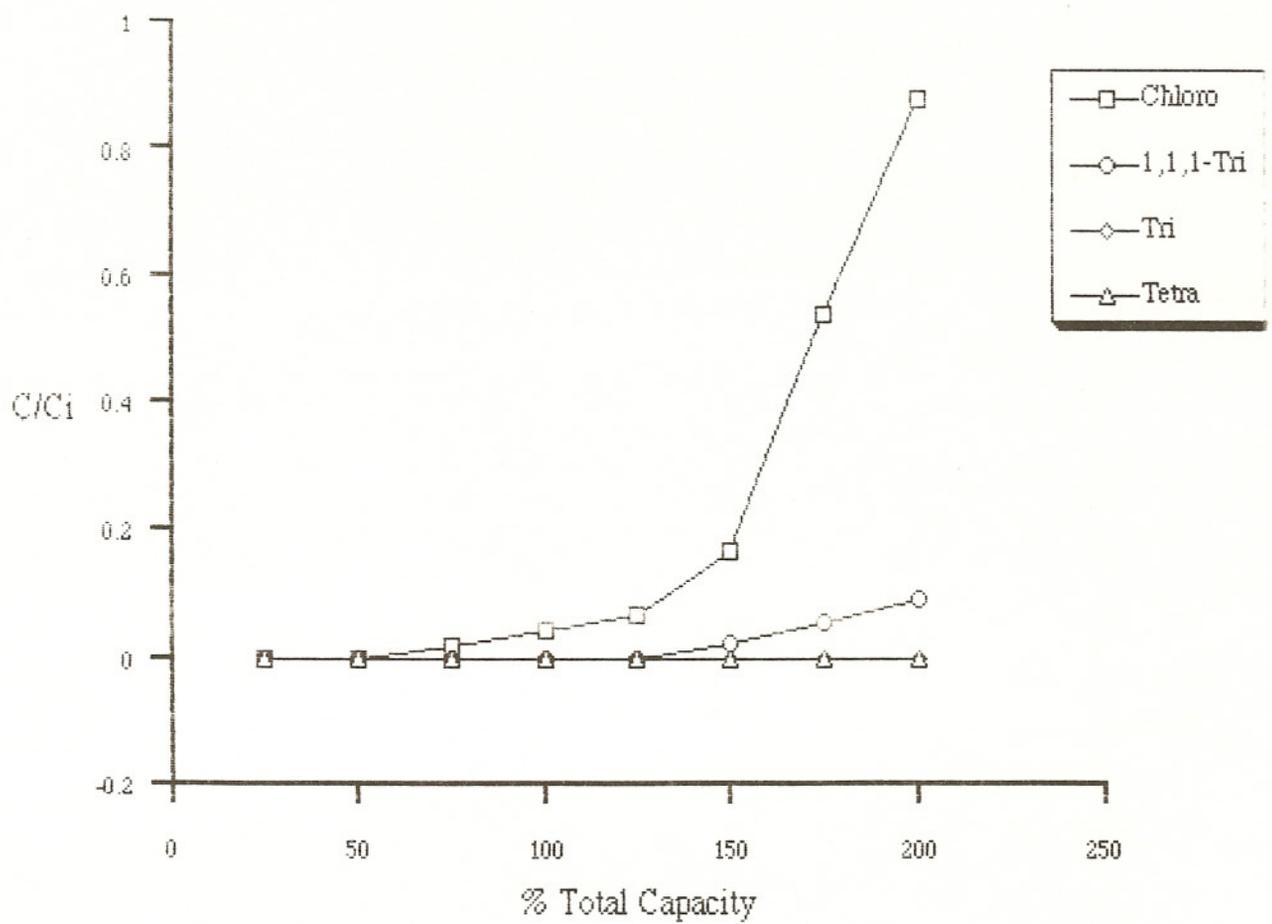
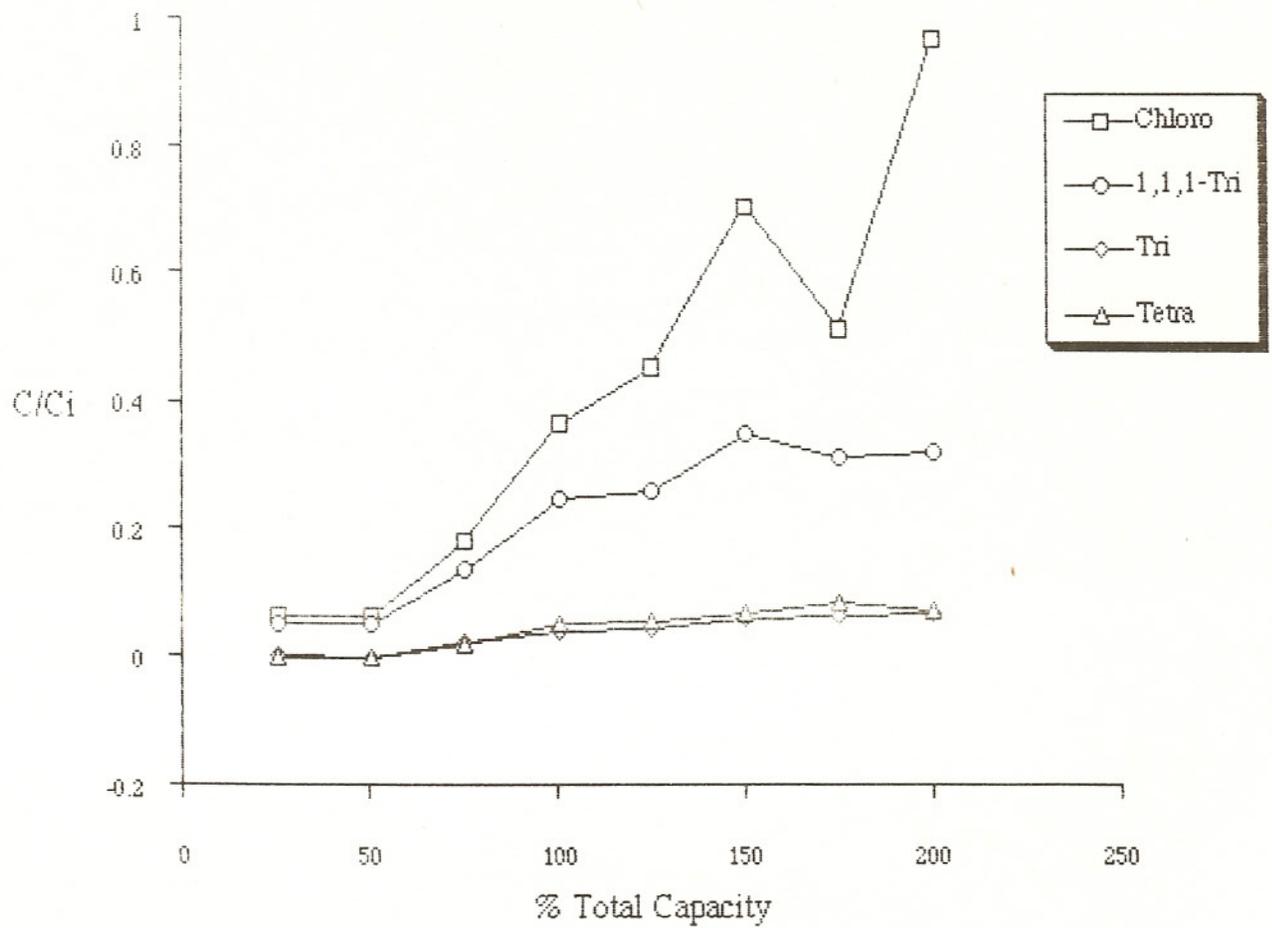


Figure 20. Adsorption Curves for the AFT Filter.

1.0 gpm, pH5 Multi-Solute System



for 1,1,1-trichloroethane. There were no notable effect of pH 5.0 for the other two compounds, trichloroethene and tetrachloroethene.

Same as before, the performance of filter P was poor for contaminant removal. All four compounds were not adsorbed on the filter and reached a concentration similar to the influent at an early stage (Figure 21).

b. Tests at pH 9.

In Table 16, the adsorption data for each volatile organic compound (VOC) on filters, C, AW, AFT, and P at a pH value of 9 are given. Two sets of data are provided for each filter, the concentration and rated volumetric capacity of the first detectable quantity and the concentration at the termination point (200% of rated capacity). In the pH 9.0 system, the removal efficiencies for the four compounds were significantly improved on filters AW, C, and AFT. There was no significant change for filter P as usual.

For each compound, filter performance follows the sequence : AW / C > AFT > P.

There was a considerable reduction of chloroform concentration in the effluents at pH 9 for filter AW (comparing Figure 22 with 19). Filter AW showed a chloroform breakthrough at 75% of capacity with a C/Ci of 0.048 (1.77 ug/l) but with a C/Ci of 0.20 (15.44 ug/l) at 200% of capacity. This result with chloroform is similar to 1.0 gpm (neutral conditions) but much better than at pH 5 where the C/Ci) values were 0.20 (1.10 ug/l) at 75% capacity and .875 (46. ug/l) at the termination point, respectively. Also, the result of 1,1,1-trichloroethane is similar or a little better than at pH5 with a longer period before breakthrough (175% to 150%

Figure 21. Adsorption Curves for the Pollenex Filter.

1.0 gpm. pH5 Multi-Solute System

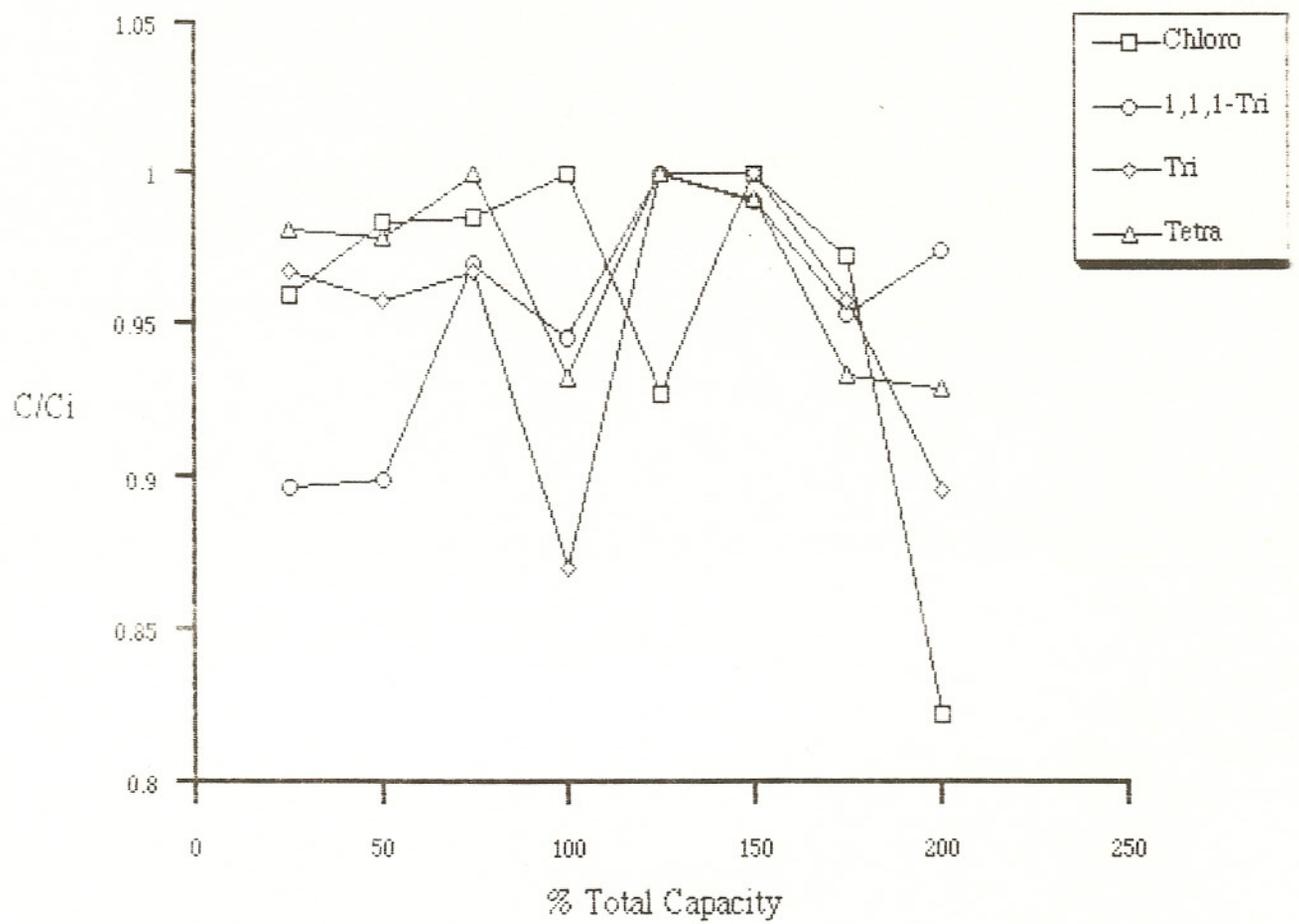


Table 16. Compound Concentrations in Effluent Filter Samples at 1.0 gpm, pH 9.0

Compound	Occurrence	Filter Capacity %	Throughput volume - gal.	Concentration ug/l	C/OI
<u>Culligan</u>					
Chloroform	F ^a	75	1500	1.67	0.024
	FT ^b	200	4000	32.78	0.451
1,1,1-Trichloroethane	F	150	3000	1.53	0.044
	FT	200	4000	2.37	0.050
Trichloroethylene	F	--	--	ND ^c	ND
	FT	200	4000	ND	ND
Tetrachloroethylene	F	--	--	ND	ND
	FT	200	4000	ND	ND
<u>Amway</u>					
Chloroform	F	75	1125	1.77	0.048
	FT	200	3000	15.44	0.200
1,1,1-Trichloroethane	F	175	2625	1.75	0.043
	FT	200	3000	2.60	0.082
Trichloroethylene	F	--	--	ND	ND
	FT	200	3000	ND	ND
Tetrachloroethylene	F	--	--	ND	ND
	FT	200	3000	ND	ND

a: First detectable concentration.
 b: Point of termination of run.
 c: Not detected.

Table 16 (con). Compound Concentrations in Effluent Filter Samples at 1.0 gpm, pH 9.0

Compound	Occurrence	Filter Capacity %	Throughput volume - gal.	Concentration ug/l	C/Ci
<u>AFT</u>					
Dichloroform	F ^a	25	250	2.25	0.040
	FT ^b	200	2000	46.19	0.636
1,1,1-Trichloroethane	F	25	250	1.70	0.047
	FT	200	2000	10.67	0.245
Trichloroethylene	F	175	1750	0.65	0.026
	FT	200	2000	0.69	0.024
Tetrachloroethylene	F	--	--	ND ^c	ND
	FT	200	4000	ND	ND
<u>Pollenex</u>					
Dichloroform	F	25	600	50.67	0.918
	FT	200	4800	65.31	0.845
1,1,1-Trichloroethane	F	25	600	69.54	0.994
	FT	200	4800	37.23	0.843
Trichloroethylene	F	25	600	47.39	0.928
	FT	200	4800	23.36	0.871
Tetrachloroethylene	F	25	600	44.51	0.935
	FT	200	4800	29.39	0.870

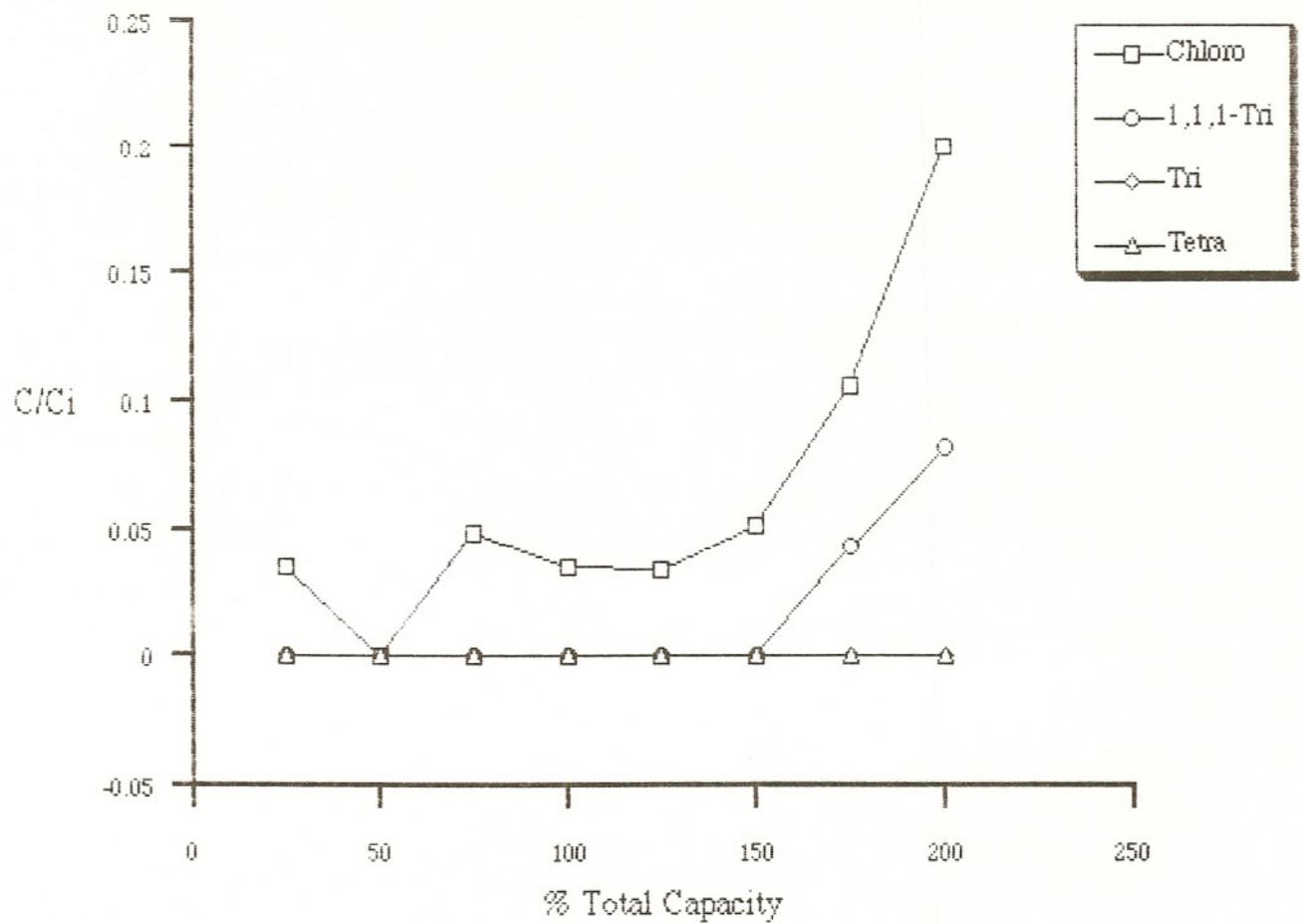
a: First detectable concentration.

b: Point of termination of run.

c: Not detected.

Figure 22. Adsorption Curves for the Amway Filter.

1.0 gpm, pH9 Multi-Solute System



capacity) and a lower C/Ci value (0.082 to 0.092) at the termination point. Similar to the pH 5 and 1.0 gpm (neutral) results there was no breakthrough for trichloroethene and tetrachloroethene.

There was a great improvement of removal efficiencies of chloroform and 1,1,1-trichloroethene of filter C as the pH value was increased from 5 to 9 (as comparing Figures 18 and 23). Filter C shows a breakthrough of chloroform at 75% of the rated capacity with a C/Ci of 0.024 (1.69 ug/l). The breakthrough of 1,1,1-trichloroethane occurred at 150% of rated capacity with a C/Ci of 0.044 (1.53 ug/l). The C/Ci values at 200% of capacity are 0.451 (32.78 ug/l) for chloroform and 0.050 (2.39 ug/l) for 1,1,1-trichloroethane, respectively. These values are less than half of those at pH 5. Similar to the pH 5 and 1.0 gpm (neutral) results, there was no breakthrough of trichloroethene and tetrachloroethene. Overall, these results are generally better than those at pH 5 but not better than those at 1.0 gpm (neutral).

All four compounds were removed to a greater extent and took longer to breakthrough at pH 9 than at pH 5 for filter AFT (Figures 24 and 20). Filter AFT showed a breakthrough of chloroform and 1,1,1-trichloroethane both at 25% rated of capacity with C/Ci of 0.040 (2.85 ug/l) and 0.047 (1.70 ug/l) respectively. At the termination point, the C/Ci value for chloroform was 0.636 (46.19 ug/l) and 0.245 (20.67 ug/l) for 1,1,1-trichloroethane. Filter AFT showed a breakthrough of trichloroethene at 175% of rated capacity with a C/Ci of 0.026 (0.65 ug/l) and ended the run with a C/Ci of 0.024 (0.69 ug/l) at 200% of rated capacity. There was no

Figure 23. Adsorption Curves for the Culligan Filter.

1.0 gpm, pH 9 Multi-Solute System

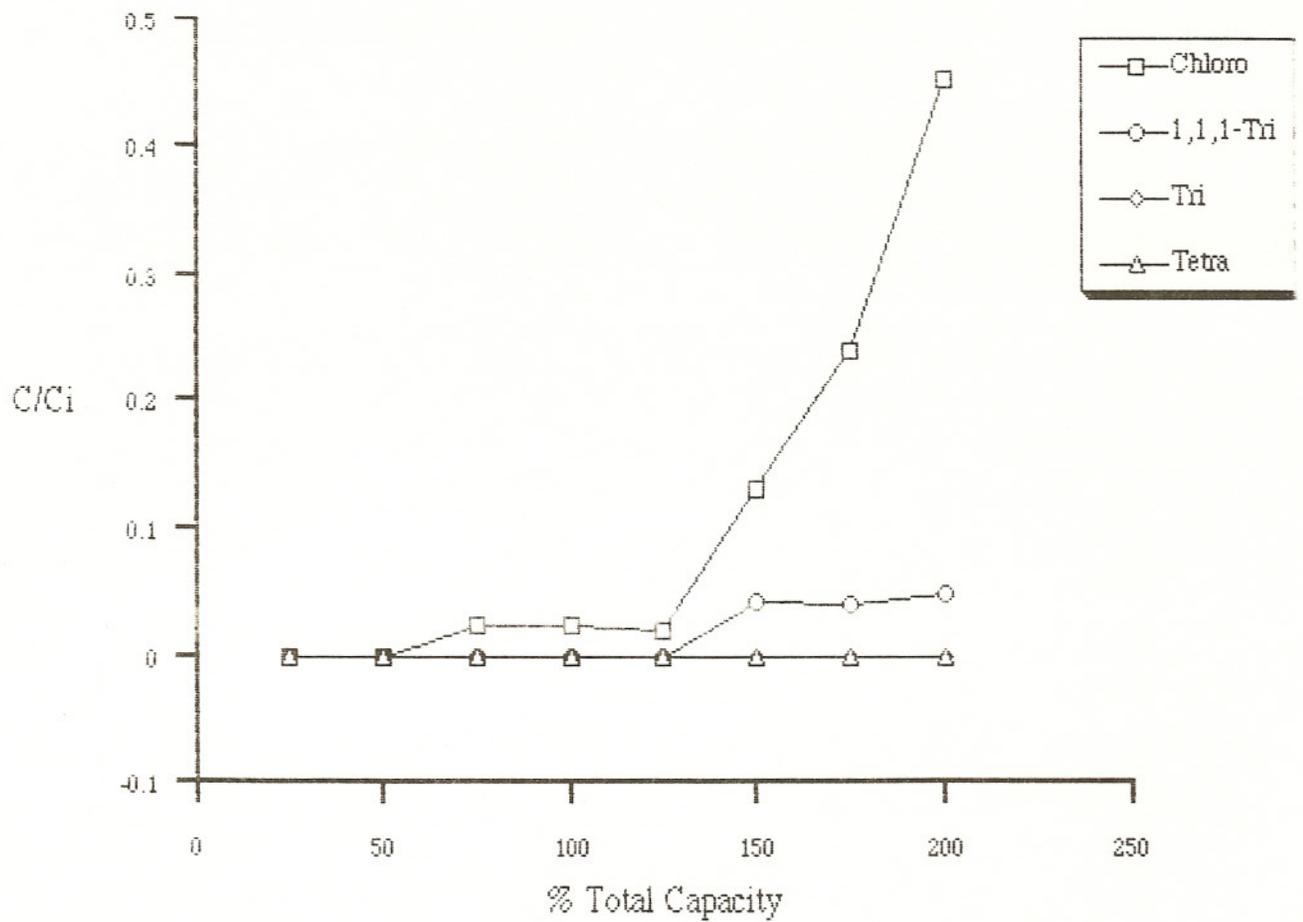
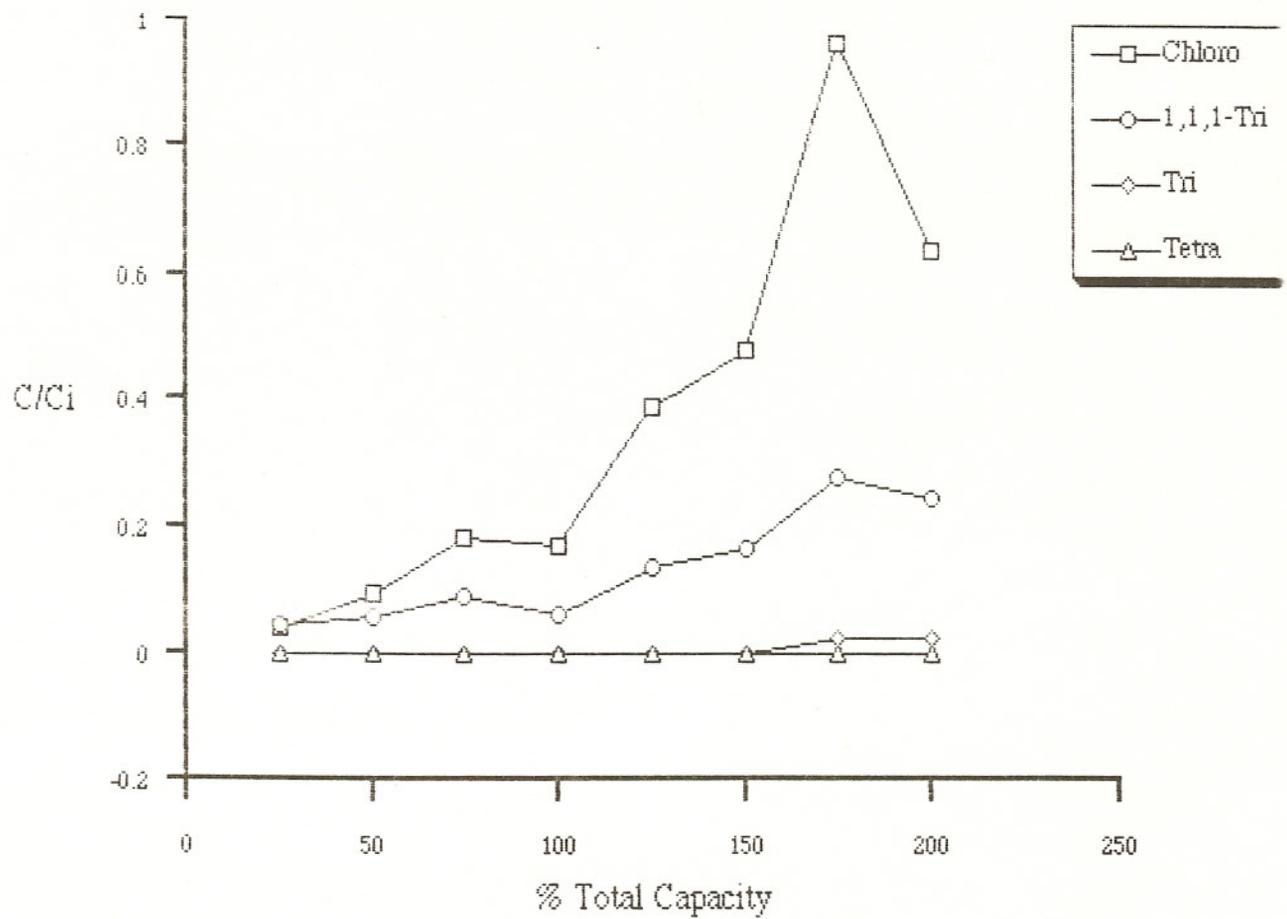


Figure 24. Adsorption Curves for the AFT Filter.

1.0 gpm, pH 9 Multi-Solute System



breakthrough of tetrachloroethene for filter AFT. These results are a lot better than those at pH 5.0 but are close to those at 1.0 gpm (neutral).

Similar to previous results, the performance of filter P was poor for contaminant removal (Figures 25 and 21). All four compounds were excluded from the filter and reached a concentration similar to the influent at an early stage in the run.

4. Comparison of Filter Performance

a. Average Percentage Removals

Table 17 gives a summary of the average percentage removals of each compound on each filter at pH values of 5.0 and 9.0 when the flow rate was 1.0 GPM. Also included in this table are the average removals at the unbuffered pH value of New Brunswick tap water in the 6.5. to 7.5 range when the flow rates were 0.5 and 1.0 GPM. That the $[H^+]$ concentration may be factor affecting adsorption was observed only by chloroform on all four filters. For example, at a flow rate of 1.0 GPM, the average removal of chloroform was: at pH 5.0, 65.6%, at pH 6.5 - 7.5, 96.4%, and at pH 9.0, 88.9% on the Culligan filter. Similar observations can be made for chloroform on the other three filters.

The factors of $[H^+]$ and flow rate apparently do not influence the adsorption of 1,1,1-trichloroethane, trichloroethylene, and tetrachloroethylene on the four carbon filters. Average percentage removals are approximately the same for these three compounds at the pH values of 5.0, 6.5 - 7.5, and 9.0 at a flow rate of 1.0 GPM. Similar observations are seen at a flow rate of 0.5 GPM. Duplicate runs for the Pollenex filter at 0.5 GPM did not confirm the initial

Figure 25 Adsorption Curves for the Pollenex Filter.

1.0 gpm, pH 9 Multi-Solute System

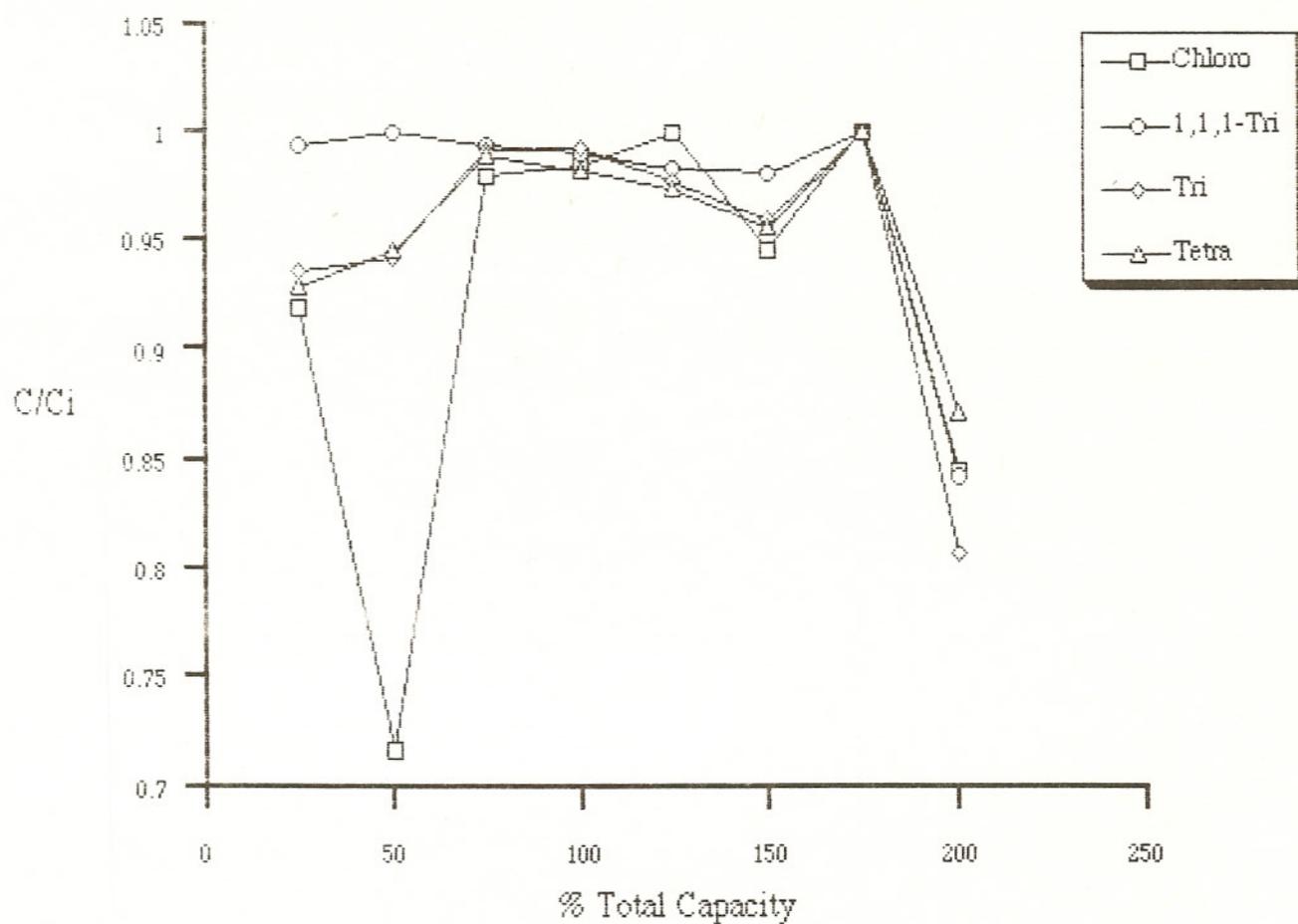


Table 17. Average Percentage Removal of Compounds by Filters at Different Treatments.

Compound	<u>Average Removal %</u>			
	<u>0.5 gpm</u>	<u>1.0 gpm</u>	<u>pH 5.0</u>	<u>pH 9.0</u>
			<u>Culligan</u>	
CHCl ₃	96.9	96.4	65.6	88.9
1,1,1 TCE	100.0	100.0	97.0	98.3
TCE	100.0	100.0	100.0	100.0
TetraCE	100.0	97.0	100.0	100.0
			<u>AMWAY</u>	
			*	
CHCl ₃	92.1	95.9	90.9	78.5
1,1,1 TCE	98.8	100.0	98.6	97.8
TCE	99.5	100.0	100.0	100.0
TetraCE	99.2	100.0	100.0	100.0
			<u>AFT</u>	
			*	
CHCl ₃	72.0	63.0	61.9	58.5
1,1,1 TCE	86.6	74.7	90.7	78.2
TCE	99.1	96.9	99.8	96.1
TetraCE	100.0	95.9	100.0	95.5
			<u>POLLENEX</u>	
			*	
CHCl ₃	1.9	10.8	9.3	4.4
1,1,1 TCE	1.5	38.0	10.1	4.5
TCE	0.5	96.8	8.3	4.8
TetraCE	0.8	99.5	5.4	3.2

* = Duplicate Sample Run.

run where average removals ranged from 0.5 to 1.9% for the four compounds. A second duplicate was run whose results compared favorably with the first duplicate (compare Figures 14 and 15). These results may indicate the erratic behavior of the Pollenex filter that has performed consistently poor in this study.

Overall, the efficiency of filter performance remains: Culligan/Amway > AFT > Pollenex regardless of pH and flow rate. This observation applies to all four VOCs in a competitive matrix.

b. Total Amounts of VOCs Adsorbed

Adsorption of organic compounds on carbon is inhibited or suppressed in the presence of other similarly structured compounds. This is presumably due to competition of the molecules for adsorption sites on the carbon's surface. Evaluation of competitive effects can be made by comparing the adsorption of an equal mass of a given compound under identical test conditions from mixed solute and from single solute solutions. Table 18 compares the adsorption of the four compounds in mixed solute solutions at 0.5 and 1.0 GPM, respectively. Data are included also for adsorption of single solutes by the Culligan filter at 0.5 GPM from the previous study (Cotton, et al., 1989). There does not appear to be any consistent and significant difference between the adsorption of the four VOCs on the four filters due to flow rate. For example, 803 mgs of CHCl_3 were adsorbed on the Culligan filter at 0.5 GPM and 733 mgs at 1.0 GPM. On the other hand, 721 mgs of 1,1,1-trichloroethane were adsorbed on the Culligan filter at 0.5 GPM and 800 mgs at 1.0 GPM. Also, greater amounts of trichloroethylene and tetrachloroethylene were adsorbed on the

Table 18. A Comparison of the Total Amounts of the Challenge Compounds Adsorbed from Mixed and Single Solute Systems.

Filter	Mixture			Single		
	mg ^a		F.C.-%	Volume-gal.	F.C.-% ^e	Volume-gal. ^e
	0.5 ^b	1.0 ^c				
<u>Chloroform</u>						
C	803	733	200	4000	40.6	1624
AW	521	580	200	3000	-	-
AFT	334	300	200	2000	-	-
P	- ^d	66	200	4800	-	-
<u>1,1,1-Trichloroethane</u>						
C	721	800	200	4000	23.2	880
AW	502	580	200	3000	-	-
AFT	355	270	200	2000	-	-
P	-	100	200	4800	-	-
<u>Trichloroethylene</u>						
C	551	633	200	4000	Filter plugged	
AW	339	433	200	3000	Not Detected	
AFT	310	267	200	2000	-	-
P	-	67	200	4800	-	-
<u>Tetrachloroethylene</u>						
C	478	533	200	4000	Not Detected	
AW	281	400	200	3000	Not Detected	
AFT	247	233	200	2000	-	-
P	-	33.3	200	4800	-	-

a. From Figure 26, total mass in mg adsorbed at PT.

b. 0.5 GPM

c. 1.0 GPM

d. No adsorption

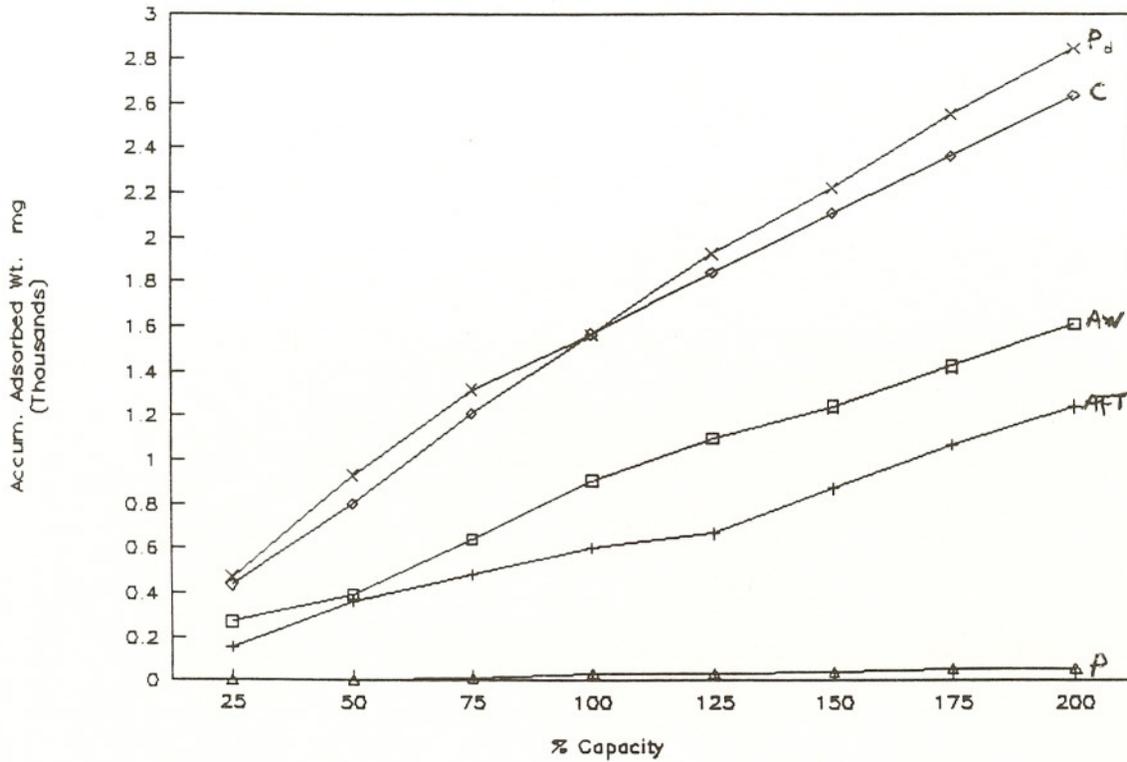
e. F.C. and throughput volume to adsorb same mass as a single compound.

Culligan filter at 1.0 GPM than at 0.5 GPM. Presumably a lower flow rate affords a longer contact time than at a higher flow rate. Consequently greater quantities of the four VOCs should be adsorbed at the lower flow rate. However, all of the data do not support this presumption. Only the AFT filter exhibited higher adsorption of the four VOCs at 0.5 GPM than at 1.0 GPM. Perhaps the bed volumes of these carbon units are so small that decreasing the flow rate does not increase the contact time to such an extent for the kinetics of adsorption to become a significant factor. In any event, the observation that the order of filter efficiency C>AW>AFT>P, is consistent at 0.5 GPM with 1.0 GPM and part 1 of this study.

Figure 26 shows the total accumulated mass, of the four compounds throughout each run of the four filters at 0.5 GPM and 1.0 GPM, respectively. The terminal point of each curve represents the total mass adsorbed of all four compounds for each filter. This presentation of the data facilitates comparison of each filter's efficiency of removal. At 1.0 GPM, the order of efficiency is: C/AW, AFT, and P. This same order is observed at 0.5 GPM with the exception of the P duplicate anomaly.

Figure 27 shows the total accumulated mass of the four compounds throughout each run of the four filters at pH values of 5.0 and 9.0 (1.0 GPM), respectively. Here again, the terminal point on each curve represents the total mass adsorbed for each filter. The order of efficiency remains C, AW, AFT, and P at both pH values. However, the C and AW filters appear to remove more total mass at pH 5.0 than at pH 9.0 whereas AFT and P have

0.5 GPM Conditions



1.0 GPM Conditions

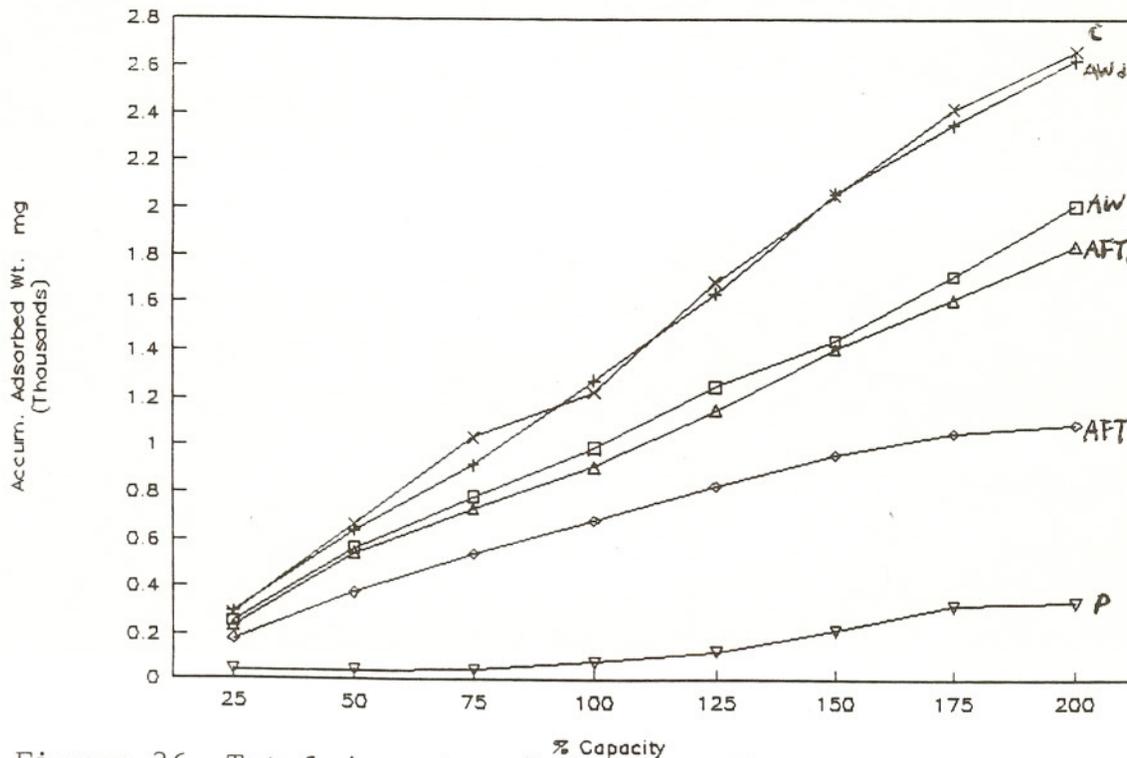
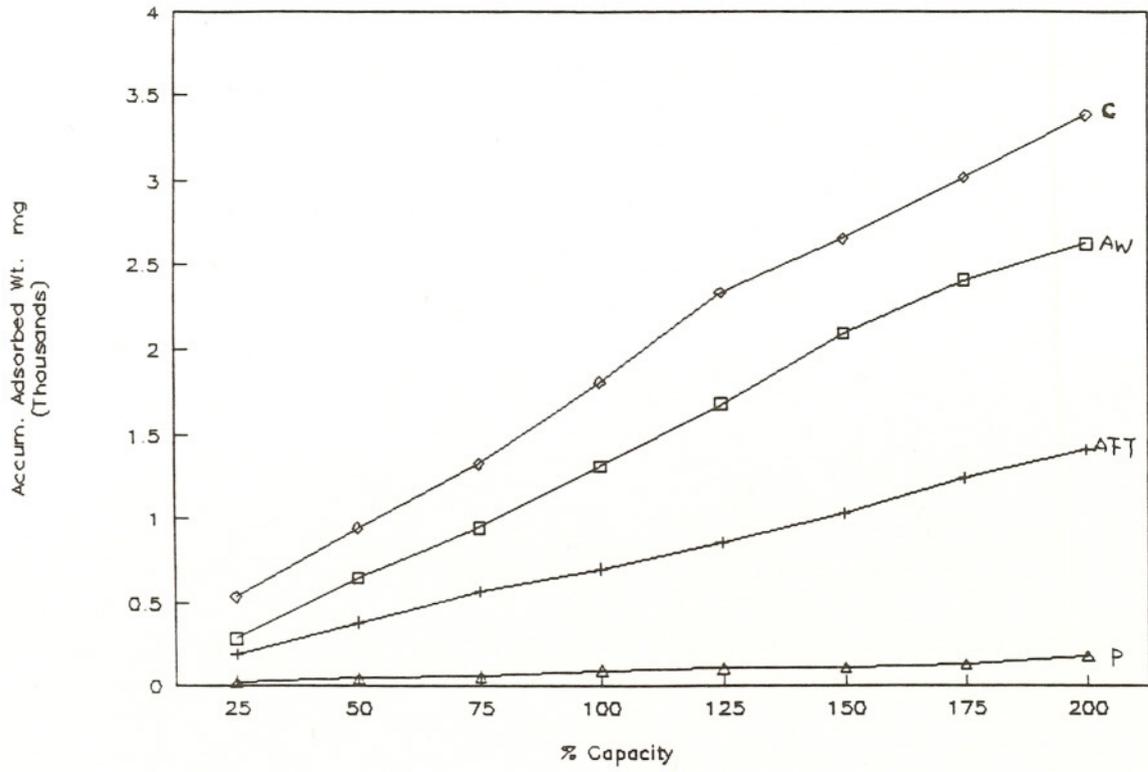


Figure 26. Total Amounts of the Four VOCs Adsorbed at Point of Termination at 0.5 and 1.0 GPM.

pH 5.0 Condition



pH 9.0 Condition

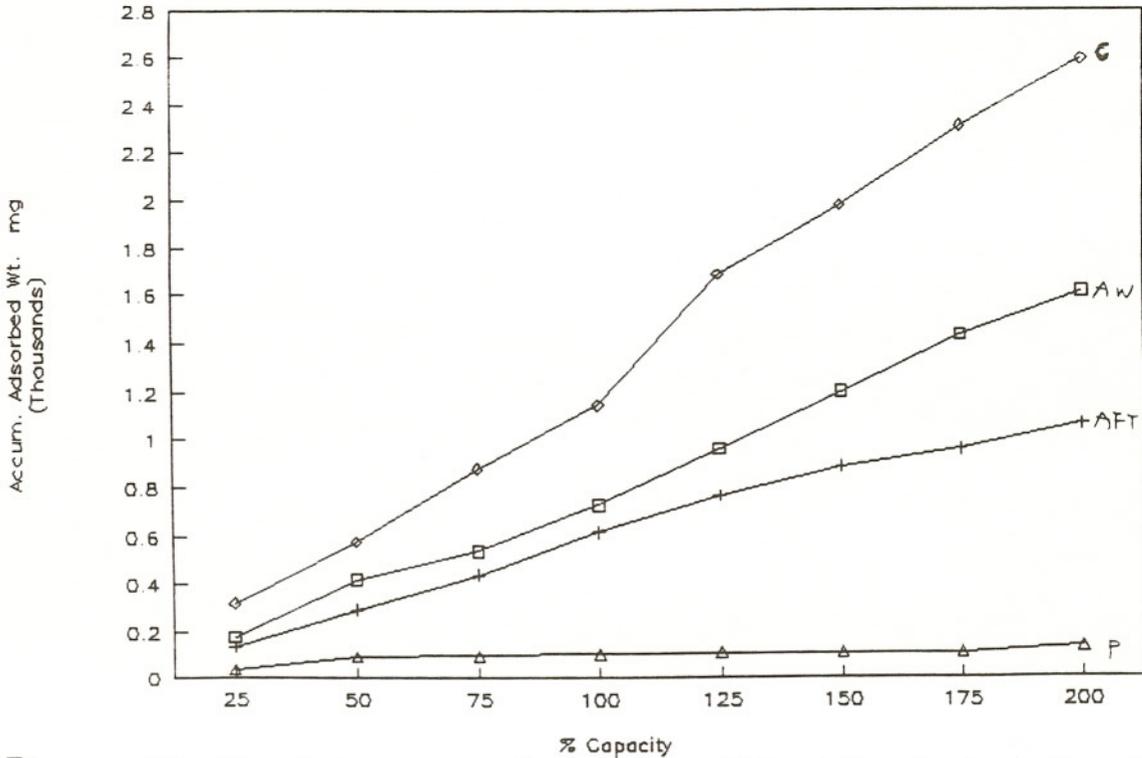


Figure 27. Total Amounts of the Four VOCs Adsorbed at the Point of Termination at pH Values of 5.0 and 9.0.

approximately the same removals at both pH values.

Table 19 summarizes these total accumulated masses from Figures 26 and 27. These data certainly indicate each filter's efficiency of removal in terms of total mass presented to each filter. However, these data may not represent the maximum capacity of each filter to adsorb the four compounds. This would be especially true of the C and AW filters with their greater quantities of carbon (863 and 1002 grams, respectively) than the AFT and P filters (399 and 283 grams, respectively).

c. Amounts of VOCs Adsorbed/Gram Carbon

In Table 20 there is a comparison of the masses of the four VOCs that were adsorbed per gram of carbon at the point of termination. There does not appear to be any consistent effect of $[H^+]$ when the adsorptive efficiency is expressed in this manner. For example, slightly higher amounts of chloroform were adsorbed at a pH value of 9.0 than at 5.0 on all four filters. However, lesser amounts of the other three VOCs were adsorbed per gram of carbon at pH 9.0 than at 5.0. This observation is reflected also when the individual amounts are summed to a total mass adsorbed per gram. Also, the pH 5.0 and 9.0 adsorptive amounts are not appreciably different than those observed in the mixed systems run at 1.0 GPM where the pH value was approximately 6.5 - 7.5 (unbuffered New Brunswick tap water). The C and AFT filters adsorbed a total mass/gram that was slightly higher than the AW filter and significantly higher than the P filter (except the duplicate anomaly).

Table 19. Total Amounts of the Four VOCs Adsorbed at Point of Termination, Expressed as mg x 10³ (thousands).

<u>Filter</u>	<u>Carbon Wt - g</u>	<u>pH5.0^a</u>	<u>pH 6.5 - 7.5</u>		<u>pH 9.0^a</u>
			<u>0.5 GPM</u>	<u>1.0 GPM</u>	
C	863	3383.	2555.	2667.	2589.
AW	1002	2625.	1643.	2039. ^b	1613.
AFT	399	1408.	1249.	1464. ^b	1065.
P	283	187.	56.6 ^c	337.	147.

a. at 1.0 GPM

b. Average of duplicates

c. duplicates not included.

Table 20. A Comparison of Amounts Adsorbed per gram of Carbon at Point of Termination.

	Carbon Wt-g	Treatment	CHCl ₃ mg/g	1,1,1 -TCE mg/g	TCE mg/g	TETRACE mg/g	SUM mg/g
Filter C	863	S 1.0 gpm	2.09	4.00	FP ^a	ND	-
		M 0.5 gpm	0.93	0.84	0.64	0.55	2.96
		M 1.0 gpm	0.83	0.90	0.74	0.62	3.09
		pH 5.0	0.74	1.11	1.04	1.03	3.92
		pH 9.0	1.20	0.77	0.54	0.49	3.00
AW	1002	S 1.0 gpm	1.54	2.93	ND	ND	-
		M 0.5 gpm	0.52	0.50	0.34	0.28	1.64
		M 1.0 gpm	0.56	0.58	0.45	0.41	2.00
		M 1.0 gpm ^b	0.64	0.75	0.63	0.59	2.61
		pH 5.0	0.59	0.71	0.66	0.66	2.62
		pH 9.0	0.66	0.43	0.28	0.24	1.61
AFT	399	S 1.0 gpm	3.27	2.26	4.32	3.29	-
		M 0.5 gpm	0.84	0.89	0.78	0.62	3.13
		M 1.0 gpm	0.73	0.69	0.69	0.61	2.72
		M 1.0 gpm ^b	0.77	1.49	1.24	1.12	4.62
		pH 5.0	0.65	0.92	1.01	0.95	3.53
		pH 9.0	0.88	0.68	0.59	0.52	2.67
	283	S 1.0 gpm	1.37	2.44	4.07	7.46	-
		M 0.5 gpm	0.08	0.04	0.04	0.04	0.20
		M 0.5 gpm ^b	0.58	1.88	3.85	3.74	10.05
		M 1.0 gpm	0.33	0.39	0.29	0.18	1.19
		pH 5.0	0.18	0.19	0.18	0.11	0.66
		pH 9.0	0.32	0.04	0.08	0.08	0.52

^aFilter plugged.

^bDuplicate Sample Run.

General Discussion

Manufacturers of the four filters employed in this study recommend flow through rates of 0.5 GPM (C) to 1.0 GPM for the P and AFT filters. The AW filter lies within this range at 0.75 to 0.95 GPM. In turn, these flow through rates dictate the retention time of the water within the filters. At best, the retention times within these point-of-use filters are the order of a few seconds (90 at most). Consequently, kinetics of adsorption of the four compounds in the matrix becomes extremely significant. Affinity of the compounds for the carbon's surface is important also. This latter point is seen in Table 2 where the Freundlich K values suggest that the order of decreasing affinity is: tetrachloroethylene, 1,1,1-trichloroethane, trichloroethylene, and chloroform.

The flow through rate of 1.0 GPM was evaluated first (Table 12). The above cited order of adsorption affinity was observed in all four filters. Generally, chloroform broke through each filter before the other three compounds at volumetric capacities ranging from 25% (AFT and P) to 100% (C), and to 125% (AW). Another general observation is that 1,1,1 trichloroethane, trichloroethylene, and tetrachloroethylene were not detected or had "low" C/C_i values at the points of termination (200% of volumetric capacity) for the C, AFT, and AW filters. This is consistent with the higher Freundlich K values for these three compounds than for chloroform. In the context of adsorption affinity, the decreasing order of filter performance is C/AW, AFT, and P.

Subsequent experiments reduced the flow through rate to 0.5

GPM which is the lowest recommended by the manufacturers. This lower flow rate presumably increases the retention time within the filter. Very few differences were observed in the adsorption of the four compounds at 0.5 GPM (Table 13) than at 1.0 GPM (Table 12). This is seen by comparison of the % filter capacity data at the first detectable concentration (F) and at the points of termination (PT). For example, at 1.0 GPM (AW filter) chloroform first appeared at 25% of filter capacity whereas at 0.5 GPM this value was 50%. The C/Ci for chloroform on the AW filter was 0.03 at 1.0 GPM and 0.04 at 0.5 GPM at the points of termination. Similar observations can be made for the other three compounds on the C, AFT, and P filters. The order of filter performance remained at C/AW > AFT > P for the 0.5 GPM flow rate.

Desorption of the four VOCs should occur in the reverse order of adsorption affinity. That is, chloroform should be desorbed more so than trichloroethylene, 1,1,1 trichloroethane, and tetrachloroethylene. Certainly this order was observed for a given filter (Table 14). For example, 45% of the chloroform was desorbed from the AW filter that was followed by 9.2% of the 1,1,1-TCE and virtually none of the TCE and TetraCE. In general, this same order was followed by the C, AFT, and P filters. However, only 11.4% of chloroform was desorbed from the C filter, 22% from the AFT filter, and 20.9% from the P filter. These results suggest that only those quantities of the four VOCs on the external surface of the carbon were eluted. Any compound that has penetrated into the internal pore structure of the carbon may not be available for desorption. Certainly the inability of the carbon filters to

release 100% of the adsorbed compounds would not affect household use. The manufacturers recommend a once use concept wherein the filters are discarded when their rated volumetric capacity is reached.

Adsorption of the four VOCs was observed at pH values of 5.0 and 9.0 in an effort to evaluate any influence of $[H^+]$. The hypothesis is that functional groups on the carbon's surface would be altered that, in turn, would affect the adsorptive behavior of the four compounds. There is some evidence in Tables 15 (pH 5.0) and 16 (pH 9.0) that chloroform adsorption was decreased somewhat on filters C and AW at the higher $[H^+]$ concentration. There is no apparent explanation for this observation. There may be some competition of the H^+ with chloroform for adsorption sites. The evidence for this explanation is tenuous at best. No pH effect was observed for chloroform adsorption on the AFT and Pollenex filters. There were not any significant effects observed for the adsorption of the other three VOCs on all four filters. For the latter, there were some minor differences in filter performance at the two pH values that may very well be within the reproducibility of the experimental protocol.

Individual filter performances may be compared by transformation of the adsorption data into common denominators. For example, Table 17 expresses the average percentage removals of each VOC on each filter at flow rates of 0.5 and 1.0 GPM, and at pH values 5.0 and 9.0 (1.0 GPM). These removals represent an average of eight volumetric increments throughout a filter run from 0 to 200% of capacity. Consequently, each of the filter's removal

performance may be compared at the point of termination of each run. Overall the C filter gave the highest average removals that were followed by AW, AFT, and P filters.

That the C filter performed exceptionally well is seen in Table 17 where nearly 100% of TCE, 1,1,1-TCE, and TetraCE was removed at the two flow rates and at the two pH values. Chloroform was removed at 96 to 97% by the C filter at 0.5 and 1.0 GPM. There were also significant reductions in the average removals of chloroform at pH 5.0 (66%) and pH 9.0 (89%).

The overall performance of the AW filter was similar to the C filter with nearly 100% removals of TCE, 1,1,1-TCE, and TetraCE. In the pH study, the AW filter gave significantly higher removals of chloroform than the C filter with 78.5% at 5.0 and 93.6% at pH 9.0. Again the effect of the higher $[H^+]$ was evident.

The AFT filter ranked third in overall removal performance. TCE and TetraCE were removed at nearly 100% at 0.5 and 1.0 GPM and at pH 5.0 and 9.0. Chloroform and 1,1,1-TCE were removed at percentages in the 58 to 91% range. Hydrogen ion concentration apparently was not a factor affecting removal of chloroform by AFT.

Generally the P filter performed poorly under the experimental conditions in this study. Most of the average percentage removals were less than 10%. There was an anomalous result from two duplicate runs for the P filter at 0.5 GPM. This may indicate erratic behavior of the P filter with its 283 grams of carbon, the least amount of the four filters.

Another means of comparing each filter's performance is the total mass of each compound adsorbed at 0.5 and 1.0 GPM at the

point of termination. Table 18 shows these values. For example, the total masses of chloroform were 733, 580, 300, and 66 mg on the C, AW, AFT, and P filters, respectively, at 1.0 GPM. This order of decreasing total masses was observed also with the other three compounds. There was no consistent effect on the total adsorbed masses by the lower flow rate of 0.5 GPM. Only chloroform on filter C and all four VOCs on filter AFT were adsorbed to a greater extent at 0.5 GPM than at 1.0 GPM. Consequently, flow rate is apparently not a factor influencing adsorption of VOC on these point-of-use filters.

There is some evidence for competitive effects on the adsorption of chloroform and 1,1,1 TCE on the C filter by the other two VOCs. Table 18 gives the filter capacity (%) and the volume of water from which the same masses of chloroform and 1,1,1-TCE were adsorbed as single compounds. For example, the same mass of chloroform (733 mg) was adsorbed at 40.6% of filter capacity (single compound) whereas 200% of filter capacity was required in the mixed system.

Filter performance and the influences of operational variables may be evaluated by comparison of the total masses of the four VOCs adsorbed on the four filters. Table 19 gives these amounts at the two flow rates and the two pH values. These data clearly show the superior performances of the C filter that is followed by the AW, AFT, and P filters. Also, the C and AW filters adsorbed greater total masses at a pH of 5.0 than at pH 6.5 - 7.5 (0.5 and 1.0 GPM) and at pH 9.0. The AFT and P filters were inconsistent in their performances with respect to the influence of $[H^+]$. It is

interesting to note that greater quantities of the four VOCs were adsorbed at 1.0 GPM than at 0.5 GPM (middle column, Table 19). No rational explanation can be offered for this observation. Again, the inferior performance of filter P is seen in Table 19.

In Table 20, there is a comparison of the masses of the four VOCs that were adsorbed per gram of carbon at the point of termination. This is a useful technique for comparison of filter performance as well as the adsorption of individual compounds under the various operating conditions. The amounts of individual compounds adsorbed per gram of carbon for each filter are, of course, less than the amounts adsorbed from single systems. It is tempting to interpret this in terms of a competitive matrix of compounds. However, a summation of the individual masses/gram from mixed systems is generally similar to those from single solute systems. Apparently total mass presented to a carbon filter is the overriding factor influencing total adsorption in mixed and in single solute systems. If this observation is valid for this study, then competitive effects of multisolutes may not be an operational factor affecting in situ operation of these point-of-use filters.

In this study, the C and AW filters performed well in removal of the four VOCs in a matrix whose mass was approximately 250 ug/l. No experiments were conducted wherein the filters would be challenged with greater masses of VOCs. That is, the filters were not stressed to their potential capacity for adsorption. Rather, each filter was run to 200% of its rated volumetric capacity. Certainly this would exceed normal operation in a household, where

carbon-filtered water would be used only for drinking and preparation of other beverages. Consequently, this study is representative of field operation. Perhaps, a future study could examine these filters under conditions of higher VOC concentrations and determine their ultimate capacity for adsorption.

In a very general sense, this study is consistent with a previous examination of the field operation of five point-of-use filters. Bellen, et al, (1985) evaluated in situ treatment of contaminated groundwaters at Silverdale, PA. and Rockaway Township, N.J. These waters were contaminated with 8 VOCs and four THMs. The four VOCs employed in this study were in the ground waters of Silverdale and Rockaway Township. The devices in Silverdale removed the eight VOCs for the entire testing period (14 months) whereas the filters used in Rockaway Township were removing all VOCs after 24 months. The range of VOC concentrations in these two studies were:

<u>Compound</u>	<u>Silverdale</u>	<u>Rockaway</u>
	ug/l	ug/l
TCE	12.0 - 83.8	0.7 - 240.2
TetraCE	3.5 - 20.6	1.0 - 12.3
1,1,1-TCE	<1.0 - 1.4	1.0 - 2.40
Chloroform	1.0 - 6.7	1.7 - 2.1

The concentrations of the four VOCs in the Silverdale study were considerably less than in this study. Higher concentrations are apparent in the Rockaway groundwaters. However, no frequency of occurrence of the VOCs was given for Rockaway. Nevertheless, the point-of-use filters apparently performed well in the removal of

the above four VOCs.

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Appendix

Table A1. A-280 2a Contaminants List

1. Benzene
2. Carbon Tetrachloride
3. Chlordane
4. Chlorobenzene
5. Dichlorobenzene(s)
6. 1,2-Dichloroethane
7. 1,1-Dichloroethylene
8. cis-1,2-Dichloroethylene
9. trans-1,2-Dichloroethylene
10. Ethylene Glycol
11. Formaldehyde
12. n-Hexane
13. Kerosene
14. Methyl Ethyl Ketone
15. Methylene Chloride
16. Polychlorinated Biphenyls
17. Tetrachloroethylene
18. Trichlorobenzene
19. 1,1,1-Trichloroethane
20. Trichloroethylene
21. Vinyl Chloride
22. Xylene(s)

Table A2. Results of Water Quality Analyses for New Brunswick Tap Water.

<u>Parameter</u>	<u>7/86</u>	<u>11/86</u>	<u>1/87</u>	<u>2/87</u>
pH	6.7	6.5	6.8	6.8
Alkalinity	47.0 mg/l	39	33	39
Chloride	32.0 mg/l	23	36	34
Sulfate	52.0 mg/l	57	52	45
Nitrate	1.7 mg/l	1.8	1.6	1.8
Phosphate	0.42mg/l	0.15	0.16	0.18
Calcium	34.0 mg/l	51	51	55
Chlorine Residual	0.02 mg/l	0.02	0.01	0.02
Total Hardness	62.0 mg/l	73	67	87
Magnesium	28.0 mg/l	21.5	16	32
Total Organic Carbon	1.0 mg/l	1.0	1.0	1.0
Total Dissolved Solids	125-175 mg/l	125-175	138.0	138.3
Standard Plate Count	—	9/ml	—	56
Sodium	15-25mg/l	15-25	15-25	15-25
Potassium	1.5 mg/l	2.0	1.5	1.3
Iron	0.13mg/l	0.14	0.15	0.13

Table A2 (cont.)

<u>Parameter</u>	<u>3/87</u>	<u>4/87</u>	<u>5/87</u>
pH	7.0	7.1	7.2
Alkalinity	31.0 mg/l	37	50
Chloride	31.0 mg/l	35	24
Sulfate	38.0 mg/l	37	35
Nitrate	1.8 mg/l	1.7	1.3
Phosphate	0.18mg/l	0.23	0.23
Calcium	40.0 mg/l	45	51
Chlorine Residual	0.03 mg/l	0.03	0.03
Total Hardness	60.0 mg/l	72	80
Magnesium	20.0 mg/l	27	29
Total Organic Carbon	1.0 mg/l	1.0	1.0
Total Dissolved Solids	129.3mg/l	111.5	196.3
Standard Plate Count	17/ml	246	60
Sodium	15-25mg/l	15-25	15-25
Potassium	1.4 mg/l	1.4	1.3
Iron	0.14mg/l	0.10	0.10

Table A3. Incremental Removal Percentages of Compounds by Filters at pH 5.0.

Compound	Filter	Removal Percentages % Total Capacity								Ave.	Mass Ave.
		0-25	25-50	50-75	75-100	100-125	125-150	150-175	175-200		
Chloroform	C	100.0	97.0	96.2	93.1	81.0	36.6	20.9	0	65.6	65.9
	AW	100.0	100.0	98.0	95.4	93.0	83.1	46.1	12.5	78.5	79.7
	AFT	93.3	93.6	81.5	63.3	54.6	29.9	48.8	3.3	58.5	56.4
	P	4.1	1.7	1.5	0	7.2	0	2.8	17.8	4.4	2.2
1,1,1 Trichloro- ethane	C	100.0	100.0	100.0	100.0	97.7	95.4	94.0	89.2	97.0	96.8
	AW	100.0	100.0	100.0	100.0	100.0	97.7	94.2	90.8	97.8	97.9
	AFT	94.5	94.8	86.2	74.9	73.8	64.8	68.6	67.9	78.2	77.5
	P	10.3	10.1	3.0	5.4	0	1.0	4.7	2.6	4.6	2.2
Trichloro- ethylene	C	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	AW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	AFT	99.4	100.0	97.6	95.9	95.4	94.0	93.5	93.1	96.1	95.8
	P	3.3	4.2	3.3	13.0	0	0	4.2	10.4	4.8	2.3
Tetrachloro- ethylene	C	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	AW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	AFT	100.0	100.0	98.0	94.7	94.3	92.9	91.4	92.5	95.5	94.9
	P	1.9	2.2	0	6.7	0	0.9	6.6	7.1	3.2	1.6

Table A4. Incremental Removal Percentages of Compounds by Filter at pH 9.0.

Compound	Filter	<u>Removal Percentages</u>								Ave.	Mass Ave.
		% Total Capacity									
		<u>0-25</u>	<u>25-50</u>	<u>50-75</u>	<u>75-100</u>	<u>100-125</u>	<u>125-150</u>	<u>150-175</u>	<u>175-200</u>		
Chloroform	C	100.0	100.0	97.6	97.6	97.9	87.0	76.2	54.9	88.9	88.9
	AW	96.5	100.0	95.2	96.5	96.6	94.8	89.4	80.0	93.6	90.6
	AFT	96.0	90.7	82.0	83.2	61.1	52.3	4.0	36.4	63.2	66.0
	P	8.2	28.4	2.1	1.5	0	5.5	0	15.5	7.7	3.3
1,1,1 Trichloro- ethane	C	100.0	100.0	100.0	100.0	100.0	95.6	95.8	95.0	98.3	98.3
	AW	100.0	100.0	100.0	100.0	100.0	100.0	95.7	91.8	98.4	98.6
	AFT	95.3	94.4	91.1	93.9	86.2	83.4	72.5	75.5	86.5	86.7
	P	0.6	0	0.6	1.0	1.7	1.9	0	15.7	2.7	0.8
Trichloro- ethylene	C	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	AW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	AFT	100.0	100.0	100.0	100.0	100.0	100.0	97.4	97.6	99.4	99.5
	P	6.5	5.9	0.9	0.7	2.3	4.1	0	19.3	5.0	2.0
Tetrachloro- ethylene	C	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	AW	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	AFT	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	P	7.2	5.5	1.1	1.8	2.6	4.4	0	12.9	4.4	2.1