

**EPA'S RESEARCH PROGRAM IN
GRANULAR ACTIVATED CARBON**

Robert M. Clark
Director
Drinking Water Research Division

Thomas F. Speth
Environmental Engineer
Organics Control Branch

Benjamin W. Lykins, Jr.
Chief
Systems and Field Evaluation Branch
Risk Reduction Engineering Laboratory
Cincinnati, Ohio

INTRODUCTION

Research into Granular Activated Carbon (GAC) for use in drinking water treatment has a long history in the Drinking Water Research Division and its predecessor organizations. Studies were conducted by the U.S. Public Health Service in the late fifties and early sixties to examine the use of GAC for taste and odor removal.¹ Additional work was conducted during the sixties to evaluate the use of GAC for removal of pesticides, the effectiveness of reactivation and to determine the optimal design of carbon systems.^{2,3,4}

With the passage of the Safe Drinking Water Act of 1974, the United States Environmental Protection Agency (USEPA) proposed a two-part regulation for organic contaminant control in drinking water in February 9, 1978.⁵ This document specified a Maximum Contaminant Level (MCL) for the control of trihalomethanes and further specified that GAC be installed at water utilities for the control of other synthetic organic chemicals (SOCs) where source waters were significantly contaminated. Both parts of this proposed rule had an impact on the direction of EPA's research into the use of GAC. The generally negative reaction to a GAC treatment requirement caused the USEPA to initiate a field scale research effort which will be described briefly in the following sections. The trihalomethane control portion of the regulation led to an interest in the role that GAC might play in disinfection by-products control.

In 1986, the Safe Drinking Water Act was amended and GAC was declared to be the base-line technology against which all other technologies must be measured for SOC control. According to the Amendments, any other technology, treatment technique,

or other method found to be best available for the control of SOC's must be as effective as GAC for this purpose. In many ways the Amendments accomplished by legislative action what EPA failed to accomplish with its original trihalomethane and treatment rule.⁶

In the following sections, the various aspects of the USEPA's Drinking Water Research Divisions (DWRDs) GAC research program will be discussed. First the bench- and pilot-scale studies devoted to the application of GAC will be presented. Then, results from field-scale studies and the possible use of GAC for disinfection by-products control will be discussed. The paper will conclude with a few comments on the development of cost and performance criteria for GAC application.

GAC RESEARCH

For each contaminant regulated under the Safe Drinking Water Act, a MCL must be set, or treatment technique may be required where it is infeasible to ascertain the level for regulated contaminants in water. The 1986 Amendments to the Safe Drinking Water Act have accelerated the requirements for development of MCLs and increased the number of contaminants that will be regulated.⁷

These Amendments will broaden and deepen the impact of the Safe Drinking Water Act on public water utilities. The USEPA Administrator is required to establish a feasible treatment technology for each regulated contaminant using the best technology available or other means, taking cost into consideration.

The Amendments specify that GAC for SOC (includes volatile organic chemicals) control is considered to be feasible. Therefore, any alternative treatment technique for control of SOC's must be as effective as GAC. For each national primary drinking water regulation that establishes an MCL, the Administrator must list the technologies that he determines are feasible for meeting an MCL.

The DWRD has a major role in evaluating the performance of technologies considered as part of drinking water regulations. Traditionally, DWRD's technology program has utilized the approach of carefully evaluating process kinetics on the bench, scaling up for engineering feasibility at the pilot scale, and making a field-scale evaluation to incorporate process economics.⁸ This approach may take several years for completion and may involve millions of dollars for each technology examined. A recent development is to predict GAC use rates based on the application of adsorption models and the scale-up of microcolumn adsorption data.⁹ This approach

was approved by a peer panel of consultants, GAC researchers, hemia, water company representatives and GAC manufacturers.¹⁰

DWRD has taken an approach that has produced the following type of data in extramural and in-house projects: 1) adsorption capacity by isotherms, 2) microcolumn breakthrough curves, 3) laboratory-generated adsorption rate data by differential column batch reactor and short bed adsorber studies, 4) pilot-column breakthrough curves, 5) full-scale breakthrough curves, 6) model-predicted full-scale GAC use rates based on isotherm capacity data and on rate data taken either from laboratory studies or from literature correlations, 7) predicted full-scale GAC use rates based on scale up of microcolumn breakthrough curves, 8) predicted fullscale GAC use rates based on scale up of pilot-column breakthrough curves, and 9) GAC use rates based on full-scale operation.

ISOTHERMS

The DWRD has developed isotherms for a number of contaminants under regulatory consideration. Isotherms serve as a useful tool for purposes of preliminary design of GAC systems and as inputs for model predictions of GAC system performance. Table 1 presents isotherm values for volatile contaminants.^{11,12} Three waters were used in these isotherm studies: distilled (DD), a groundwater taken from the Great Miami Aquifer (GMA), and Ohio River water (OR). For comparative purposes, isotherm values for trihalomethanes (THMs) are included in Table 1. Generally, the THMs are more weakly adsorbed, as suggested by their Freundlich K values, than other SOC's. Because lower K values indicate relatively shorter GAC bed lives, GAC was not selected as best available treatment (BAT) for THM control. Comparing the capacities at 14°C and 24°C, the data in Table 1 supports the theory of generally higher adsorption capacity at lower temperatures. Because different batches of natural water may have contained different background matrices, multiple natural-water isotherms are given separately. An examination of these multiple isotherm values indicated the variability that might be expected when testing different batches of the same source water. The OR-water isotherms generally showed a reduction in capacity from the DD-water isotherms. The GMA-water isotherms, however, were generally close to those of the DD-water. Other studies of OR-water suggest that its low levels of multiple SOC's offer a more competitive matrix than does the GMA-water, which was not found to contain SOC's.^{12,13} Comparative DD- and OR-water isotherms are given in Figure 1 for dibromochloropropane (DBCP) and illustrate the effects of competition on adsorption capacity.

Microcolumns have frequently been suggested as an alternative method to predictive modeling or pilot studies for obtaining carbon use rates. Small columns are designed to have perfect similarity to the larger columns they replicate.¹⁴ The practice of scaling small columns to full-scale conditions has many advantages over conducting pilot-scale studies: the time requirement is generally a fraction of that required for a pilot study, no other adsorption tests are required, and only a relatively small amount of water is required. The DWRD has conducted microcolumn studies whose scaled-up results were compared to pilot column operation for verification.¹⁵ These studies utilized *cis*-1,2-Dichloroethene (c-DCE) in GMA-water.

Figure 2 compares the scaled-up results of two microcolumns and a pilot column. For each column run, the average influent concentration is plotted. Although the empty bed contact times (EBCTs) and the influent concentrations were slightly different between the scaled-up microcolumns and the pilot column, there was a significant difference in capacity between the two types of columns. One of the assumptions of the scale-up procedure is that there is perfect similarity between the capacities of the smaller and larger columns. This important condition was violated because of the lower capacity that was observed in the pilot column. Isotherm studies of *cis*-DCE in GMA-water for virgin carbon, and for carbon that had been preloaded for several weeks with GMA-water, indicated reduced capacity for the preloaded carbon. Because the microcolumns were operated in a matter of days, preloading was restricted. Hence, Figure 2 indicates false, longer bed lives based on microcolumn scaleup. Therefore, microcolumns may not be able to accurately predict natural-water field-scale columns, especially those that have large EBCT's in which carbon is preexposed to the field water for an extended period of time. Work is currently ongoing in the areas of preloaded carbon and different scale-up techniques.

PILOT DATA

A number of field studies have been conducted by the DWRD at pilot- and full-scale conditions to examine control of SOC's by GAC systems. Pilot columns were placed in the field in the late 1970s shortly after trichloroethylene (TCE) and other SOC's were first detected in groundwaters. Their designs were based on bed depth and loading rates typical of GAC systems studied for taste-and-odor or THM control. In some cases, no companion isotherm studies were conducted. At the other extreme, some pilot columns were placed following extensive development of isotherms, laboratory studies to determine kinetic parameters, and predictions of GAC column

performance by the use of fixed-bed adsorption models. Selected results demonstrate the effectiveness of fixed-bed GAC columns for SOC control. A number of pilot column studies were conducted in conjunction with the field-scale studies and are discussed in the following sections.

At a well in South Brunswick, New Jersey, seven SOC's were present. Principal contaminants were 1,1,1-trichloroethane (TCA) averaging 237 ug/L and tetrachloroethene (PCE) averaging 94 ug/L. A 0.76-m (30-inch) deep pilot column of Whitcarb 950 GAC was employed. At a 2.5 m/hr (1.0 gpm/ft²) loading rate, TCA breakthrough was not evident until the 30th week of operation and the column was not exhausted until the 52nd week (Figure 3). If a 200 ug/L TCA MCL dictated GAC replacement in a full-scale column based on this design, a bed life of nearly 11 months would result.¹⁶ At 52 weeks of operation, breakthrough of PCE had not occurred. This behavior is consistent with the relative isotherm capacities of TCA and the more strongly adsorbed PCE.¹⁶ Similar relative capacities of TCA and PCE are noted in Table 1 where Filtrasorb 400 GAC was employed.

FIELD SCALE STUDIES

As mentioned, earlier the DWRD initiated a series of field-scale projects designed to study the cost and performance of GAC. The following nine utilities participated in cooperative GAC research efforts: Cincinnati, Ohio; Manchester, New Hampshire; Jefferson Parish, Louisiana; Evansville, Indiana; Miami, Florida; Huntington, West Virginia; Beaver Falls, Pennsylvania; Passaic Valley, Little Falls, New Jersey; and Philadelphia, Pennsylvania.

Each full-scale facility involved in the GAC research effort utilized essentially the same treatment scheme: predisinfection, coagulation/ flocculation, settling, filtration, and post-disinfection.

GAC adsorption was investigated under actual operating conditions to provide adsorption efficiency data that considered the mix of compounds in drinking water sources and the competition for available adsorption sites.

At Jefferson Parish, Louisiana several chlorinated hydrocarbon insecticides (CHIs) were detected at concentrations averaging less than 10 ng/L (Table 2). The total CHI concentration prior to GAC adsorption ranged from 18-88 ng/L with an annual average of 36 ng/L. The CHIs were effectively removed by GAC during one year of evaluation using a 20 minute EBCT (Figure 4). Another CHI detected at higher

concentrations of alachlor. Concentrations of alachlor ranged from 13-593 ng/L during the one-year evaluation with an average of 127 ng/L. Alachlor was observed to be very effectively removed with a 20 minute EBCT GAC column as shown in Figure 5.

The Cincinnati Water Works, which uses river water as its source, has also detected many organics in the influent. GAC has been shown to remove most of the contaminants. Figure 6 shows a gas chromatographic (GC) profile of these organics in the conventional plant effluent and removal through GAC after 15 minutes EBCT. Many of the peaks controlled by GAC represent various organic compounds including SOCs. The GC profile demonstrates GAC's ability to perform as a broad spectrum adsorbent.

Although GAC is effective in removing many organic compounds from water, it will eventually become exhausted. A major cost of using GAC is associated with the replacement or reactivation of spent carbon.¹⁷ On-site reactivation offers the possibility of minimizing these costs. However, associated with on-site reactivation is the potential of producing by-products from the precursor materials or organics adsorbed on the carbon. These by-products could consist of polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) depending on the precursors available for reaction in the reactivation furnaces.

An evaluation of this possibility was investigated for two different types of granular activated carbon furnaces; fluidized-bed and infrared. The fluidized-bed furnace was located at Cincinnati, Ohio, and processed 265 kg/hr (583 lb/hr) of carbon that had been exposed to Ohio River water. The infra-red furnace was located at Jefferson Parish, Louisiana, and processed 98 kg/hr (216 lb/hr) of carbon that had been exposed to lower Mississippi River water.

Low concentrations of PCDDs and PCDFs were emitted into the atmosphere during GAC reactivation accompanied by an afterburner. However, the resulting cancer risks to the exposed population were between 5×10^{-11} and 1.3×10^{-7} as shown in Table 3.¹⁸

Control of Disinfection By-Products. The major disinfection by-products of concern in the United States have been the trihalomethanes (chloroform, bromodichloromethane, dibromochloromethane, and bromoform). These organic compounds are produced by free chlorine reaction with naturally occurring humic precursors. Concentrations of several hundred parts per billion (ppb) at a consumer's

tap have not been uncommon. A regulation promulgated by the Environmental Protection Agency requires community water systems to maintain a total trihalomethane concentration of less than 0.10 mg/L.

Three approaches have been investigated for trihalomethane control: 1) removal of trihalomethanes, 2) removal of trihalomethane precursors, and 3) the use of disinfectants other than free chlorine.¹⁹ Figure 7 illustrates the reduction in trihalomethane formation potential that can be accomplished by GAC.²⁰

Current Field Studies. Most of the research conducted in the past by DWRD has been devoted to demonstrating the effectiveness of GAC for surface water treatment.²¹ More recently, DWRD has been conducting studies that incorporated the use of carbon treatment for removal of SOCs from groundwater.²² GAC has been studied for removing contaminants from groundwater at Suffolk County, New York; California's San Joaquin Valley, and Wausau, Wisconsin. Each of these projects were designed to examine a different aspect of GAC application and, except for Wausau, they are intended to deal with pesticide contamination problems.⁶ In Tiffin, Ohio, powdered activated carbon has been studied for its use in removing pesticides from surface water.²³ A project in Jefferson Parish, Louisiana examined the effects of alternate disinfectants and the production and control of disinfection byproducts.

In Suffolk County, the removal of organics and pesticides, including aldicarb, carbofuran, 1,2-dichloropropane, 1,2,3-trichloropropane, and nitrates have been studied. Two parallel treatment systems (one consisting of GAC and ion exchange and the other consisting of reverse osmosis) have been operated at low flows similar to home usage (Figure 8). The carbon system treated 56.8 Lpm (15 gpm) of water. Three contactors in series were used. Each GAC contactor contained 0.08 m³ (3 ft³) of carbon which amounted to 5 minutes of EBCT. Examples of GAC performance over a one-year period are shown in Figures 9 through 11. The costs for these two systems were established along with unit operating efficiency so that a larger public water supply system can be designed and tested. The results from this study will be applicable to other areas, especially in farming communities where multiple contamination of groundwater is identified.

The principal objectives of the San Joaquin Valley study were to: 1) develop cost-effective design criteria for the removal of dibromochloropropane and other pesticides from water supplies by GAC, and 2) to improve and strengthen existing administrative guidelines and jurisdictional responsibilities pertaining to both community water systems and private wells containing the compounds of interest.

Pilot studies conducted with GAC, and results were compared with those from existing operating systems. Microcolumn studies were used to predict breakthroughs. The focus in this study was on point-of-entry GAC units that are now being used by small systems, individual homeowners, and farmers in the area.

Powdered activated carbon, added to the water normally treated only by conventional treatment at Tiffin, Ohio, appears to be effective for removing periodically high concentrations of pesticides.²³

During a study at Jefferson Parish, Louisiana designed to study the effects of alternative disinfectants (ozone, chlorine dioxide, chloramine, and chlorine) and GAC adsorption removal of over one hundred volatile and semi-volatile organic compounds were evaluated.²⁴ Also, a number of disinfection by-products were detected with the majority observed for chlorine. Some of these halogenated and non-halogenated compounds were identified but a majority were unidentified.

In May, 1989, a second study will begin at Jefferson Parish to focus on the alternative disinfectants previously evaluated and the production and control of disinfection byproducts. The by-products include trihalomethanes, haloacetonitriles, haloacids, haloaldehydes, haloketones, chlorophenols, chloropicrin and cyanogen chloride. The effectiveness of GAC following sand filtration in removing these by-products, their precursors, and other organic compounds will be evaluated. Another site, in Wausau, Wisconsin, has multiple contaminants in its groundwater source from a nearby Superfund site. GAC was the primary technology studied, but air-stripping was examined as a companion technology. The Wausau project was unique in that modeling techniques were used to predict full-scale design criteria for a GAC plant. These predictions were evaluated against the actual cost and performance associated with the building of GAC contactors onsite. The results from this study provided a useful methodology for extension to other GAC applications. The modeling techniques will be particularly useful in studying SOC's. In addition to modeling, microcolumn technology was also studied.

In Wausau, cis-1,2-dichloroethene (c-DCE) was present in the groundwater along with several other SOC's.²⁵ A full-scale GAC bed employing Filtrasorb 400 and operated at 6.25 m/hr (2.6 gpm/ft²) was employed. Breakthrough profiles for the column midpoint and the column effluent are given in Figure 12 and, similar to the pilot operation in Suffolk County, New York, indicate increased bed life with operation of a deeper contactor. During the fifth month of operation, effluent cis-DCE concentrations exceeded the influent concentrations. Higher effluent concentrations were

likely the result of more strongly adsorbed TCE and PCE, displacing cis-DCE from the top of the bed. Because influent cis-DCE concentrations were decreasing following the third month of operation, the desorption of cis-DCE may have also resulted from this shift in equilibrium. Assuming a 70 ug/L MCL for cis-DCE and examining the performance of the contactor before the influent cis-DCE concentration began to decline, it appears that GAC replacement would not have been necessary until near the fourth month of operation.

At a site in Lansdale, Pennsylvania where aeration technologies were studied by EPA, the affected authority operated full-scale GAC contactors in series. The influent water contained a 30 to 100 ug/L concentration of TCE that varied seasonally and only trace levels of other SOC's. Contactors employing 1.5-m (5-ft) depths of Filtrasorb 300 provided 7.5-min EBCT each. GAC replacement would have been required during the third or seventh month of operation, depending on contact time, as dictated by a 5 ug/L MCL.²⁶ Of interest was the fact that TCE never reached exhaustion in the first contactor. It was assumed that a microbial population was established that degraded 5 to 10 ug/L of influent TCE. Similar patterns of assumed biodegradation were noted in earlier DWRD-sponsored studies of chloroform and THM adsorption.²⁷

Prediction of Adsorber Performance

One of the critical parameters in determining the cost of GAC treatment is the bed-life as determined by the carbon use rate, i.e., quantity of carbon required to treat a specified volume of water. As mentioned earlier, because of the short regulatory deadlines imposed by the Amendments to the SDWA and decreasing research funds, the DWRD is not able to field test for control of every SOC. Therefore, the DWRD has opted to use mathematical models to supplement pilot- and full-scale data.

The constant-pattern-homogeneous-surface-diffusion model (CPHSDM) has been used to estimate GAC use rates for selected single-solute SOC's.²⁸ Input parameters required by the CPHSDM are: the Freundlich K and 1/n values as determined from an isotherm, adsorptive rate data concerning the surface diffusion and film transfer coefficients, the mean carbon particle radius, the carbon's bulk and apparent densities, the hydraulic loading rate, the EBCT, and the mean influent concentration of the SOC.

The correlation developed by Williamson, et al.²⁹ was used to determine the film transfer coefficient. The surface diffusion coefficient was determined from a

correlation used by Dobrzelewski.³⁰ The CPHSDM-predicted use rates presented in Table 4 were determined using a poresurface-diffusion-flux ratio (PSDFR) of 3.72 for all SOC's by Crittenden, et al.³¹ In addition, use rates for some of the relatively less strongly adsorbed SOC's were determined using a PSDFR of 0.4 to examine the subsequent reduction in bed life. A PSDFR of 0.4 has been suggested when influent waters are higher in background organic material that both preloads the bed and offers competition to SOC's for adsorption sites.³¹

Table 4 presents selected influent and effluent criteria and CPHSDM-predicted use rates. For each SOC, the CPHSDM-predicted use rate and bedlife are shown corresponding to the single-solute isotherm data and the type of water in which the isotherm studies were conducted. The predicted use rates assumed a single, post-filter, full-scale contactor with an EBCT of 15 minutes, hydraulic loading of 9.6 m/hr (4 gpm/ft²), using Filtrasorb 400 GAC.

The predicted performance indicates GAC bed lives generally in the range of three months to two years. Although conditions are not the same, this range of bed lives is consistent with those observed in DWRD field studies noted earlier. Where GAC is used for taste-and-odor control, bed lives of two-to-three years are typical and considered to be affordable. Therefore, the use of mathematical models predicting bed lives for VOC control in the range of two or more years may be a sufficient substitute for field studies where time and resources are limited.

The limitations of the CPHSDM are of greater concern when short bed lives (and higher costs) are predicted. The data presented in Table 4 involve single-solute SOC's. In natural waters, multi-solute SOC's would be expected. A weakly adsorbed SOC in the presence of more strongly adsorbed compounds would likely exhibit higher GAC use rates (shorter bed-lives) resulting from competitive adsorption and displacement. Even strongly adsorbed SOC's in the presence of other strongly-adsorbed compounds may exhibit higher use rates resulting from competitive adsorption. The modeling used in this analysis also did not account for possible reductions of the GAC's capacity from naturally occurring dissolved organic matter being preloaded onto the carbon. While PSDFR's of 3.72 and 0.4 are largely unproven, the use of the 0.4 ratio yields the shorter bed lives anticipated in competitive situations. The potential effects of backwashing the carbon were also not considered by the model. Nevertheless, the CPHSDM-predicted use rates for the selected SOC's give a general picture of adsorbability, useful for preliminary design and cost analysis.

The ability of the CPHSDM to predict column performance was verified at the

Wausau, Wisconsin project. Wausau water spiked with cis-D. was treated on the pilot scale where Filtrasorb 400 GAC was loaded at 9.5 m/hr (3.9 gpm/ft²). The column performance compared reasonably with the predicted performance, as described in Figure 13. The ability of this model to predict breakthrough profiles of single-SOC contaminants lends support to the data presented in Table 4. The ability of models to predict multi-SOC performance in matrices of higher concentrations of naturally-occurring dissolved organic material remains largely unverified, however.

Cost and Performance Analysis

DWRD has conducted extensive studies applying cost analysis together with performance data to predict full scale system behavior.³² Figure 14 which illustrates the results of this analysis, shows where various SOC's with their specified criteria fall on the cost curves, based on the results of the adsorption modeling presented earlier. Most of the SOC's presented in Table 1 exhibited bed lives of two years or more which is typically observed for taste-and-odor control by GAC. In this analysis, GAC treatment cost estimates for compounds having multi-year bed lives appear to range from about 41 cents/1000 gal for a 1 MGD system, to about 27 cents/1000 gal for a 10 MGD system to about 14 cents/1000 gal for a 100 MGD system.

SUMMARY AND CONCLUSIONS

DWRD and its predecessor organizations have been conducting research into the use of GAC as applied to water treatment for many years. The 1986 Amendments to the Safe Drinking Water Act make GAC a baseline technology against which all other organic control technologies must be measured. Although DWRD has a tradition of evaluating a technology at the bench, pilot and field scale, the accelerated regulatory schedule under the Amendments will not allow the time for this type of evaluation. Therefore, DWRD has incorporated modeling with bench, pilot-column and field-scale data to predict full-scale cost and performance.

REFERENCES

1. Woodward, R. L., Dostal, K. A. and Robeck, G. G. Granular Activated Carbon Beds for Odor Removal." *JAWWA*, 56:3:287-295, 1964.
2. Robeck, G. G., Dostal, K. A., Cohen, J. M., Kreissl, J. F., "Effectiveness of Water Treatment Processes in Pesticide Removal." *JAWWA*, 57:2:181-120, 1966.

3. Dostal, K. A., Pierson, R. C., Hager, D. G., Robeck, G. G., "Carbon Bed Design Criteria Study at Nitro, W. Va." JAWWA, 57:5:663674, 1965.
4. Dostal, K. A., Harrington, T. J., Clark, R. M., and Robeck, G. G., "Development of Optimization Models for Carbon Bed Design." JAWWA, 58:9:1170-1186, 1966.
5. Federal Register, 43, No. 28, 5756-5780 (February 9, 1978).
6. The Safe Drinking Water Act Amendments of 1986, PL 99-339.
7. Dyksen, J. E., Hildebrand, D. J., and Racsko, R. F., "SDWA Amendments: Effect on the Water Industry." JAWWA, 80:1:30-35, 1988.
8. Clark, R. M., Adams, J. Q. and Miltner, R. M., "Cost and Performance Modeling for Regulatory Decision Making." Water Spring 1987, Vol. 28, No. 1, pp. 20-27.
9. Clark, R. M., Fronk, C. A., Lykins, B. W. Jr., "Removing Organic Contaminants from Groundwater." Environmental Science and Technology, Vol. 22, No. 10, October 1988, pp. 1126-1129.
10. U.S. Environmental Protection Agency "Program Peer Review. Granular Activated Carbon Research vs. Regulatory Agenda Needs for Phase II Organic Compounds." Drinking Water Research Division, March 1986.
11. Clark, R. M., Miltner, R. J., Fronk, C. A., Speth, T. F., "Unit Process Research for Removing VOCs from Drinking Water: An Overview." In Significance and Treatment of Volatile Organic Compounds in Water Supplies, Lewis Publishers, Inc., Chelsea, Mich., 1989 (In Press).
12. Speth, T. F., Miltner, R. J., "An Evaluation of GAC Adsorption Capacities for SOCs." Submitted to JAWWA for possible publication in 1989.
13. Westerhoff, G. P. and R. Miller (1986) "Design of the GAC Treatment Facility at Cincinnati." JAWWA 78:4:146.
14. Crittenden, J. C., Berrigan, J. K. and Hand, D. W., "Design Of Rapid Small Scale Adsorption Tests for a Constant Surface Diffusivity." JWPCF 58:4: 312-310, 1986.

15. Speth, T. F. and Miltner, R. J. (1988) "Effect of Preloading Scale-Up of GAC." JAWWA 1:4, 141-148, 1989.
16. Love, O. T. and Eilers, R. G., (1982) "Treatment of Drinking Water Containing Trichloroethylene and Related Industrial Solvents." JAWWA 74:8:413-425.
17. Adams, J. Q., Clark, R. M., Lykins, Jr., B. W., and Kittredge, D., "Regional Reactivation of Granular Activated Carbon." JAWWA 78(5), 38-41, 1986.
18. Lykins, Jr., B. W., Clark, R. M., Cleverly, D. H., "Polychlorinated Dioxin and Furan Discharge During Carbon Reactivation." Journal of Environmental Engineering, ASCE, 114:2:300-316, 1987.
19. Symons, J. M., Stevens, A. A., Clark, R. M., Geldreich, E. E., Love, O. T., and DeMarco, J., "Treatment Techniques for Controlling Trihalomethanes in Drinking Water." EPA-600/2-81-156, 1981.
20. Lykins, B. W. Jr., Clark, R. M., Adams, J. Q., "Granular Activated Carbon for Controlling THMs." JAWWA, 80:5, 85-82, 1988.
21. Lykins, Jr., B. W., Geldreich, E. E., Adams, J. Q., Ireland, J. C., and Clark, R. M., "Granular Activated Carbon for Removing Nontrihalomethane Organics from Drinking Water." EPA-600/S2-84-165, 1984.
22. Feige, W. A., Clark, R. M., Lykins, Jr., B. W., and Fronk, C. A., "Treatment of Water from Contaminated Wells, Rural Groundwater Contamination." Lewis Publishers, Inc., 1987.
23. Miltner, R. J., Baker, D. B., Speth, T. F., and Fronk, C. A., "Treatment of Seasonal Pesticides in Surface Waters." JAWWA 81:4 43-56, 1989.
24. Koffskey, W. E. and Lykins, B. W. Jr., "Alternative Disinfectants and Granular Activated Carbon Effects on Trace Organic Contaminants." EPA/600/52-87/006, 1987.
25. Hand, D. W., Crittenden, J. C. and Gehin, J. L. (1988) "Performance of Air Stripping and GAC for SOC and VOC Removal from Groundwater." CR811/50, USEPA, Drinking Water Research Division, Cincinnati, OH.
26. "Technologies and Costs for the Removal of VOCs from Potable Water

Supplies." (ESE 84-912-156, USEPA, Drinking Water, Washington, DC.

27. Symons, J. M., Stevens, A. A., Clark, R. M., Geldrieck, E. E., Love, O. T. and DeMarco, J. (1981) "Treatment Techniques for Controlling Trihalomethanes in Drinking Water." EPA-600/2-81-156, USEPA, Drinking Water Research Division, Cincinnati, OH.

28. Hand, D. W., Crittenden, J. C. and Thacker, W. E., "Simplified Model for Design of Fixed-Bed Adsorption Systems." Journal of Environmental Engineering, ASCE 110:2:440-456, 1984.

29. Williamson, J. E., Bazaire, K. E. and Geankopolis, C. J. (1963) "LiquidPhase Mass Transfer at Low Reynolds Numbers." Industrial and Engineering Chemistry Fundamentals 2:2:126-129, 1963.

30. Dobrzewski, M. (1985) "Correlations for the Determination of Surface Diffusivities of Organic Chemicals Adsorbed onto Granular Activated Carbon." MS Thesis, Michigan Technological University, Houghton, MI.

31. Crittenden, J. C., Hand, D. W., Arora, H. and Lykins, Jr., B. W. "Design Considerations for GAC Treatment of Organic Chemicals." JAWWA 79:1:74-82, 1987.

32. Adams, Jeffrey Q. and Clark, Robert M., "Cost Estimates for GAC Systems." JAWWA, 81:1:35-42, 1989.

TABLE 1. ISOTHERM VALUES USING FILTRASORB 400 CARBON

Compound	Water	Temperature °C	Number of Data Points	Ce Range** ug/L	Freundlich Values		
					K (ug/g) (L/ug) ^{1/n}	1/n	1/n
Benzene	DD*	24	10	462-3.3	1260	2.5	0.533
Bromobenzene	DD	24	14	2531-23.2	17200	2.12	0.364
Bromodichloro- methane	DD	24	9	333-12.0	241	22.2	0.655
Bromoform	DD	24	16	130-1.9	929	91.8	0.665
	DD	14	17	13240-48.4	2890	96.5	0.492
	OR	24	7	100-5.9	1350		0.428
Carbon tetrachloride	DD	24	18	429-9.1	387	23.4	0.594
Chlorobenzene	DD	24	16	732-15.4	9170	101	0.348
	OR	24	7	401-14.1	11100		0.302
	OR	24	4	369-31.9	7690		0.343
Chloroform	DD	24	14	226-11.2	95.5	9.7	0.669
	DD	14	27	7074-16.4	155	16.0	0.671
	OR	24	8	100-10.2	112		0.564
o-Chlorotoluene	DD	24	16	2150-6.0	23200	316	0.378
Dibromochloro- methane	DD	24	7	116-5.0	585	47.3	0.636
	DD	14	20	6470-9.3	1110	39.5	0.517
1,2-Dibromo-3- chloropropane (DBCP)	DD	24	17	69.2-0.2	6910	220	0.501
	OR	24	9	85.8-0.3	3780		0.452
	OR	24	3	53.7-0.8	4250		0.417
	OR	24	8	30.8-0.2	4190		0.511
1,2-Dibromoethane (EDB)	DD	24	17	111-0.2	888	23.0	0.471
	DD	14	21	10000-15.2	1400	53.7	0.528
	OR	24	10	139-1.1	765		0.541
1,2-Dibromomethane	DD	24	14	175-22.6	44.4	12.0	0.811
o-Dichlorobenzene	DD	24	16	1056-13.7	19300	263	0.378
	OR	24	8	293-58.9	8430		0.530
p-Dichlorobenzene	DD	24	29	234-5.7	4970	588	0.691

"Design Considerations for GAC Treatment of Organic Chemicals",

TABLE 1. (Cont'd)

Compound	Water	Temperature °C	Number of Data Points	Con Range** µg/L	Freundlich Values K (µg/g) ^{1/n} 1/n
1,1-Dichloroethane	DD	24	25	559-13.4	64.6 8.5 0.706
1,2-Dichloroethane	DD	24	9	717-42.8	129 5.1 0.533
1,1-Dichloroethane	DD	24	6	392-69.0	470 16.5 0.515
cis-1,2-Dichloroethane	DD	24	38	615-5.1	202 11.7 0.587
	DD	24	7	5180-11.3	396 0.526
	DD	24	8	214-9.7	123 0.533
	DD	24	8	382-8.6	129 0.648
	DD	24	8	210-18.9	121 0.638
trans-1,2-Dichloroethane	DD	24	17	415-13.5	618 14.0 0.452
	DD	24	10	406-26.5	533 0.424
1,2-Dichloropropane	DD	24	29	196-4.1	313 0.597
	DD	24	7	126-4.6	452 0.442
	DD	24	5	108-7.3	357 0.545
Ethylbenzene	DD*	24	7	565-39.4	9270 16.3 0.415
	DD	24	10	2820-4.4	17700 0.307
Methylene Chloride	DD	24	9	715-8.1	6.25 1.6 0.801
Styrene	DD*	24	8	148-11.8	12200 334 0.479
1,1,1,2-Tetra-chloroethane	DD	24	14	738-1.2	1070 69.4 0.604
Tetrachloroethane	DD	24	29	421-3.6	4050 14.3 0.516
	DD	24	15	8021-22.4	6820 0.478
Toluene	DD*	24	12	104-2.3	5010 9.7 0.429
	DD	24	10	2450-5.2	9910 0.328
	DD	24	9	672-2.5	6140 0.365
1,3,5-Trichlorobenzene	DD	24	16	856-6.8	63800 59.8 0.324
1,1,1-Trichloroethane	DD	24	11	860-14.6	335 13.1 0.531
	DD	24	8	375-7.8	364 0.501
	DD	24	9	366-56.9	520 0.456
	DD	24	5	601-29.2	352 0.495
Trichloroethane	DD	24	17	442-7.7	2000 55.9 0.482
	DD	24	23	8430-3.0	4710 0.361
	DD	24	9	380-21.2	1180 0.484

TABLE 1. (Cont'd)

Compound	Water	Temperature °C	Number of Data Points	Con Range** µg/L	Freundlich Values K (µg/g) ^{1/n} 1/n
1,2,3-Trichloropropane	DD	24	15	741-3.4	1080 74.5 0.613
	DD	24	7	256-12.2	1540 0.449
m-Xylene	DD	24	4	3784-38.5	35800 2.00 0.249
o-Xylene	DD	24	5	4378-52.7	30900 16.3 0.241
	DD	24	5	522-10.4	9760 0.474
p-Xylene	DD	24	8	32.7-1.6	12600 2.26 0.418
	DD	24	5	232-3.9	7660 0.459

* = ethanol co-solvent used

** = liquid-phase equilibrium range

DD = distilled water

OR = filtered Ohio River water

GWA = Great Miami Aquifer, OH

$$Let \quad K_1 = \left(\frac{mg}{g} \right) \left(\frac{L}{mg} \right)^{1/n}$$

TO CONVERT TO

$$K_2 = \left(\frac{mg}{g} \right) \left(\frac{L}{mg} \right)^{1/n}$$

$$K_2 = \frac{K_1}{1000} \left(\frac{1000}{mg} \right)^{1/n}$$

TABLE 2. CHLORINATED HYDROCARBON INSECTICIDES (CHI) DETECTED
AT JEFFERSON, PARISH, LA

CHI	Occurrence	Detected Conc. (ng/L)		
	Frequency (%)	Min	Max	Avg
aldrin	100	0.20	0.92	0.53
α -BHC	100	1.14	6.75	2.78
β -BHC	100	0.87	3.33	1.64
γ -BHC (lindane)	100	0.40	9.06	1.39
α -chlordane	100	0.12	0.47	0.27
γ -chlordane	100	0.15	0.55	0.31
oxy-chlordane	92	0.02	0.35	0.09
α -chlordene	89	0.02	0.46	0.14
β -chlordene	93	0.08	32.5	7.55
γ -chlordene	96	0.06	0.77	0.43
DCPA*	100	0.17	5.42	1.42
o,p'-DDD	100	0.13	1.13	0.44
m,p'-DDD	56	0.03	1.34	0.36
p,p'-DDD	93	0.17	1.28	0.57
o,p'-DDE	96	0.08	0.83	0.30
p,p'-DDE	100	0.06	0.32	0.16
o,p'-DDT	59	0.03	7.80	0.68
p,p'-DDT	85	0.07	1.25	0.36
dieldrin	100	1.63	5.80	2.84
endosulfan-2	96	0.02	0.72	0.29
endrin	100	0.25	1.58	0.67
heptachlor	92	0.03	33.3	6.95
heptachlor epoxide	100	0.28	1.68	0.73
hexachlorobenzene	100	0.35	1.59	0.66
pentachloronitrobenzene	96	0.04	0.27	0.15
perthane	77	0.86	23.4	8.99

*dimethyl-2,3,5,6-tetrachloroterephthalate

TABLE 3. RISK EXPOSURE FROM GAC REACTIVATION

Reactivator Type	Size (kg/hr)	Compounds	Afterburner	Maximum Individual Cancer Risk ^c
Fluidized Bed	265 ^a	TCDD	d	1.3 x 10 ⁻⁷
Fluidized Bed	265 ^a	2,3,7,8-TCDD ^a Equivalence	on	5 x 10 ⁻⁸
Fluidized Bed	265 ^a	2,3,7,8-TCDD Equivalence	on	5 x 10 ⁻¹¹
Fluidized Bed	1,141 ^b	2,3,7,8-TCDD Equivalence	off	4 x 10 ⁻⁸
Fluidized Bed	1,141 ^b	2,3,7,8-TCDD Equivalence	on	6 x 10 ⁻¹¹
Infrared	98 ^a	2,3,7,8-TCDD Equivalence	on	3 x 10 ⁻⁹

a - Pilot plant

b - Estimated full-scale from pilot plant

c - Defined as the probability of cancer to an individual continuously exposed for 70 years to the maximum ambient concentration of 2,3,3,7,8-TCDD equivalence.

d - No afterburner in reactivation system.

e - Tetrachloro-dibenzo-p-dioxins

TABLE 4. PREDICTED FULL-SCALE GAC USE RATES FOR SINGLE-SOLUTE SOCS

SOC	Water Type	PSDFR	Freundlich		Selected Criteria		CPHSDM Pr	
			K ₁	1/n	Co (ug/L)	Ce (ug/L)	Use Rate (lbs/1000 g)	Use Rate (lbs/1000 g)
Cis-1,2-dichloroethylene	1	3.72	30.5	0.59	200	70	0.379	
Cis-1,2-dichloroethylene	2	3.72	23.0	0.63	200	70	0.491	
Cis-1,2-dichloroethylene	3	3.72	16.7	0.36	200	70	0.809	
Cis-1,2-dichloroethylene	4	3.72	29.4	0.64	200	70	0.383	
Cis-1,2-dichloroethylene	3	0.4	16.7	0.36	200	70	0.930	
Cis-1,2-dichloroethylene	4	3.72	29.4	0.64	100	70	0.279 ^c	
Cis-1,2-dichloroethylene	3	--	--	--	200	70	0.910 ^c	
Cis-1,2-dichloroethylene	6	--	--	--	200	70	0.464 ^c	
Alachlor	4	3.72	328.0	0.38	100	2	0.015	
Aldicarb	4	3.72	194.0	0.41	500	10	0.0833	
Aldicarb	4	0.4	194.0	0.41	500	10	0.1404	
Aldicarb	4	0.4	194.0	0.41	100	10	0.0524	
Aldicarb Sulfone	5	--	--	--	50	9	0.365 ^c	
Aldicarb Sulfoxide	5	--	--	--	50	9	0.371 ^c	
Atrazine	2	3.72	787	0.36	250	5	0.0126	
Carbofuran	4	3.72	376	0.36	100	40	0.0136	
Chlorobenzene	4	3.72	381.0	0.31	600	6	0.0742	
Chlorobenzene	4	3.72	381.0	0.31	100	5	0.0211	
Chlordane	1	3.72	346	0.33	50	2	0.0065	

TABLE 4. Cont'd

SOC	Water Type	PSDFR	Freundlich		Selected Criteria		CPHSDM Pr	
			K ₁	1/n	Co (ug/L)	Ce (ug/L)	Use Rate (lbs/1000 g)	Use Rate (lbs/1000 g)
2,4-D	1	3.72	194	0.27	500	70	0.0813	
2,4-D	1	3.72	194	0.27	100	70	0.0239	
DBCP	4	3.72	206.0	0.46	20	0.2	0.0116	
1,2-Dichloropropane	4	3.72	35.8	0.48	100	5	0.2332	
1,2-Dichloropropane	4	0.4	35.8	0.48	100	5	0.3430	
1,2-Dichloropropane	4	0.4	35.8	0.48	10	5	0.0737	
1,2-Dichloropropane	5	--	--	--	100	6	0.494 ^c	
o-Dichlorobenzene	1	3.72	865	0.38	1000	600	0.0316	
EDB	4	3.72	69.3	0.54	50	0.5	0.733	
EDB	4	0.4	69.3	0.54	50	0.5	0.1541	
EDB	4	0.4	69.3	0.54	5	0.05	0.0534	
Ethyl Benzene	1	3.72	507	0.53	1000	700	0.0464	
Heptachlor Epoxide	1	3.72	2020	0.75	10	0.2	0.0021	
Lindane	4	3.72	455	0.39	10	0.2	0.0026	
Methoxychlor	1	3.72	223	0.36	500	300	0.0473	
Pentachlorophenol	4	3.72	403.0	0.365	1000	200\50	0.0499	
Silvex	1	3.72	479	0.38	500	5	0.0294	
Styrene	1	3.72	1083	0.48	500	5	0.0191	
Tetrachloroethylene	1	3.72	341.2	0.516	500	5	0.0469	
Trichloroethane	1	3.72	160	0.48	100	5	0.048	
Trichloroethane	4	3.72	98.2	0.44	100	5	0.078	

TABLE 4. (Cont'd)

SOC	Water Type	PSDR	Freundlich Isotherm		Selected Criteria		DWSM Pr USF 331E (lbz/1000)
			F Isotherm 1/n	CS (mg/L)	CS (lbz/1000)		
Carbon tetrachloride	1	3.72	55.9	0.89	25	5	0.083
1,2-dichloroethane	1	3.72	15.1	0.52	25	5	0.306
1,1,1-trichloroethane	3	3.72	33.8	0.53	500	200	0.471
	4	3.72	32.9	0.52	500	200	0.493
1,1-dichloroethene	1	3.72	63.2	0.52	27	7	0.087
Benzene	1	3.72	185	0.53	25	5	0.031
	7 ^a	3.72	96.3	0.51	25	5	0.064
Toluene	2	3.72	348	0.50	500	200	0.064
Toluene	2	3.72	348	0.50	500	50	0.0734
	4	3.72	38.5	0.39	200	70	0.3422
Trans-1,2-dichloroethylene	4	3.72	38.5	0.39	100	100	0.218
Trans-1,2-dichloroethylene	4	0.4	38.5	0.39	200	70	0.4015
m-Xylene	1	3.72	410	0.75	1000	50	0.0432
p-Xylene	1	3.72	603	0.47	1000	50	0.0487
p-Xylene	2	3.72	611	0.46	1000	50	0.0490

NOTE: WATER TYPE: 1 = TREATMENT WATER

2 = Great Miami Aquifer, Ohio

3 = Hudson, NJ groundwater, 10°-13°C

4 = Filtered Ohio River water

5 = Suffolk County, New York groundwater

6 = Miami, Florida groundwater

a - Single collector, 4 feet³, 15 minute EMT, Filtration 400, 80°C, unless noted

b - 8 in (20 cm) (1/2 in) (12.5 mm)

c - 100 mesh (150 microns) scaling

d - 2 gm/1% competing SOC

e - 2 gm/1% competing SOC

f - 3.5 gm/1% competing SOC

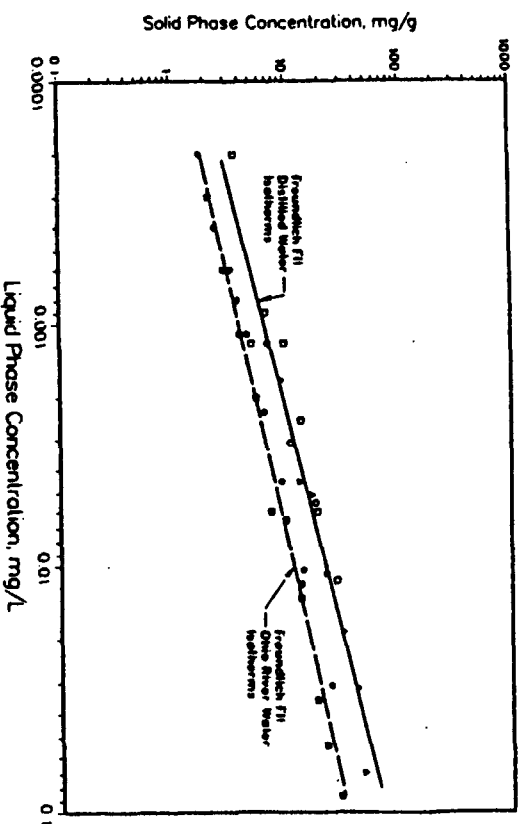


FIGURE 1. ISOTHERMS FOR DIBROMOCHLOROPROPANE

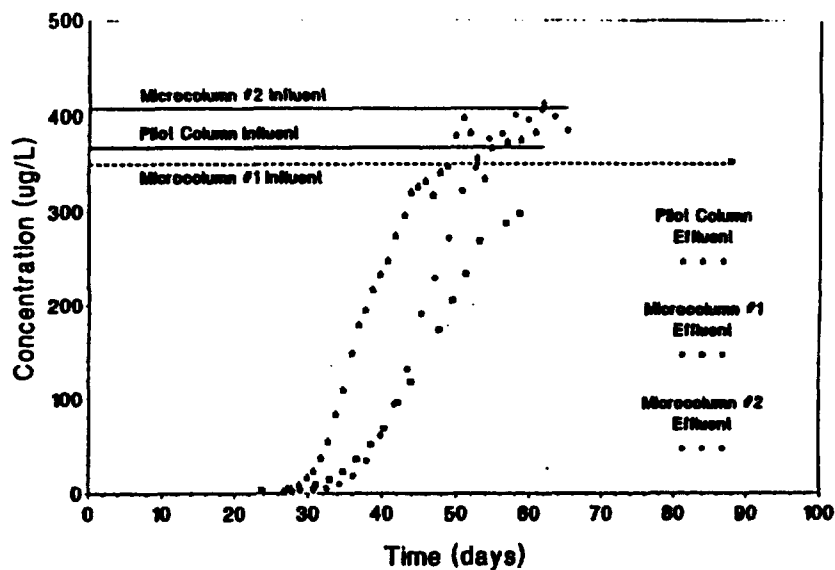


FIGURE 2. COMPARISON OF SCALED-UP MICROCOLUMNS
(CIS-1,2-DICHLOROETHENE)

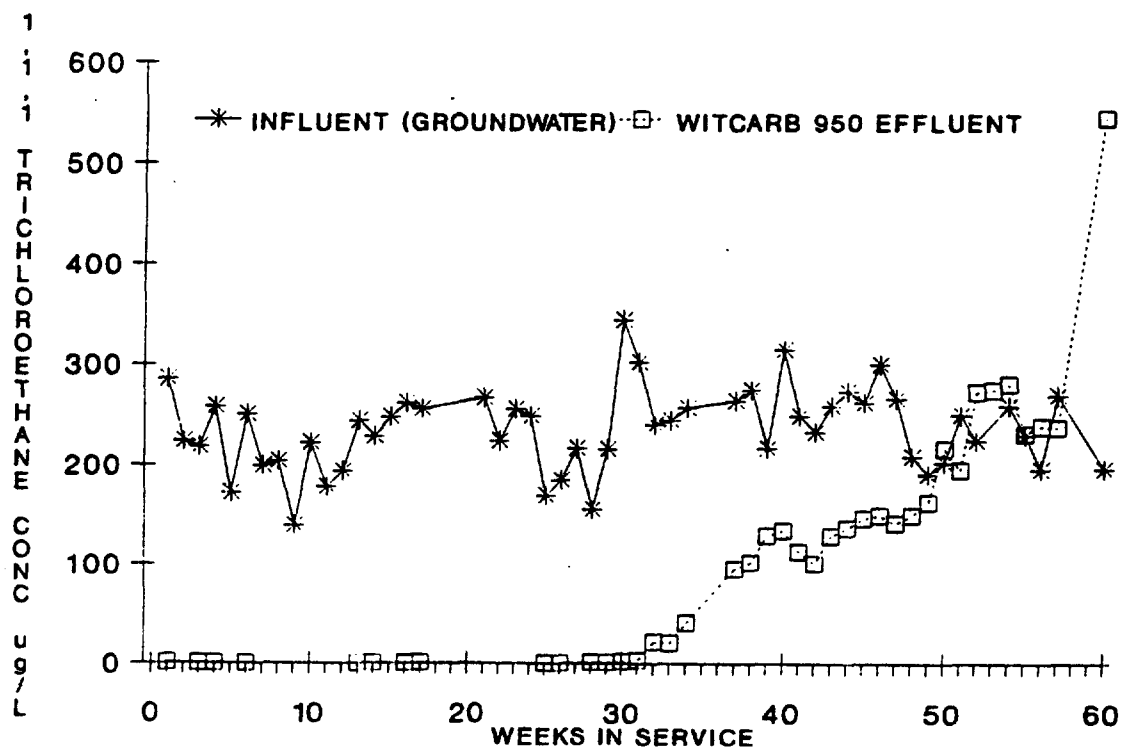


FIGURE 3. SOUTH BRUNSWICK, NJ PILOT STUDY

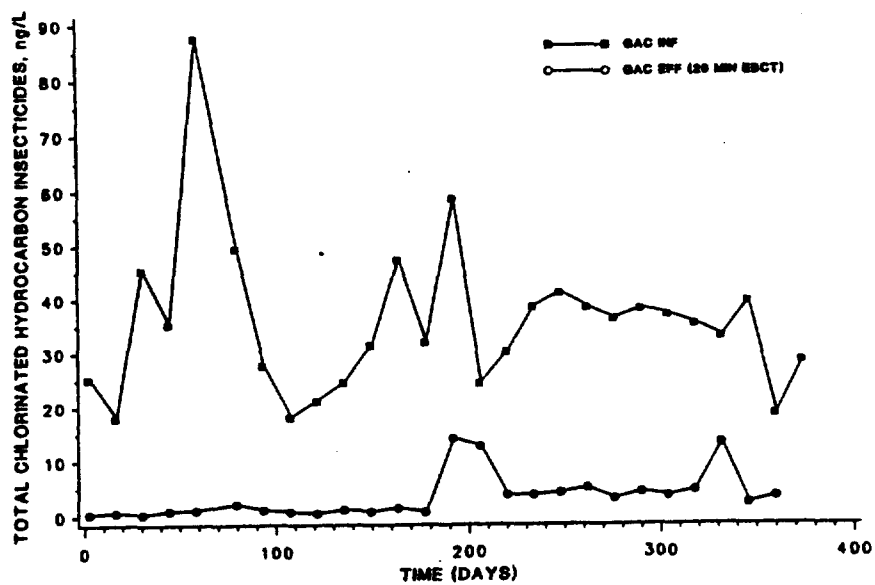


FIGURE 4. TOTAL CHLORINATED HYDROCARBON INSECTICIDE REMOVAL BY GAC AT JEFFERSON PARISH, LA

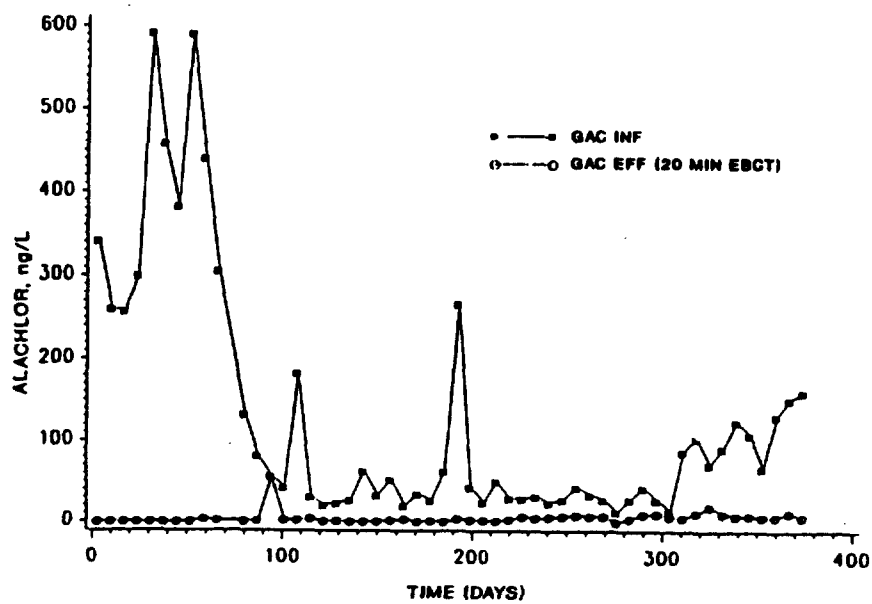


FIGURE 5. ALACHLOR REMOVAL BY GAC AT JEFFERSON PARISH, LA

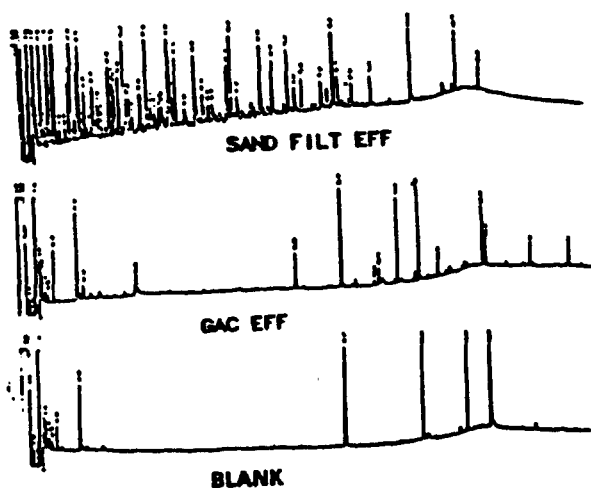


FIGURE 6. GC/FID CAPILLARY COLUMN PROFILES AFTER 29 DAYS OF OPERATION - CINCINNATI, OH

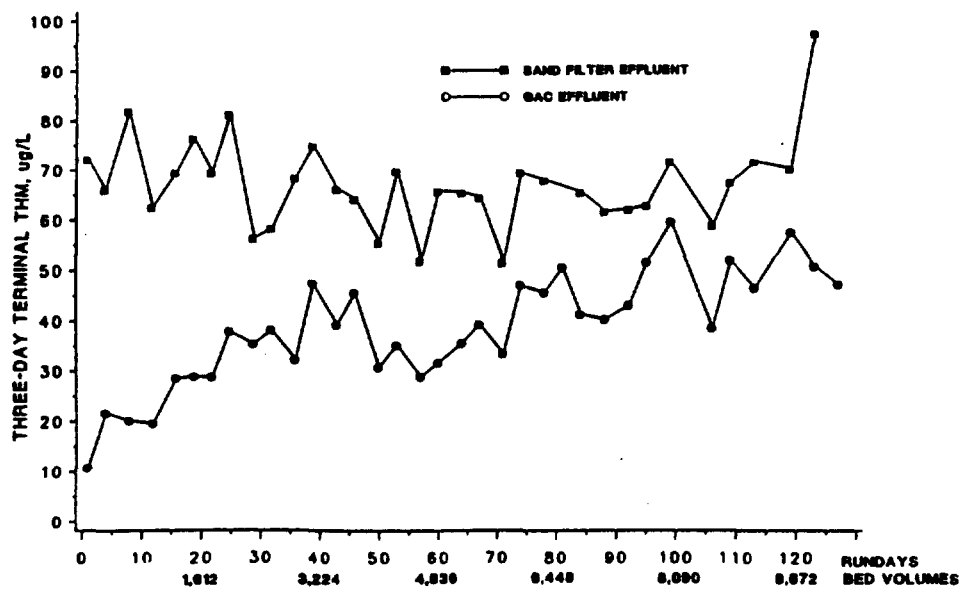


FIGURE 7. TERMINAL THM CONCENTRATIONS AFTER GAC ADSORPTION AT MANCHESTER, NH

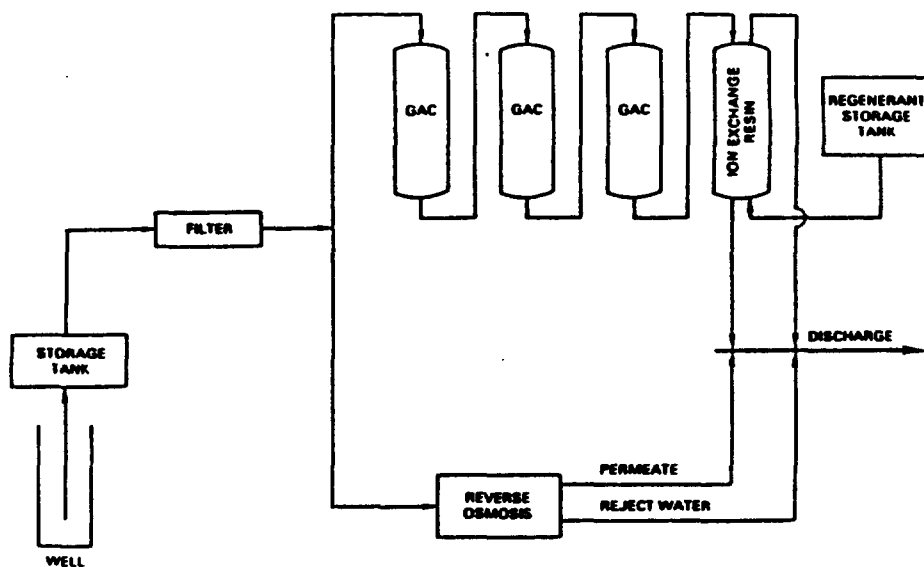


FIGURE 8. FLOW SCHEMATIC FOR PILOT PLANT -
SUFFOLK COUNTY, NY

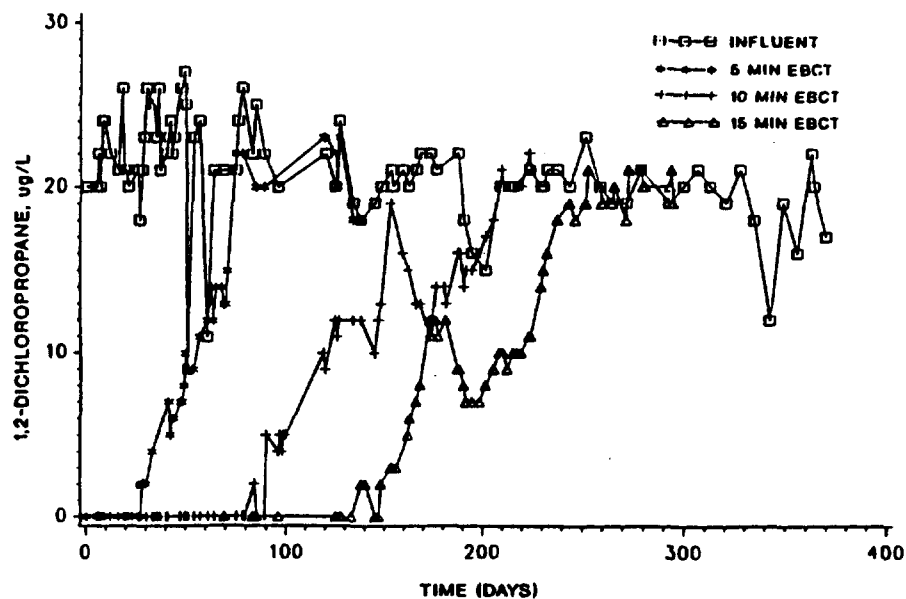


FIGURE 9. REMOVAL OF 1,2-DICHLOROPROPANE BY GAC -
SUFFOLK COUNTY, NY

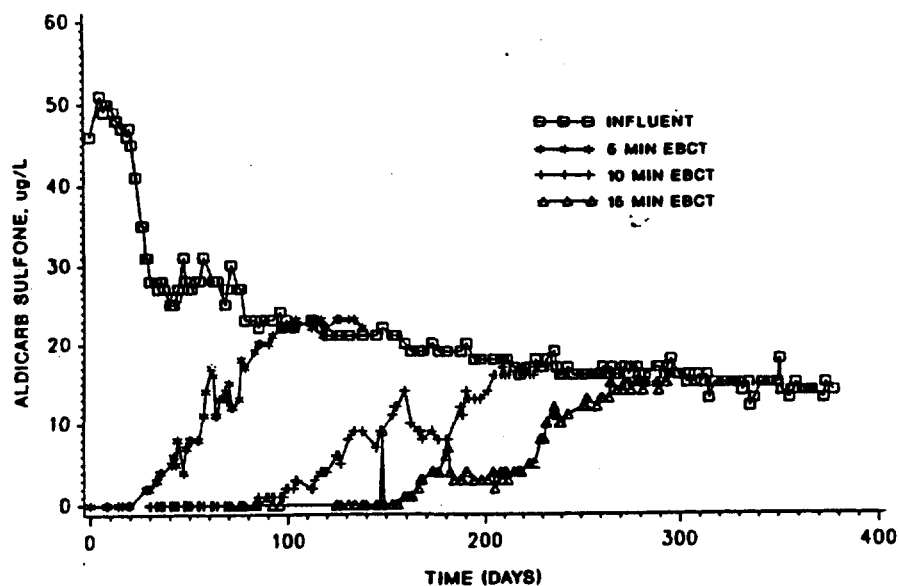


FIGURE 10. REMOVAL OF ALDICARB SULFONE BY GAC - SUFFOLK COUNTY, NY

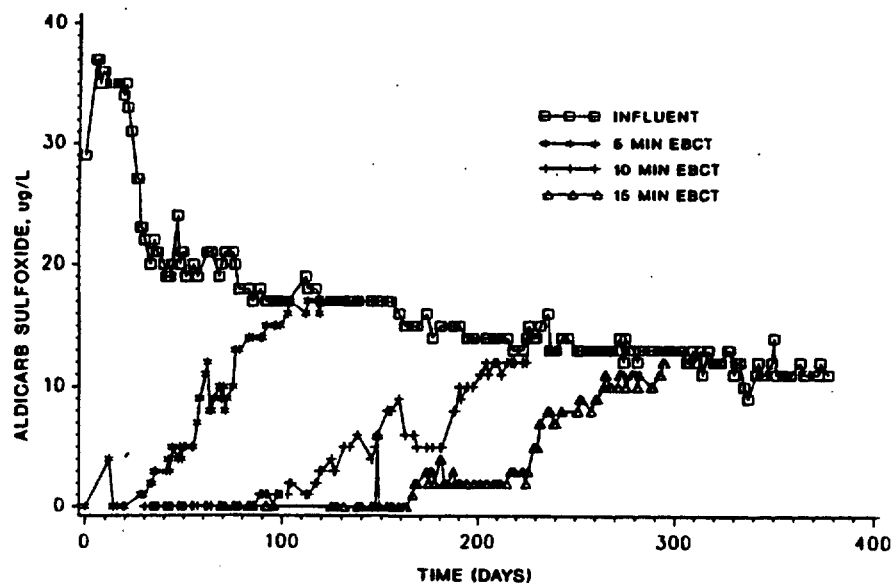


FIGURE 11. REMOVAL OF ALDICARB SULFOXIDE BY GAC - SUFFOLK COUNTY, NY

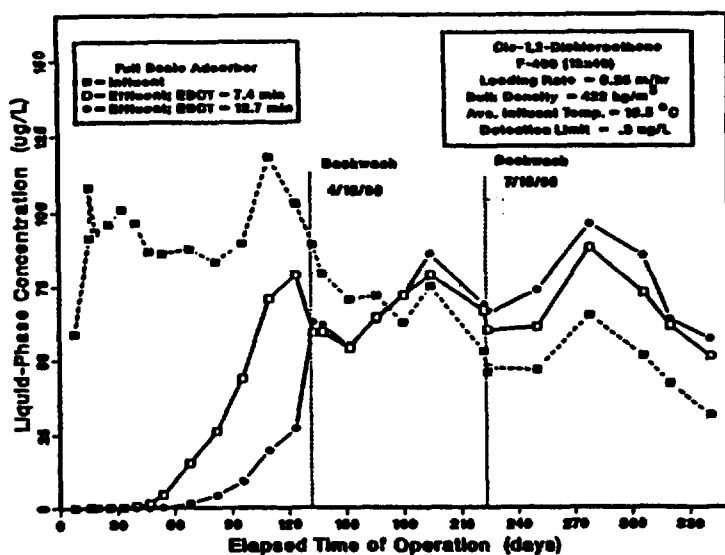


FIGURE 12. BREAKTHROUGH CURVES FOR FULL SCALE ADSORBERS AT WAUSAU, WISCONSIN

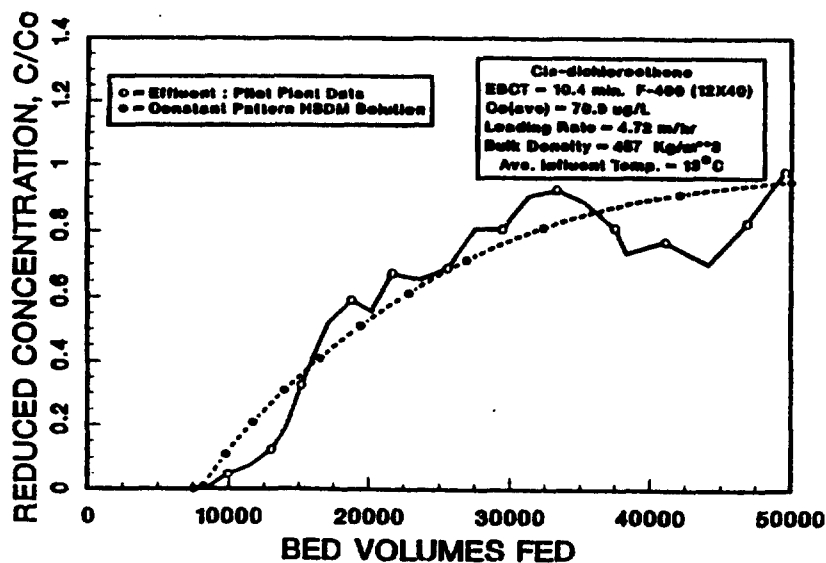


FIGURE 13. PILOT COLUMN EFFLUENT VERSUS MODEL PREDICTIONS