



## Project Summary

# Performance of Air Stripping and GAC for SOC and VOC Removal from Groundwater

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A liquid-phase GAC pilot-plant, a full-scale GAC adsorber, and a full-scale air stripping tower were operated to evaluate process performance for the removal of trichloroethene (TCE) and other volatile organic chemicals (VOCs) and synthetic organic chemicals (SOCs) present in this water supply. Extensive laboratory investigations, including single and multi-solute isotherms, batch rate experiments, and film transfer studies, were conducted to evaluate GAC capacity and kinetics. Rapid small scale column tests (RSSCTs), or mini-columns, were developed and their predictive ability tested by comparison to GAC pilot data. Mathematical models and correlations for obtaining kinetic and single solute isotherm parameters were developed and tested by comparing their results to those obtained from the pilot plant. Possible surrogate parameters such as total organic halogen (TOX), total organic carbon (TOC), trihalomethane formation potential (THMFP), total organic halogen formation potential (TOXFP), and UV absorbance for use in monitoring GAC performance were investigated. Costs of an actual full-scale air stripping process designed for minimum tower volume (lowest capital costs) and energy requirements (lowest operation and main-

tenance costs) and liquid-phase GAC fixed-bed processes designed from pilot-plant data are compared. In addition, the costs for air stripping with GAC off-gas are presented.

*This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).*

### Introduction

Groundwater is the primary source of raw water in Wausau, WI. In 1981, the City of Wausau discovered that several of its wells adjacent to the Wisconsin River were contaminated with SOCs and VOCs. Among the VOCs identified and targeted for study were cis-1,2-dichloroethene (DCE), trichloroethene (TCE), tetrachloroethene (PCE), vinyl chloride, and 1,1,1-trichloroethane. Among the SOCs targeted for study were toluene, ethylbenzene, and isomers of xylene.

The objectives of this project were to compare the ability and cost effectiveness of two treatment techniques, granular activated carbon (GAC) and packed tower aeration (air stripping), in removing these SOCs and VOCs from the same water matrix without any form of pretreatment.

A GAC pilot plant, a full-scale GAC adsorber, and a full-scale air stripping tower provided the data used to evaluate

process performance. In cooperation with the American Water Works Association Research Foundation, a gas-phase pilot plant study evaluated the effectiveness of GAC for removing the SOCs and VOCs emitted from the off-gas of the full-scale air stripping tower.

Extensive laboratory studies evaluated the capacity of the GAC. Equilibrium isotherm studies were conducted to quantify the adsorption potential of the SOCs and VOCs. Single solute, multi-component, TOX, and TOC isotherms were conducted with the Wausau water matrix. An examination was made of the effects of temperature, pH, and equilibration time on isotherm results. Methods for estimating single solute isotherm parameters and procedures to characterize the adsorbing strength of the unknown components of a water were investigated. Competitive interactions among the VOCs, SOCs, and naturally occurring background organics (NOM) for adsorption sites were also considered.

Extensive laboratory studies were performed to describe the kinetics of adsorption. Batch rate studies were conducted to examine intraparticle mass transfer kinetics and a correlation was developed for the estimation of intraparticle mass transfer coefficients for halogenated one and two carbon aliphatics and aromatic compounds. Short column experiments were conducted to determine mass transfer coefficients and verify existing film transfer correlations.

RSSCTs were developed and tested as a predictive method for examining GAC performance. Mathematical models capable of predicting solute breakthrough and carbon usage rate from equilibrium and kinetic parameters were developed and compared to pilot plant and full-scale breakthrough profiles.

### Composition of the Wausau Water Matrix

A summary of Well No. 4's raw water characteristics observed during each phase of the project is presented in Table 1. In addition to the compounds presented in Table 1, many other synthetic, volatile, and non-volatile organic compounds were found in trace quantities.

The concentrations reported represent the time weighted averages observed during each phase of the project. Air-stripper values are based on the first 4 mo of operation (August-November 1984). GAC pilot-plant values are based on 12 mo of operation beginning August

**Table 1. Average Raw Water Characteristics of Wausau's Well No. 4 During Each Phase of the Wausau Project**

Compound or Parameter	Air Stripper Influent	GAC Pilot-Plant Influent	GAS Full-Scale Influent
<i>cis</i> -1,2-Dichloroethene, µg/L	82.3	70.9	71.5
Trichloroethene, µg/L	72.0	47.9	17.1
Tetrachloroethene, µg/L	59.6	37.6	27.9
Toluene, µg/L	30.9	19.3	7.2
Vinyl Chloride, µg/L	8.4	8.2	4.1
1,1,1-Trichloroethane, µg/L	1.3	0.9	.61
Ethylbenzene, µg/L	5.1	4.5	3.6
Xylenes*, µg/L	16.6	14.5	15.0
Manganese, mg/L	1.10	1.36	1.70
Iron, mg/L	5.02	4.94	4.21
Fluoride, mg/L	0.35	0.32	.29
Dissolved Oxygen, mg/L	< 1.0	< 1.0	2.2
Alkalinity, mg/L	81.	82.	76.
Hardness, mg/L	80.	80.	79.
pH	6.8	6.8	7.0
TOC, mg/L	8.34	8.35	9.13
TOX, µg/L	173.0	141.0	88.9
TOXFP†, µg/L	846.0	805.0	na7#
THMFP‡, µg/L	na	235.0	na
Influent Temperature, °C	11	13.	10.5
Effluent Temperature, °C	11	17.	11.0

\* Sum of *m*, *o*, and *p* isomers.

† Increase in TOX resulting from a 5-day incubation period at a chlorine dose of 20 mg/L and a chlorine residual of 0.2 mg/L.

‡ Yield of THMs resulting from a 5-day incubation period at a chlorine dose of 20 mg/L and a chlorine residual of 0.2 mg/L.

# na - not available.

28, 1984. GAC full-scale values are based on 12 mo of operation beginning November 26, 1985.

### GAC Liquid-Phase Equilibrium Studies

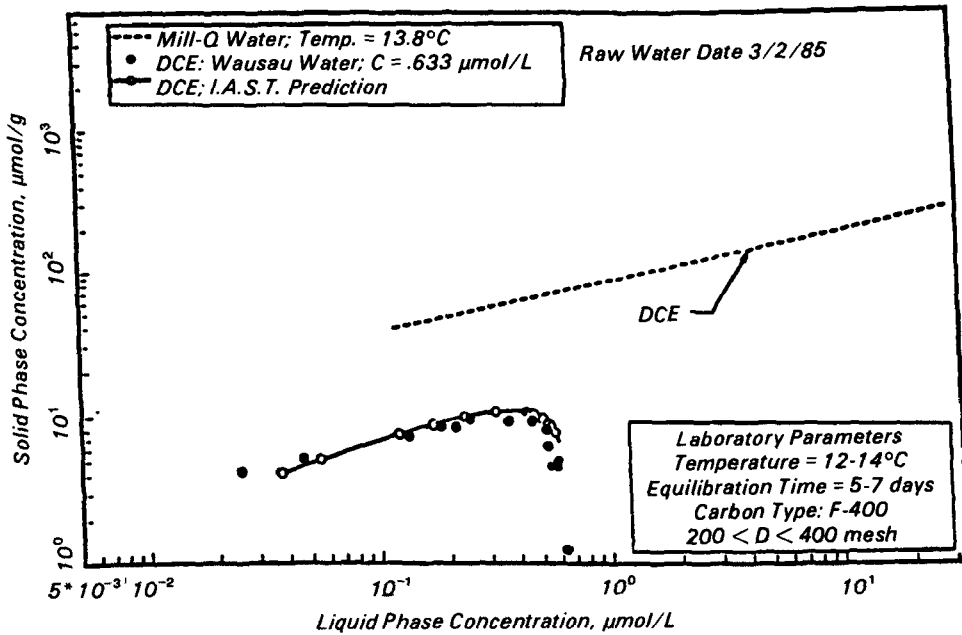
Single solute isotherms were conducted on most of the compounds shown in Table 1 with Calgon's F-400\* carbon. TOX and TOC isotherms were also conducted. Correlation for F-400 carbon was developed to estimate the Freundlich isotherm parameters, *K* and *1/n*, for hydrophobic compounds in organic free water. This correlation is easy to use and requires only knowledge of the liquid density and solubility of the solute.

Ideal adsorbed solution theory (IAST) calculations successfully predicted multi-component adsorption equilibria from single solute isotherms for DCE as shown in Figure 1 and identical results found on another date. The IAST

\* Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

predictions assumed that only the VOCs and SOCs displayed in Table 1 were present in the water matrix to compete with DCE for adsorption sites. IAST predictions for the other VOCs and SOCs were not successful. IAST may have failed due to many reasons. The most likely reasons are the inaccuracy of chemical analyses of these VOCs and SOCs at concentrations near their detection limits and the fact that the VOCs and SOCs did not account for all the organics in the background as the NOM concentration was (measured as TOC) 7.66 mg/L. Competition with the NOM in an isotherm bottle may not have been significant enough to slow the much faster diffusing DCE. During equilibration in an isotherm bottle, DCE can easily diffuse into the GAC particles ahead of the NOM and no competition is observed. However, it has been shown that the GAC capacity for a number of chlorinated aliphatics in an isotherm bottle is significantly reduced if the GAC that is used was first exposed to NOM.

The impact of the Wausau water NOM on the GAC adsorption equilibrium fo



and SOC isotherm capacities on the full-scale carbon to be greater at the top of the adsorber as compared to the middle and bottom because the GAC at the top of the adsorber contains a larger fraction of the smaller particles that are not fouled by NOM as fast as larger particles. These results are significant because they show that the impact of preadsorption of NOM in fixed-beds is a function of exposure time, adsorber length, and the degree of GAC bed stratification.

### GAC Liquid-Phase Kinetic Studies

Both liquid-phase and intraparticle mass transfer parameters are normally required for conducting fixed-bed model calculations. Short fixed-bed column studies were conducted to determine the experimental liquid-phase mass transfer coefficients for TCE and compared with values obtained from various correlations presented in the literature. The Williamson correlation was found to be adequate for preliminary design calculations. The Gnielinski correlation, however, provided a better description when the external surface area is adjusted to fit the data.

Batch rate studies were conducted on a number of halogenated one and two carbon molecules and some substituted aromatic compounds to estimate surface diffusion coefficients. These values and

Figure 1. IAST prediction for cis-1,2-dichloroethene.

TCE and toluene was examined for exposure times of 1, 3, 5, 8, and 10 wk. Adsorption isotherms were conducted on GAC exposed to NOM for TCE and toluene. Figure 2 displays the results of such isotherms for TCE. The TCE isotherms on GAC pre-exposed to NOM are approximately parallel to the single solute virgin carbon isotherm with GAC capacity for TCE decreasing as the time of exposure to NOM increases. Similar results were found for toluene. Isotherms conducted on GAC taken from the full-scale adsorber after 50 wk of operation appear to be approximately parallel to their virgin and pre-exposed isotherms but show much less residual capacity. (The mass of TCE and toluene already adsorbed onto the GAC were determined and accounted for in the mass balance on the isotherm bottle.) The parallel shift of the isotherms enables the impact of NOM on GAC capacity to be expressed as a reduction of the Freundlich isotherm capacity parameter. For both TCE (Figure 2) and toluene (not shown), the isotherms on GAC taken from the top of the adsorber show slightly higher residual capacities than the mid-depth or bottom.

One possible explanation for the higher TCE and toluene isotherm capacities at the top of the full-scale adsorber as compared to the middle and bottom may be due to stratification of the bed caused by backwashing. Sieve analyses conducted on these three samples of GAC

after 50 wk operation showed that the sample taken at the top of the adsorber had a greater proportion of the smaller size carbon than the middle or bottom. Previous work has shown that the relative rate of reduction in TCE capacity due to NOM fouling is less for smaller size particles as compared to larger ones. Therefore, one would expect the VOC

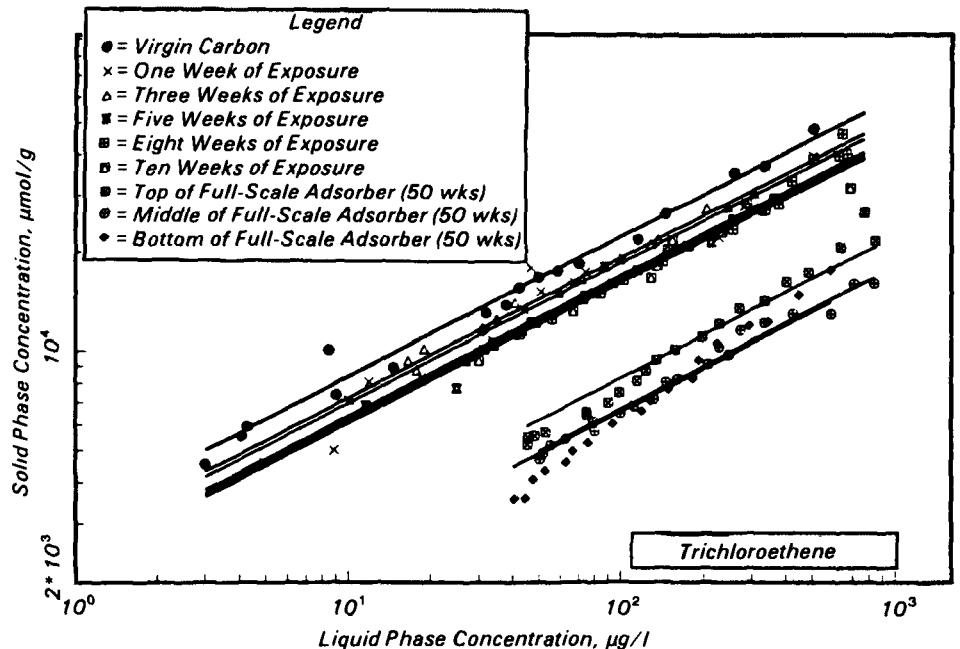


Figure 2. Adsorption isotherms for trichloroethene on GAC exposed to natural organic matter.

others obtained from the literature were used to develop a correlation to estimate surface diffusion coefficients. This correlation was based on the determination of the surface to pore diffusion flux ratio (SPDFR).

An SPDFR of 3.72 was found adequate for estimating effective surface diffusion coefficients used in predicting SOC and VOC breakthrough data in small laboratory columns in which NOM was absent (i.e., conducted in organic free water (OFW)). However, these results in OFW estimate  $D_s$  values that are too large when NOM is present. A SPDFR value of 0.4 was required to describe DCE breakthrough profiles for the pilot plant and full-scale columns. If a typical value for the tortuosity is taken as 2.5, a SPDFR of 0.4 would imply that pore diffusion has become more important than surface diffusion. In limited testing, lower SPDFR values were required for higher NOM concentrations. Accordingly, fouling of the GAC by NOM seems to slow down and in some cases appears to eliminate surface diffusion.

The impact of NOM fouling on intraparticle mass transfer was investigated. The surface diffusivity of TCE was found to decrease with exposure time approaching a constant value after about 4 wk. SPDFR's corresponding to this decrease in diffusivity were evaluated; after a 10 wk exposure to NOM, an initial SPDFR of 8.0 in OFW was reduced to 1.97.

### Rapid Small Scale Column Studies

Small columns containing GAC, scaled to ensure perfect similarity to full-scale adsorbers containing larger carbon, were evaluated as a method to predict GAC performance. Advantages of using the RSSCT for design include significant cost and time savings. Unlike predictive mathematical models, extensive isotherm and kinetic studies are not required when RSSCTs are used to predict full-scale performance. The choice of a smaller particle size determines the time reduction, proper hydraulic loading rate, and empty bed contact time for the RSSCT.

Two sets of scaling equations were developed to relate the small column to the large column while ensuring perfect similarity. The scaling equations were derived from the dimensionless groups appearing in the dispersed flow, pore surface diffusion model. RSSCT scaling equations were developed for the case when the surface diffusion coefficient is

assumed to be independent of adsorbent particle radius (constant diffusivity) and for the case when the value of the surface diffusivity depends on particle radius (proportional diffusivity).

Near perfect similarity was obtained between the small and large column results for all the components in a six component mixture in OFW assuming a constant diffusivity. Field testing of this RSSCT based on constant diffusivity failed at Wausau where NOM was present. When the scaling equations for proportional diffusivity were used, satisfactory results were obtained for TCE, DCE, PCE, and toluene.

The RSSCT procedure is a promising predictive technique. Considerable time and expense can be saved in determining full-scale adsorber performance with a properly designed small column study. However, more field testing is required because the extent to which surface diffusivity changes with particle size and the impact of NOM on the RSSCT procedure have yet to be fully characterized.

### GAC Pilot Plant Studies

A pilot plant consisting of 6 columns containing varying amounts of GAC was operated to obtain effluent profiles of the SOCs and VOCs for nominal EBCTs of 1, 3, 5, 10, 20, and 30 min. Influent and

effluent concentration breakthrough profiles were developed for TCE (Figure 3), and the other compounds listed in Table 1. The profiles were used to evaluate GAC performance.

The specific volume, or number of liters of water treated per gram of carbon, was assessed for each compound at a treatment objective of 5  $\mu\text{g/L}$ . Figure 4 displays the liters of water treated per gram of carbon for TCE for the six EBCTs investigated in the pilot study. For the range of EBCTs examined in this pilot study, the specific volume increased as EBCT increased (see Figure 5). The other VOCs and SOCs showed similar results.

### Comparison of Pilot and Full-Scale GAC Studies

A single GAC contactor, 7 ft in diameter, was installed to treat 100 gpm at a nominal EBCT of 10 min. Influent mid-depth (7.4 min EBCT), and effluent (12.7 min EBCT) concentration breakthrough profiles were developed for TCE (Figure 6), and the other compounds listed in Table 1. As in the pilot-plant study, the effluent profiles in Figure 6 were plotted in terms of the specific volume treated to evaluate GAC performance. Figure 7 displays the specific volume treated for TCE, as observed in the full-scale adsorber.

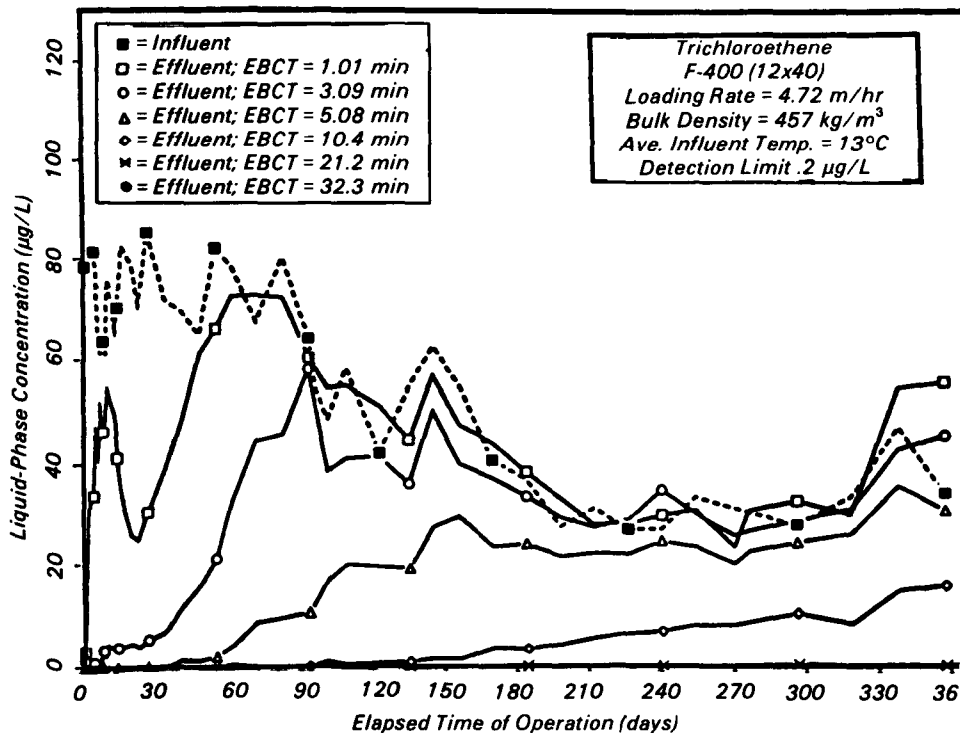


Figure 3. Pilot plant trichloroethene profiles.

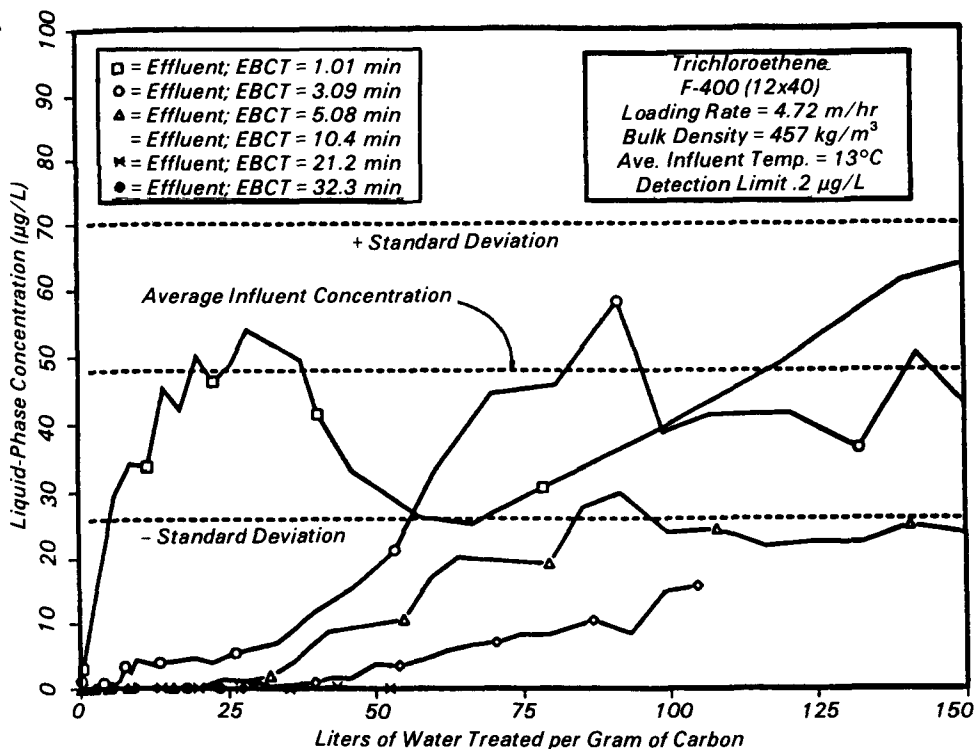


Figure 4. Specific volume treated in the pilot plant for trichloroethene.

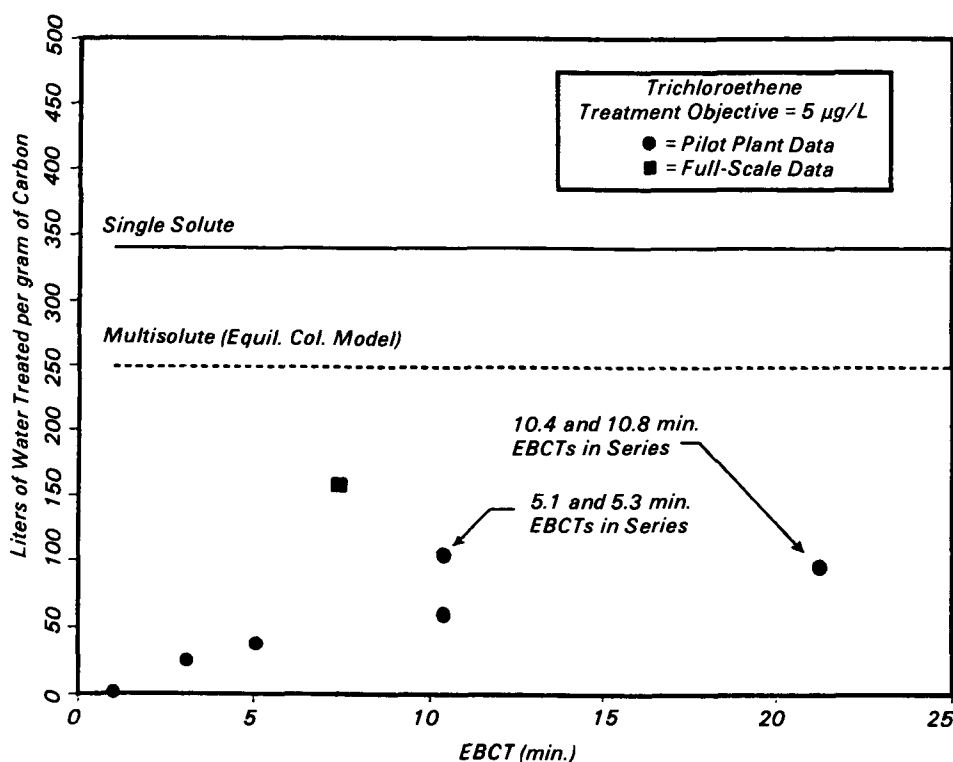


Figure 5. Specific volume treated as a function of EBCT and adsorber configuration for trichloroethene.

The specific volume of water (L/gram) treated was evaluated as a function of EBCT and configuration. Figure 5 displays the impact of EBCT on the specific volume for TCE using a treatment objective of 5 µg/L for the pilot-plant data and the full-scale data. Equilibrium column model (ECM) calculations and the single solute calculations are also shown. For TCE, the pilot-plant data shows that the specific volume is very sensitive to small changes in EBCT for about the first 10 min of EBCT and then appears to become less sensitive for longer EBCTs.

For the loading conditions encountered in the pilot study, adsorbers in-series were found to provide about a 40% to 50% improvement in specific volume over single adsorbers. Figure 5 can be combined with cost calculations to determine the optimum adsorber bed length and configuration to obtain the least cost process.

The specific volume of water treated by the full-scale adsorber was observed to be slightly greater at the mid-depth than at an EBCT of 12.7 min. Both strongly and weakly adsorbing SOCs and VOCs demonstrated this behavior. These results contradict the pilot-plant results that showed the specific volume to increase as EBCT increases. However, differences with respect to the stratification of the GAC particles in the full-scale adsorber as compared to the pilot plant and SOC and VOC influent concentrations may explain the conflicting results. Previous work has shown that the specific volume treated is less in a stratified bed as compared to an unstratified one. Therefore, one would expect as indeed was found, that the specific volume treated in a backwashed full-scale adsorber would be less than that observed in an unbackwashed pilot-plant column. In addition, stratification of the GAC in a fixed-bed adsorber can cause NOM fouling to have a greater impact on the specific volume of water treated for a stratified bed as compared to an unstratified bed.

The impact of backwashing is most evident for TCE (Figure 6) and PCE (not shown), in which a 1 hr backwashing raised the effluent concentrations for several weeks. The concentration at the mid-depth drops because less exhausted carbon is brought up to the mid-depth by backwashing and the effluent concentration rises because more exhausted carbon is brought to the bottom of the adsorber. Backwashing did not affect the weaker adsorbing components (DCE, vinyl chloride, 1,1,1-

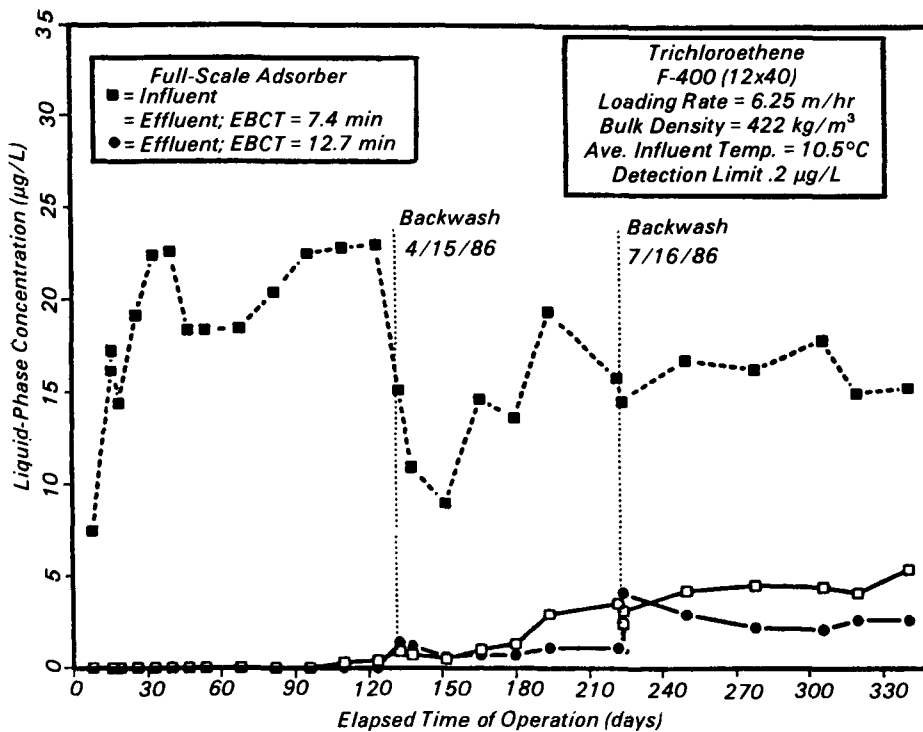


Figure 6. Full-scale trichloroethene profiles.

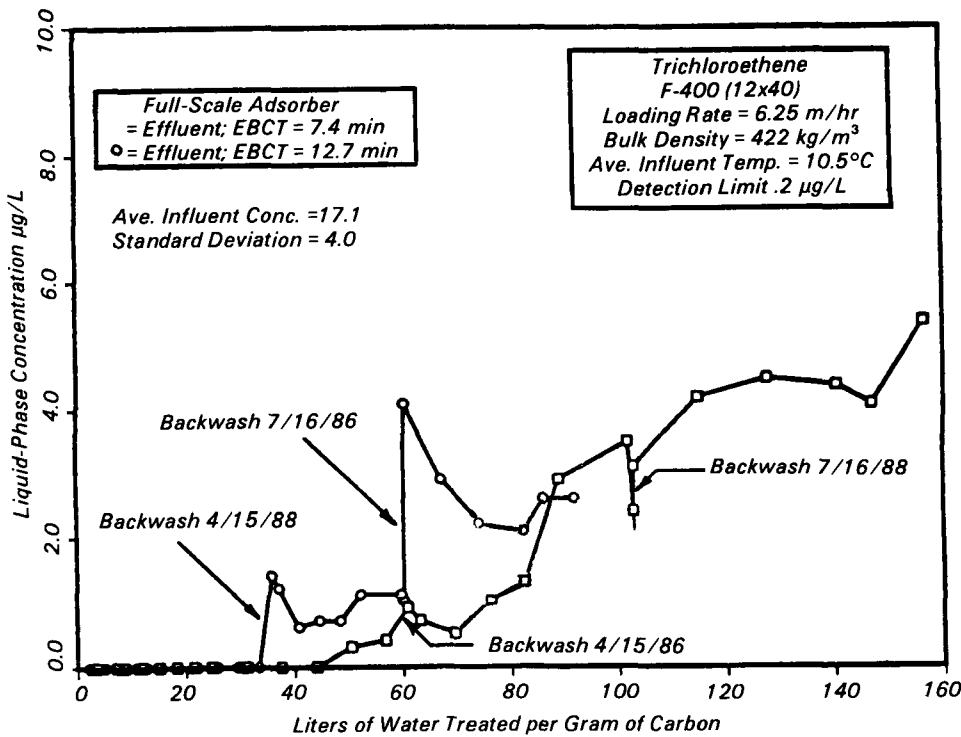


Figure 7. Specific volume treated in the full-scale GAC adsorber for trichloroethene.

trichloroethane) to the same degree as the more strongly adsorbing components because the effluent concentrations, at the time of backwashing, were already at or near their influent values.

The impact of backwashing was also observed in terms of TOX loading on the GAC. The trend in the TOX profiles before backwashing showed TOX loadings on the GAC to decrease as the EBCT increased. However, the redistribution of the carbon after backwashing caused the TOX profiles to become much flatter, indicating that the GAC was well mixed especially in the top half of the adsorber. These results suggest that the impact of a mild backwashing on GAC adsorber performance is important and must be considered in design.

### Predictive Modeling

The pore surface diffusion model (PSDM) was used to predict fixed-bed removal of the adsorbates. The PSDM incorporates the following mechanisms: (a) advective flow, (b) liquid-phase mass transfer resistance, (c) local adsorption equilibrium at the exterior and interior of the adsorbent, (d) surface diffusion, (e) pore diffusion, and (f) competitive equilibrium of solutes upon the carbon surface. Competitive effects are considered by multi-solute equilibrium expressions (IAST) and there are no multicomponent diffusion interactions. The model parameters required to make PSDM calculations were determined from the various correlations and laboratory experiments discussed previously.

Seven component and single solute PSDM simulations were made. In general, model calculations showed later breakthrough (greater capacity) with steeper profiles (too fast an adsorption rate) compared to effluent data. Model predictions improved when it was assumed that pore diffusion controlled intraparticle mass transfer. Good comparisons between PSDM calculations and pilot-plant breakthrough data were obtained for DCE, TCE, PCE, and toluene at an EBCT of 3.09 min when a tortuosity value of 3.0 was used to determine the pore diffusion coefficient. PSDM calculations for the more strongly adsorbing components (ethylbenzene and xylenes) under the same conditions did not compare well to the pilot-plant breakthrough data. DCE, TCE, and PCE were the only compounds that could be modeled at an EBCT of 5.08 min using the conditions successful at an EBCT of 3.09 min. TCE was the only compound

that could be modeled at an EBCT of 10.4 min using the conditions successful at an EBCT of 3.09 min.

The modeling efforts demonstrated that current model parameter estimation methods provide parameters that adequately describe SOC and VOC profiles in organic free water. However, the model estimation methods do not always provide parameters that adequately describe SOC and VOC profiles when NOM fouling occurs. NOM fouling reduces intraparticle mass transfer and GAC capacity for SOCs and VOCs. Accordingly, more work is required to improve methods to characterize the impact of NOM fouling on GAC capacity and kinetics.

### Full-Scale Air Stripping Studies

Following a procedure developed for a design of a least-cost air stripping tower, an 8 ft diameter packed tower was built at the water treatment plant in Wausau, WI to treat the SOCs and VOCs shown in Table 1. The air stripper was designed for minimum tower volume and energy requirements to obtain 95% removal of TCE. Excellent removals were observed for all the VOCs and also the SOCs because of their low concentrations.

Operational problems encountered during this study were the formation of poorly settling iron floc in the water treatment plant, an increase in the TOXFP in the effluent water from the air stripping unit, and iron precipitation that may reduce the performance of high-efficiency packing media. Analyses of the effluent from the air-stripping tower showed that no pathogens are present that may cause a health threat including Legionella.

### Treatment Costs

The studies at Wausau demonstrated that both air stripping and aqueous phase GAC adsorption are two treatment techniques that can effectively remove SOCs and VOCs from a contaminated drinking water supply without pretreatment.

The costs of these two processes were evaluated for treating 1,500 gpm, the normal flow rate for contaminated Well No. 4, to below the 5 µg/L level set for DCE and TCE by the Wisconsin DNR. The aqueous phase GAC designs were based on the behavior observed in the pilot and full-scale studies. The capital and operational costs for aqueous and

gas phase GAC treatment processes are estimates based on manufacturer's price quotations for installation in Wausau, WI. Air stripping costs are actual costs based on several months operation of a full-scale tower. Two methods of handling spent carbon were investigated; 100% carbon replacement with ultimate disposal of the spent GAC by incineration and off-site regeneration assuming 10% attrition losses.

Many design alternatives exist for removing DCE and TCE and consequently the more strongly adsorbing compounds that exist in the Wausau water matrix. When off-gas control is not required, air stripping at 4.3 cents/1,000 gal was found to be the least cost process to remove DCE and TCE. Aqueous phase GAC was found to cost 29.8 cents/1,000 gal for DCE and 20.0 cents /1,000 gal for TCE. In the event that off-gas treatment is required, the cost advantage of air stripping was found to be significantly reduced with air stripping plus GAC off-gas treatment costing 20.4 cents/1,000 gal for DCE and 12.8 cents/1,000 gal for TCE.

For all the various adsorber configurations investigated, the lowest cost adsorber configuration for DCE and TCE was found to be two 5-min EBCT adsorbers in-series. Costs for several other EBCTs and configurations were reported to demonstrate the costs of improper design. The costs for aqueous phase adsorption are comparable to those found in West Germany, where a number of full-scale systems have been in operation for several years. For example, the Pforzheim water treatment plant treats about 1,500 gpm. The water contains about 40 µg/L of TCE and 20 µg/L of PCE and is treated using 8 aqueous phase GAC ad-sorbers that are arranged 4 in parallel with 2 in series. The spent GAC is regenerated off site and about 10% is lost during regeneration. Even after about 8 regeneration cycles the capacity of the GAC was found to be slightly higher than the virgin carbon. The cost of treatment is about 24 cents/1,000 gal at Pforzheim, which compares well to costs determined in this study for TCE.

### Conclusions

- Correlations were developed that successfully predicted aqueous phase Freundlich isotherm parameters of hydrophobic liquid compounds for two different GACs.
- IAST was able to predict the multicomponent competitive inter-

actions of DCE from single solute isotherm data obtained in the field when the competition from the NOM was neglected.

- TCE and toluene isotherms were conducted on GACs that were exposed for various times to natural organic matter from Well No. 4. These results showed the Freundlich isotherm capacity to decrease with increasing exposure times.
- TCE and toluene isotherms conducted on carbon taken from the top of the full-scale GAC adsorber after 50 wk of operation showed higher residual capacities than those conducted on GAC taken from the middle and bottom. This was caused by stratification of the GAC bed. A larger fraction of smaller GAC particles, which are not fouled by NOM as fast as larger ones, were found at the top of the GAC adsorber. These experimental results show that the impact of preadsorption of NOM in fixed-beds is a function of preloading time, adsorber length, and the degree of GAC bed stratification.
- A correlation developed for the estimation of surface diffusion coefficients was able to predict intraparticle mass transfer behavior of SOCs and VOCs in fixed-bed adsorbers where NOM is absent. However, when surface diffusivities obtained from this correlation were used to predict the pilot-plant results, surface diffusivities were found to be much larger than the observed intraparticle mass transfer rate.
- Small columns containing GAC (RSSCTs), scaled to ensure perfect similarity to full-scale adsorbers containing larger carbon, were evaluated as a method to predict GAC performance.
- When the PSDM was fit to the 3.09 min EBCT pilot-plant data, good descriptions of most of the data could be obtained if the surface diffusivities were set equal to zero and the pore diffusivities were calculated from the liquid diffusivities using a GAC particle tortuosity of 3.0. Good descriptions were also obtained for the 5.08 and 10.4 min EBCTs.
- The pilot-plant data showed that for the EBCTs investigated, specific volume in terms of liters of water treated per gram of carbon increased for increasing EBCTs. By plotting the pilot-plant data in terms of specific volume as a function of EBCT, as shown in Figure 5 for TCE a least cost

operation can be designed when combined with cost calculations.

- Backwashing of GAC adsorbers can mix-up the mass transfer zone and stratify the GAC according to size and density. These effects reduced the specific volume of water treated by the full-scale adsorber. Stratification of the GAC in a fixed-bed adsorber can cause NOM fouling to have a greater impact on the specific volume of water treated for a stratified bed as compared to an unstratified one.
- A simple procedure was developed for the design of a least-cost air stripping tower for removing SOCs and VOCs.
- The results of the cost analysis comparing air stripping with and without off-gas treatment to aqueous phase adsorption showed that air stripping without off-gas treatment is the least cost process. If off-gas control is required, air stripping plus off-gas treatment is the least cost alternative when compared to aqueous phase adsorption. The least cost aqueous phase adsorption design was found to be two beds in series using an EBCT of 5 min for each bed.

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The complete report, entitled "Performance of Air Stripping and GAC for SOC and VOC Removal from Groundwater," (Order No. PB 89-110 274/AS; Cost: \$15.95, subject to change) will be available only from:

National Technical Information Service  
5285 Port Royal Road  
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The EPA Project Officer can be contacted at:

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