TREATMENT FOR THE CONTROL OF TRICHLOROETHYLENE AND RELATED INDUSTRIAL SOLVENTS IN DRINKING WATER

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CINCINNATI, OHIO 45268

February, 1981

Treatment for the Control of Trichloroethylene and Related Industrial Solvents in Drinking Water

Several chlorinated hydrocarbon solvents -- trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethane, cis-1,2-dichloroethylene, carbon tetrachloride, vinyl chloride, and 1,2-dichloroethane -- are undergoing review for possible inclusion in the National Interim Primary Drinking Water Regulations. This paper reviews experience with the occurrence and control of these synthetic organics in drinking water.

OCCURRENCE

In general, these materials are volatile, non-flammable in air, and have poor solubility in water. These characteristics make them useful solvents; they are therefore widely used in industries and households, on military bases, and even within water treatment plants for cleaning and degreasing. These solvents are not produced as by-products of chlorination in the disinfection process (as in the reaction of chlorine with naturally occurring organics to produce chloroform and related trihalomethanes). Carbon tetrachloride, however, is a known contaminant of chlorine produced by the graphite-anode process (1). This can be a significant source of carbon tetrachloride in treated drinking water (2). Similarly, other products used in the production and distribution of water can also be sources of contaminants. For example, tetrachloroethylene can be leached from polyvinyl-toluene lined asbestos cement pipe (3), and trichloroethylene is present in certain joint compounds used in reservoir liners and covers. Discovering the source of contamination is sometimes complicated by analytical error. In one documented instance, trichloroethylene was thought to have been produced by chlorine used for disinfection but improved quality control in the laboratory showed the material thought to be trichloroethylene was actually a trihalomethane (4).

---These solvents do not occur naturally, and because of their volatility, they are seldom detected in concentrations greater than a few micrograms per liter (ug/L) in surface water sources. There is, however, one exception. Bodies of fresh water vulnerable to waste water discharges may contain elevated concentrations of organic solvents during periods of ice cover when volatilization is restricted. Seeger, et. al. (5) demonstrated that water sampled from the Ohio River at Cincinnati during the winter of 1977 (almost 800 miles of upstream ice cover) contained high concentrations of volatile compounds such as carbon tetrachloride and tetrachloroethylene, had high threshold odor numbers, and generated subsequent consumer complaints about taste and odor problems.

High concentrations of trichloroethylene and related solvents most frequently occur in ground water. The contaminants can enter an aquifer and be transported great distances because they have little affinity for soils (6,7,8). Recent sampling (9,10,11,12) has revealed solvent contaminated groundwaters in Massachusetts, Connecticut, New Hampshire, New York, New Jersey, Delaware, Rhode Island, Pennsylvania, Florida, Michigan, and California. This list will likely grow when other states examine the organic quality of their groundwater.

The U. S. Environmental Protection Agency Drinking Water Research Division, (USEPA-DWRD) has found that contaminated groundwater usually contains two or more predominant organic compounds and several identifiable ones of lesser concentrations. Frequently, within a well field, one well may be uncontaminated, yet a nearby well may contain as high as 1 to 2 milligrams per liter (mg/L) of trichloroethylene and several hundred micrograms per liter (ug/L) of tetrachloroethylene and 1,1,1-trichloroethane. However,

another well within the same area but perhaps drawing from a different aquifer may contain a preponderance of 1,1,1-trichloroethane and cis-1,2-dichloroethylene, and merely have detectable quantities of trichloroethylene.

Several possible sources for these contaminants have been suggested (13). Included are industrial discharges (either through spreading on the land or improper disposal at dumps), landfill leachates, septic tank degreasers and similar products from individual households, sewer leaks, accidental spills, cleaning and rinsing of tanks and machinery, leaking storage tanks, and from the use of treated wastes for groundwater recharge. Although contributions of organic solvents from improper pump lubricants or from well drilling aids are not likely to be major, they should be recognized as potential sources. Sometimes the source of contamination is not obvious. Crane and Freeman (14), for example, reported trichloroethylene and tetrachloroethylene were two of several solvents detected in the effluent from the anion-cation exchange resin used in their laboratory . The source of this contamination was traced to the distribution plant where the resin was sent for regeneration. The ground water used in the regeneration process was contaminated with organic solvents which then contaminated the resin.

Once an aquifer is contaminated, the water purveyor or other user must either seek an alternative source or provide treatment to remove or reduce the concentrations of these contaminants. The following information is presented for guidance on the latter option. For each solvent, general properties and water treatment data are given. Most of the treatment data were obtained through pilot plant studies. In the Discussion and Summary Section, both theory and empirical data concepts were used to estimate aeration and adsorption efficiency over a wide range of contaminant concentrations and desired effluent qualities.

TRICHLOROETHYLENE

$CHCl=CCl_2$

Molecular Weight: 131

Threshold Odor Concentration:
500 mg/L (18,19)

Solubility: 1100-1250 mg/L (15,16,17) @ 25°C

Vapor Pressure: 57.8 mm Hg @ 20°C (15,16)

Henry's Law Constant: 0.49* (15)
0.48* (16)
11.7×10^{-3} $\frac{atm\ m^3}{mole}$ (17)

Boiling point: 87°C

Other names: (20,21,59)

TCE; 1,1,2-trichloroethylene; 1,2,2-trichloroethylene; trichloroethene; acetylene trichloride; ethinyl trichloride; ethylene trichloride; Triclene; Trielene; Trilene; Trichloran; Trichloren; Algylen; Trimar; Triline; Tri; Trethylene; Westrosol; Chlorilen Gemalgene; Germalgene; Benzinol; 1,1,-dichloro-2-chloroethylene; Blacsolv; Blancosolv; Cecolene; 1-chloroethylene; Chlorylen; Circosolv; Crawhaspol; Dow-tri; Dukeron; Fleck-flip; Flock-flip; Lanadin; Lethurin; Nclco 4546; Nialk; Perm-a-clor; Petzinol; Philex; Triad; Trial; Triasol; Anamenth; Chorylen; Densinfluat; Fluate; Narcogen; Narkosoid; Threthylen; Threthylene; Trilen

Trichloroethylene is commercially produced by chlorinating ethylene ($CH_2 = CH_2$) or acetylene ($CH \equiv CH$). Its use is declining because of stringent regulations; however, it has been a common ingredient in many household products (spot removers, rug cleaners, air fresheners), dry cleaning fluids, industrial metal cleaners and polishers, refrigerants, and even anesthetics (22,23). Its ubiquitous use is perhaps why trichloroethylene is often the predominant synthetic organic contaminant in groundwater.

Other than some incidental evaporation losses, conventional water treatment (coagulation, settling, precipitative softening, and filtration) is not likely to be effective for removing trichloroethylene. In two studies (5,24) in which the trichloroethylene concentration in the source was less than 1 ug/L, no significant losses were observed through the treatment plant. Other processes, such as aeration and adsorption are effective and will be discussed individually.

*This expression is dimensionless (concentration in air divided by concentration in water at equilbrium).

Aeration

USEPA-DWRD conducted pilot scale laboratory and field aeration studies using a 4 cm (1.5 in) diameter glass column, approximately 1.2 m (4 ft) long with a fritted glass diffuser in the bottom. In the laboratory, trichloroethylene was added to Cincinnati, Ohio tap water to give concentrations of approximately 100- to 1000 ug/L and aerated (counter-current flow) at different temperatures. The efficiency of stripping trichloroethylene from water ranged from 70 to 92 percent with an air-to-water ratio (volume to volume) of 4:1 and a contact time of 10 minutes (Table 1). At a contaminated well site in New Jersey, the same aerator consistently gave over 80 percent removal of trichloroethylene where the mean influent concentration was 3.3 ug/L.

Nebolsine Kohlman Ruggiero Engineers (NKRE) (25) also evaluated diffused-air aeration on a pilot scale at a well site on Long Island, New York (Table 1). They compared a rectangular aeration tank [0.6m x 1.2m x 0.6m deep (16 ft^3)] having four diffusers with a 27 cm (10.5 in) diameter Plexiglass®* column having a single diffuser. Retention times ranged from 5 to 20 minutes and air-to-water ratios, from 5:1 to 20:1. The highest removal efficiency was 73 percent. In a follow-up study (26) using a 76 cm (30 in) diameter column, 3m (10 ft) in length with five diffusers, the efficiency of removal ranged from 69 percent to 90 percent with air-to-water ratios from 5:1 to 30:1. The trichloroethylene concentration in the unaerated water ranged from 132 to 313 ug/L. An important note is the concentrations of trichloroethylene and the other organic contaminants in the untreated water were lowest when the well pump was first started and the levels steadily increased for several hours after pumping.

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

TABLE 1. REMOVAL OF TRICHLOROETHYLENE FROM DRINKING WATER USING DIFFUSED-AIR AERATION

Location of Study	Average Influent Concentration, ug/L	Average Effluent Concentration, ug/L — Air-To-Water Ratio 1:1	2:1	3:1	4:1	8:1	16:1	20:1	Remarks
"Spiked"	1064	796	614	508	319	53	-	-	4 cm (1.5 in)diam. counter-current flow glass column with activated carbon filtered air; 10 min.contact time. Water temperature 6-16°C Area to Volume (A/V) = $0.8m^{-1}$
Cincinnati, OH	397	223	273	102	82	22	<1	<1	
Tap Water	241	136	110	61	53	8	2	3	
	110	40	28	18	9	3	<1	<1	
	73	22	14	8	6	1	<1	<1	
Contaminated Well in New Jersey	3				<1				

		Air-To-Water Ratio 5:1	10:1	15:1	20:1	
Contaminated Well on Long Island (25)	112	72[a]	48[c]			0.4 m^3 (16 ft^3) rectangular tank with 4 diffusers. A/V = $1.7m^{-1}$
	64		27[a,d]			a. 10 min contact time
				40[e]		b. 15 min contact time
	118			40[b]		
					33[f]	
	122				44[b]	

c. 5 min contact time
d. 10 min contact time
e. 15 min contact time
f. 20 min contact time

		Air-To-Water Ratio 5:1	15:1	20:1	30:1	
Contaminated Well on Long Island (26)	180	56				76 cm (30 in) diameter 3 m (10 ft) deep glass column with 5 diffusers; 10-min contact time. A/V = $0.3m^{-1}$
	218		45			
	210			35		
	225				22	

Joyce (27) reported concentrations of trichloroethylene ranging from 4.5 to 22 ug/L at Smyrna, Delaware, after water containing 20 to 70 ug/L trichloroethylene was passed through an induced-draft aerator. Although the advanced waste treatment research conducted at Water Factory 21 was not conducted directly on drinking water, it has shown trichloroethylene concentrations of approximately 1 to 2 ug/L are effectively removed (98 percent) through an ammonia stripping tower (air to water ratio of approximately 3000 to 1 when the fan is on) and similar efficiencies have been observed on waste water passed through a polyethylene packed decarbonator (air-to-water ratio approximately 22 to 1) (28,29).

Adsorption

Dobbs and Cohen (30) developed an adsorption isotherm for trichloroethylene in distilled water using pulverized Calgon Filtrasorb® 300. These data are illustrated in Figure 1 as a Freundlich isotherm. When trichloroethylene has an equilibrium concentration of 100 ug/L, the capacity predicted from this isotherm is approximately 7 mg/g. Other than isotherm data, little information is reported on the effects of powdered activated carbon for removing high concentrations of this contaminant. Singley, et al. (31) observed a 50 percent reduction in trichloroethylene concentrations (from 1.5 to 0.7 ug/L) that was attributed to a powdered activated carbon dosage of 7 mg/L in the Sunny Isles Water Treatment Plant, North Miami Beach, Florida.

Other than these two studies, most of the available adsorption data has been developed on granular adsorbents. In the summer and fall of 1977, the USEPA-DWRD installed pilot scale adsorption columns [4 cm (1.5 in) diameter, 80 cm (31 in) of media] near contaminated wells at two water utilities in New England. One was in the State of Connecticut where an industrial waste

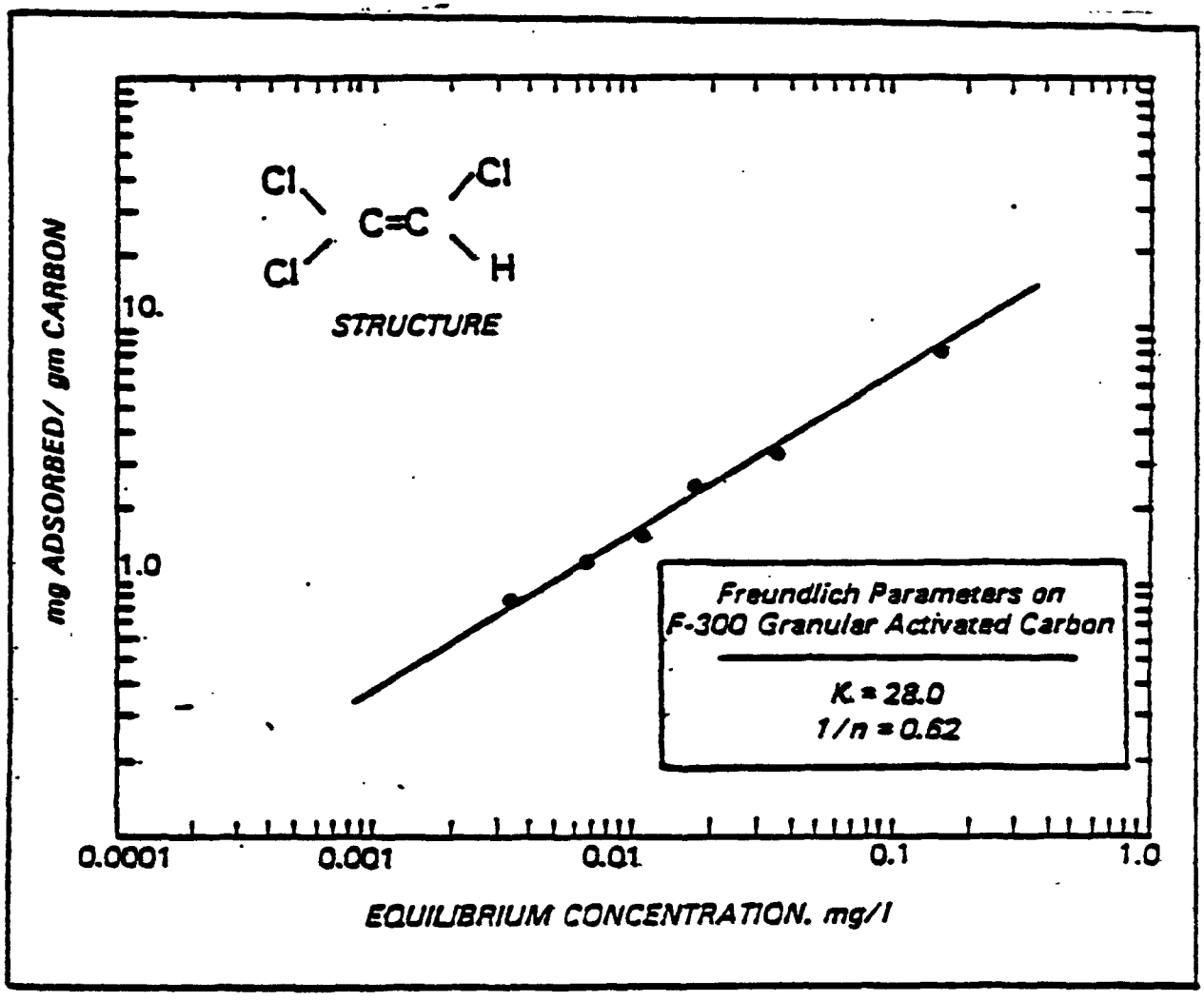

Figure 1. Adsorption Isotherm for Trichloroethylene. Reference 30.

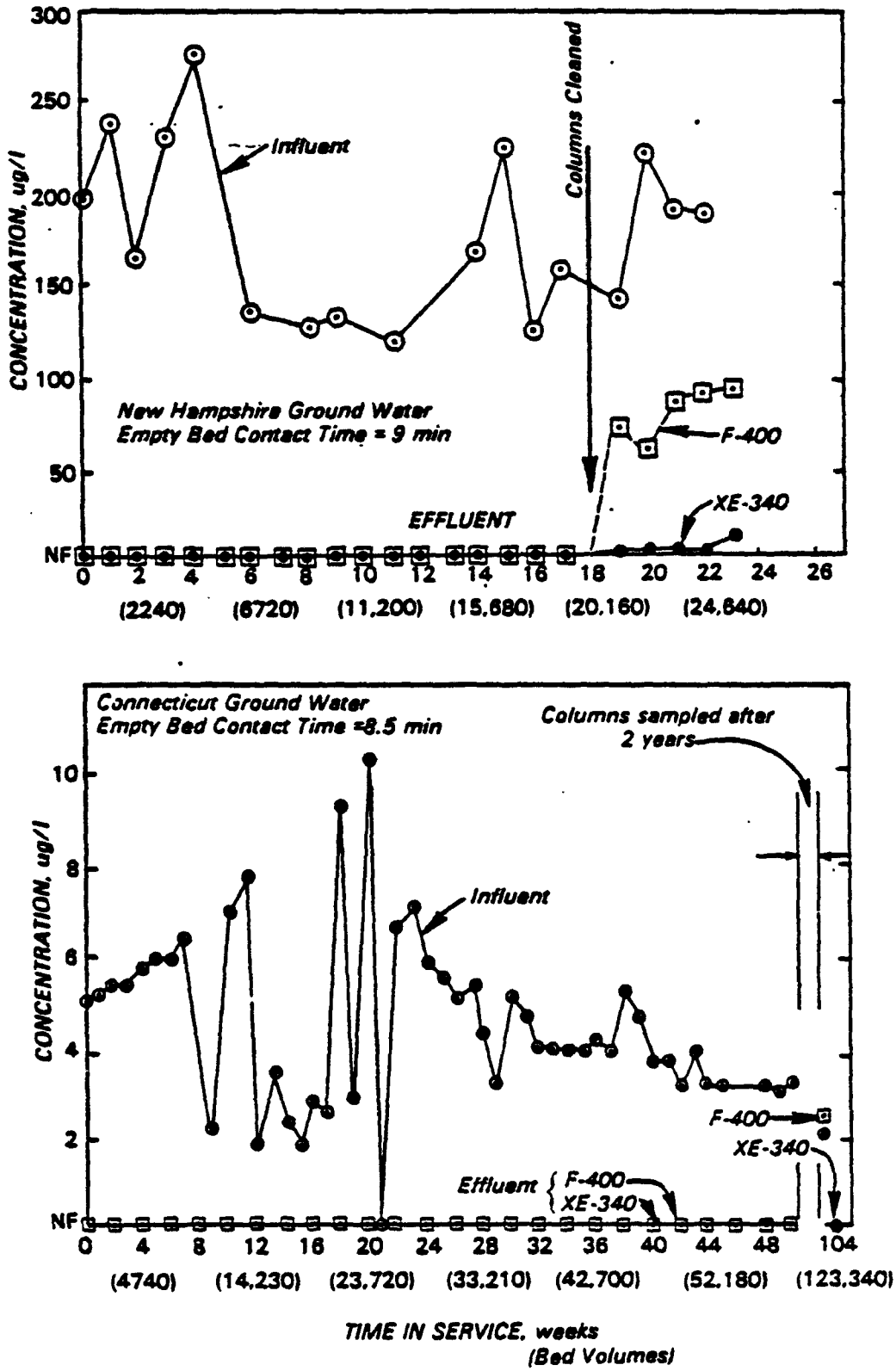

Figure 2. *Removal of Trichloroethylene by Adsorption on Granular Activated Carbon and Polymeric Resin.*

lagoon was thought to have contaminated a well field. The affected waterworks had just completed two years of pumping the contaminanted well to waste, yet volatile organics were still present. The other USEPA-DWRD pilot scale research installation was in New Hampshire. At both locations, granular activated carbon (Calgon Filtrasorb® 400) and a synthetic resin (Rohm and Haas Ambersorb® XE-340) were exposed to the contaminated water.

In the New Hampshire study, trichloroethylene was the predominant contaminant and concentrations ranged from 120 to 276 ug/L. Unfortunately, after 18 weeks, the test column became clogged with what appeared to be precipitated iron. When cleaning was attempted, the contaminant wavefront was disrupted and the study was ended after 23 weeks (Figure 2). In the Connecticut study, trichloroethylene was one of the lesser contaminants and concentrations ranged from less than 1 ug/L to 10 ug/L. The test columns were sampled weekly for one year, then allowed to run continuously, and resampled one year later. Trichloroethylene was removed to below detection (0.1 ug/L)* for the first year but the granular activated carbon was exhausted after two years. The resin was still removing trichloroethylene at the time (Figure 2).

In laboratory studies with trichloroethylene concentrations at the 2 mg/L level, Neely and Isacoff (32) report the equilibrium capacity on XE-340® is 84 mg/g. A pilot scale field study on Long Island (26) is further evaluating the XE-340® resin. In this project, 10 cm (4 in) diameter columns with different

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*For this discussion, breakthrough is the length of service when at least 0.1 ug/L of the contaminant is consistently detected in the effluent from the adsorbent. Length of service is expressed both in time and bed volumes (m^3 water/m^3 activated carbon).

different depths of adsorbents (to vary contact times) are being examined. In-place steam regeneration is also being investigated. The project is scheduled for completion in 1981 but preliminary results show trichloroethylene capacity to breakthrough on the XE-340® resin is approximately 35 mg/g. The trichloroethylene concentrations range from 132 to 313 ug/L.

In Montgomery County, Pennsylvania, some homes having private wells contaminated with trichloroethylene are using Cullar® adsorption units, a product of the Culligan Corporation. These home treatment devices contain approximately 40 kg (87 lbs) of granular activated carbon and can be effective (depending on the loading and water usage) for several months. Information on the effectiveness of other home treatment units (particularly the small, low-flow cartridges) to remove trichloroethylene is not yet available.

Boiling

Boiling is sometimes suggested as a means for individuals to rid drinking water of volatile organics. Table 2 shows the results from four studies conducted by the USEPA where 12 water samples were boiled for varying times. Because boiling is not a standarized procedure, conditions are likely to vary between households. Lataille (34) notes the importance of water depth to boiling efficiency. Trichloroethylene is more efficiently removed from a vessel containing 2 to 5 cm (1 to 2 in) of water than one having greater water depths (Table 2).

TABLE 2. REMOVAL OF TRICHLOROETHYLENE FROM DRINKING WATER BY BOILING

TIME OF BOILING, Min.	TRICHLOROETHYLENE CONCENTRATION, ug/L									
	A		B		C		D			
0 (before heating)	142	1262	137	1107	176	1830	730	1460	2920	2000
1	25	237	45	589	28	279	-	-	-	-
2	17	186	44	389	20	110	-	-	-	-
3	12	136	35	261	20	57	-	-	-	-
5	5	65	23	118	11	20	12	17	194	6[a],29[b],500[c]
10	<1	5	-	15	2	<1				

A. Spiked Cincinnati, Ohio tap water

B. Spiked distilled water

C. Contaminated well water from Pennsylvania

D. Spiked Lexington, Massachusetts tap water

a. Water depth = 2 cm (1 in)
b. Water depth = 5 cm (2 in)
c. Water depth = 11 cm (5 in)

Studies A-C by USEPA, Drinking Water Research Division, Cincinnati, OH (33). Water depth approximately 10 cm (4 in).
Study D by USEPA, Region I, Surveillance and Analysis Laboratory, Lexington, MA (34)

TETRACHLOROETHYLENE

$CCl_2 = CCl_2$

Molecular Weight: 166

Threshold Odor Concentrations:
300 ug/L (18)

Boiling Point: 121°C

Solubility: 140 mg/L @ 25°C (15)
150 mg/L @ 25°C (16,17)

Vapor Pressure: 18.6 mm Hg (15,16)

Henry's Law Constant: 1.2 (15,16)
28.7×10^{-3} $\frac{atm\text{-}m^3}{mole}$ (17)

Other Names: (20,21,59)

PCE; perchloroethylene; 1,1,2,2-tetrachloroethylene; tetrachloroethene; Ankilostin; carbon bichloride; carbon dichloride; Didakene; ENT-1860; ethylene tetrachloride; NCl-C04580; Nema; Perawin; Perc; Perclene; PerSec; Tetralex; Tetracap; Tetropil; Antisal; Fedal-Un; Tetlen; Tetraguer; Tetraleno

Tetrachloroethylene is commercially produced by chlorinating acetylene ($CH \equiv CH$) or ethylene dichloride (CH_2ClCH_2Cl, also known as 1,2-dichloroethane). This solvent is widely used in dry cleaning, textile dyeing, metal degreasing, and in the synthesis of fluorocarbons (22,23). As mentioned earlier, tetrachloroethylene has been used to apply polyvinyl-toluene liners to asbestos-cement pipe. This solvent leaches into finished drinking water from newly laid pipe as well as from pipe that had been installed for several years (3). Tetrachloroethylene concentrations from this source range from a few micrograms per liter to several milligrams per liter, the higher concentrations coming from dead-ends, where water flow is not continuous. Specifications placed on new pipe can alleviate this source of contamination, but treatment for existing polyvinyl-toluene lined pipe in the ground is a problem that needs attention. Intermittent flushing and continuous bleeding of the lines can lower the concentration of this contaminant (3). The remaining discussion on treatment involves tetrachloroethylene found in the raw water source.

Although tetrachloroethylene is mainly a groundwater contaminant, it has been found in low, measurable concentrations in some surface waters. In two

instances tetrachloroethylene was monitored before and after coagulation, sedimentation, and filtration, and it was shown that these processes are ineffective for lowering the concentration of this contaminant (5,35). Oxidation by ozone has been suggested, and Glaze (36) has shown ozonation can remove tetrachloroethylene but optimum conditions and subsequent by-products are unknown.

Aeration

Diffused-air aeration is effective for stripping tetrachloroethylene from water. Laboratory studies by the USEPA-DWRD have found that 30 to 60 percent of tetrachloroethylene can be removed with an air-to-water ratio of 1:1. Laboratory and pilot scale field studies have shown at least 95 percent removal of tetrachloroethylene at higher air-to-water ratios. (Table 3). The consulting firm, NERE, (25) using both a tank and column aerator was less successful, but a follow-up study (26) showed 75 to 95 percent removal with an improved column design. McCarty, et al. (29) reported 94 percent removal of tetrachloroethylene (average influent concentration of 2.8 ug/L) using ammonia stripping towers on highly treated waste water.

Adsorption

Dobbs and Cohen (30) developed an adsorption isotherm using a solution of tetrachloroethylene in distilled water and pulverized Filtrasorb® 300 granular activated carbon (Figure 3). If an original tetrachloroethylene concentration of 100 ug/L is assumed, an estimate of equilibrium capacity from this isotherm would be 14 mg/g.

Adsorption tests using granular material on a pilot scale were conducted in Rhode Island by the USEPA-DWRD during the summer of 1977. A portion of a drinking water distribution system had become contaminated with between

TABLE 3. REMOVAL OF TETRACHLOROETHYLENE FROM DRINKING WATER USING DIFFUSED-AIR AERATION

Location of Study	Average Influent Concentration ug/L	Average Effluent Concentration, ug/L — Air to Water Ratios 1:1	2:1	3:1	4:1	8:1	16:1	20:1	Remarks
"Spiked"	1025	698	416	304	156	16	-	-	4 cm (1.5 in)
Cincinnati, OH	636	161	177	46	34	8	<1	<1	diameter glass
Tap Water	338	139	103	47	34	4	1	2	column, 10 min.
	114	32	17	7	4	<1	<1	<1	contact time.
	107	32	17	7	4	<1	<1	<1	Area to volume (A/V) =
	17	3	2	1	1	<1	<1	<1	$0.8m^{-1}$
Contaminated Well in New Jersey	92				9				

		Air-To-Water Ratios 5:1	10:1	15:1	20:1	
Contaminated Well on Long Island (25)	55	33[a]	17[c]			$0.4 m^3$ (16 ft^3) rectangular tank with 4 diffusers. a. 10 min contact time b. 15 min contact time 27 cm (10.5 in) diameter column. $A/V=0.6m^{-1}$ c. 5 min contact time d. 10 min contact time e. 20 min contact time
	27		8[d,a]			
	46			10[d]		
				14[b]		
	65				11[a]	
					19[b]	

		Air-To-Water Ratios 5:1	15:1	20:1	30:1	
Contaminated Well on Long Island (26)	101	25				76 cm (30 in) diameter, 3 m (10 ft) deep glass column with 5 diffusers, 10 min. contact time. $A/V = 0.3m^{-1}$
	92		15			
	52			4		
	50				3	

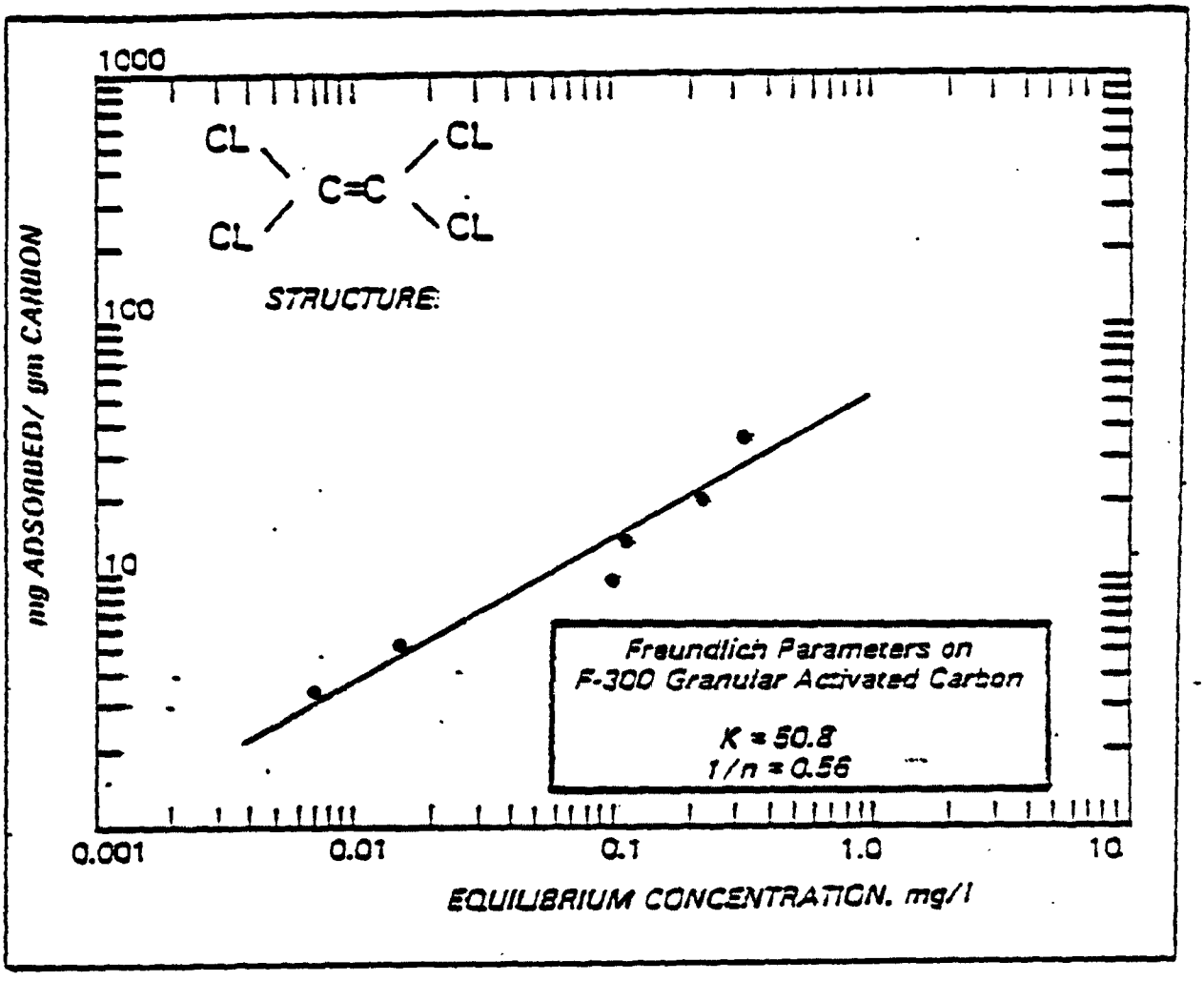


Figure 3. *Adsorption Isotherm for Tetrachloroethylene. Refence 30.*

600 ug/L and 2,500 ug/L of tetrachloroethylene from polyvinyl-toluene lined asbestos cement pipe (3). Two different adsorbents were examined in 4 cm (1.5 in) diameter glass columns. One test column contained Filtrasorb® 400 granular activated carbon and a parallel column, Ambersorb® XE-340 synthetic resin. Both columns had an 8.5 min empty bed contact time. The granular activated carbon maintained an effluent concentration of tetrachloroethylene below 0.1 ug/L for 11 weeks giving a breakthrough loading of 46.7 mg/g. Because of inclement weather, the study was stopped after 20 weeks. At that time the resin was passing an average of 0.4 ug/L tetrachloroethylene (Table 4). This gave an empirical loading to breakthrough of 45.6 mg/g for the resin. Although the resin is similar to the activated carbon in loading to breakthrough, it exhibited a relatively flat breakthrough curve. This would suggest that the rate of contaminant movement through this resin is slow relative to the wavefront movement through activated carbon.

TABLE 4. REMOVAL OF TETRACHLOROETHYLENE FROM DRINKING WATER BY ADSORPTION

Time in Operation, Weeks (bed volumes)	Average Concentration, ug/L		
	Influent	Effluent	
		Filtrasorb® 400 Activated Carbon	Ambersorb® XE-340 Resin
4 (4,700)	1367	< 0.1	< 0.1
8 (9,400)	1984	< 0.1	0.1
12 (14,100)	1950	0.1	< 0.1
16 (18,800)	906	0.2	0.2
20 (23,500)	825	2.8	0.4

Study by USEPA in Rhode Island. Empty bed contact time = 8.5 min.
Approach velocity = 5m/hr (2 gal/min-ft^2)

The objective of a USEPA-DWRD study in New Jersey was to examine the effectiveness of aeration and adsorption alone, as well as combined. A contaminated well was intermittently pumped into a stainless steel tank having a floating lid. The water was then pumped to adsorption columns and an aerator (Figure 4). In the non-aerated water tetrachloroethylene concentrations ranging from 60 to 205 ug/L were reduced to less than 0.1 ug/L for 51 weeks by the granular activated carbon (18 min empty bed contact time). Detectable quantities (<1 ug/L) appeared in the effluent for 4 weeks, then disappeared. After 58 weeks of service, the tetrachloroethylene centrations were still being reduced to less than 0.1 ug/L, giving a loading of >32,500 m^3/m^3.

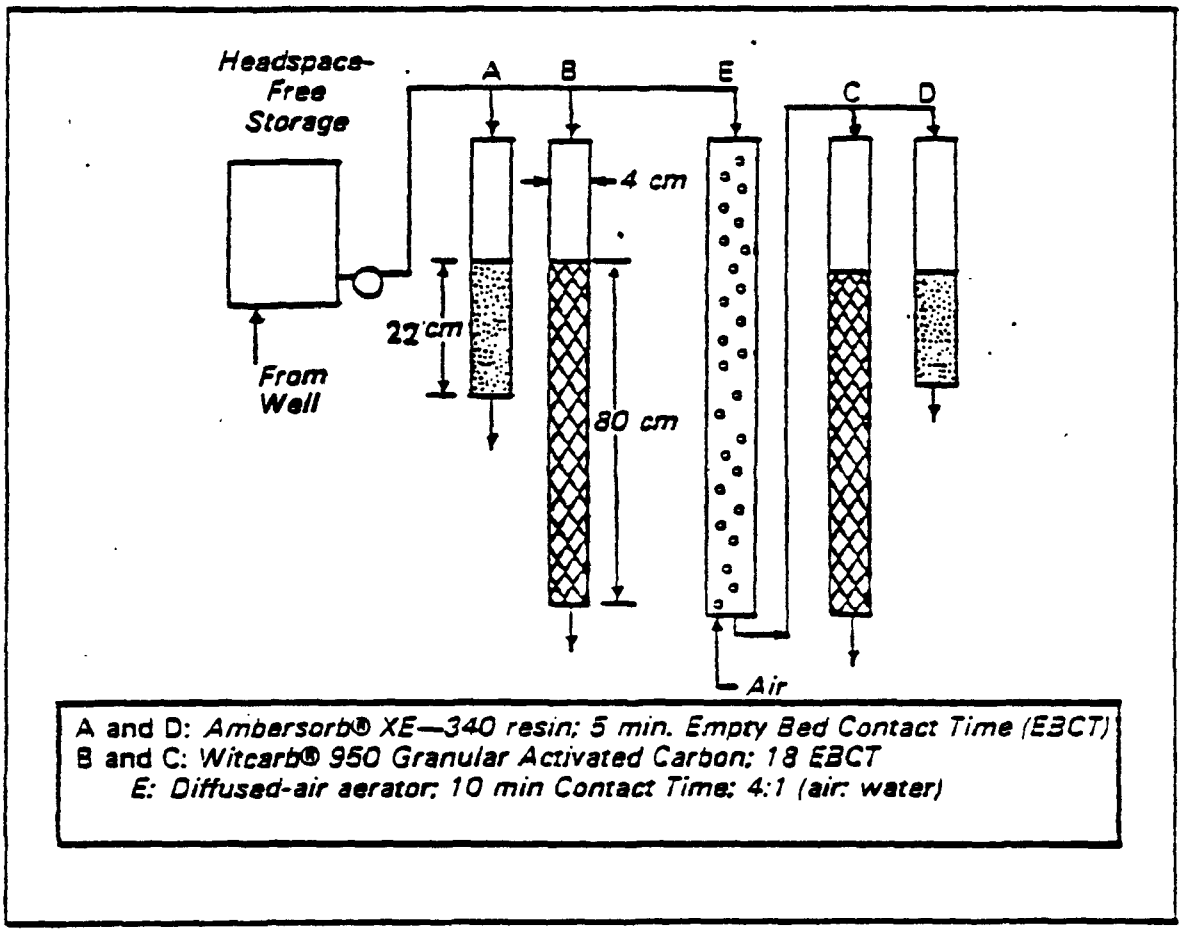


Figure 4. *Illustration of USEPA-DWRD Pilot Scale Treatment used at Contaminated Well Site in New Jersey.*

Boiling

Tetrachloroethylene has an azeotropic boiling point of 87.7°C (37). Table 5 shows the results of four separate boiling experiments by the USEPA-DWRD. Different qualities of water were used; however, about 1 to 2 percent of the initial concentration of tetrachloroethylene remained after 3 minutes of vigorous boiling.

TABLE 5. REMOVAL OF TETRACHLOROETHYLENE FROM WATER BY BOILING

Time of Boiling, min.	Tetrachloroethylene Concentration, ug/L			
	A	B	C	
0*	300	298	120	9
1	14	29	11	2
2	6	14	7	<1
3	3	5	3	<1
5	2	2	<1	<1
10	<1	<1	<1	<1

* Before heating
A. Spiked Cincinnati, Ohio tap water
B. Spiked distilled water
C. Contaminated well water from Pennsylvania

1,1,1-TRICHLOROETHANE

$C_2H_3Cl_3$

Solubility: 4400 mg/L @ 20°C (16); 720 mg/L @ 25°C (15)
5497 mg/L @ 25°C (17)

Molecular Weight: 133

Vapor Pressure: 100 mm Hg (16); 124 mm Hg (15)

Threshold Odor Concentration: Not reported

Henry's Law Constant: 0.17 (16); 1.2 (15)
4.92×10^{-3} $\frac{atm\text{-}m^3}{mole}$ (17)

Boiling Point: 74.1°C

Other Names: (20,21,59)

Methylchloroform; Chloroethene; Aerothene TT; Chlorten; NCI-C04626; alpha-trichloroethane; α-T; Chlorothane; Chlorothene NU; Chlorothene VG; Inhibisol; Methyltrichloromethane; Trichloroethane

1,1,1-Trichloroethane is commercially produced by reacting chlorine with vinyl chloride ($CH_2 = CHCl$) or acidifying vinylidene chloride (also known a 1,1-dichloroethylene, $CH_2 = CCl_2$) with hydrochloric acid. 1,1,1-Trichloroethane has replaced trichloroethylene in many industrial and household products. It is the principal solvent in septic tank degreasers, cutting oils, inks, shoe polishes, and many other products (22,23,38). Among the volatile organics found in groundwaters, 1,1,1-trichloroethane and trichloroethylene are encountered most frequently and in the highest concentrations. USEPA, Region III, has investigated an industrial well water situation in Pennsylvania, in which the wells most distant from the pollution source contained trace quantities of trichloroethylene and the wells nearest the pollution source(s) contained 1,1,1-trichloroethane. This possibly reflects the previous change in industrial solvent uses (39). 1,1,1-Trichloroethane has also been identified in drinking water taken from surface sources. In one instance, a cleaning agent containing 1,1,1-trichloroethane was being used within the water treatment plant and the contaminants detected in the finished water could have come from that source (40).

Aeration

NKRE (26) observed a 66 to 85 percent reduction in 1,1,1-trichloroethane concentrations (influent concentrations of 3 to 7 ug/L) with air-to-water ratios ranging from 5:1 to 30:1. The diffused-air aerator used in the USEPA-DWRD study in New Jersey (see Figure 4) has consistently shown approximately 90 percent removal of 1,1,1-trichloroethane (influent concentration range of 170- to 280 ug/L) at a 4:1 air-to-water ratio. Similarly, McCarty, et al. (29) obtained high removal efficiencies for 1,1,1-trichloroethane with both a packed bed degasifier and an ammonia stripping tower used for advanced waste water treatment at Water Factory 21. The influent concentrations of 1,1,1-trichloroethane, however, were less than 5 ug/L.

Kelleher, et al. (41) reported mixed results on an aeration study in Norwood, Massachusetts. They used a 10 cm (4 in) diameter glass column packed with glass raschig rings to a depth of 63 cm (25 in). Compressed air was blown up through the packing material as contaminated water trickled downward. On Well #4 (see Table 6) the removal ranged from 74 to 97 percent, for a broad spectrum of aeration conditions, whereas on Well #3, the removal was poorer. This difference could not be explained.

TABLE 6. REMOVAL OF 1,1,1-TRICHLOROETHANE FROM DRINKING WATER USING A PILOT SCALE FORCED DRAFT PACKED TOWER (41)

		Effluent Concentration of 1,1,1-Trichloroethane, ug/L			
		Range of Air-to- Water Ratios			
Source	Influent Concentration ug/L	1:1 to 10:1	11:1 to 20:1	21:1 to 50:1	>50:1
Well	110			13	5
	90	10	10		
	42	8	4	3	—
					—
Well #3	850		410	220	
	1200	460		350	49
	630	387	210		

Adsorption

Dobbs and Cohen (30) developed an adsorption isotherm for 1,1,1-trichloroethane (Figure 5). Using this isotherm, the calculated capacity for an original 100 ug/L concentration of 1,1,1-trichloroethane on Filtrasorb® 300 is 1.1 mg/g. In a full scale study at a water treatment plant in Florida, Ervin and Singley (42) found no difference in the performance of four powdered activated carbons (pulverized Calgon GW; Euskey Watercarb® Plus; ICI Hydrodarco® B; and Westvaco Aqua Nuchar® II) to remove 1,1,1-trichloroethane. At doses of approximately 7 mg/L and with 2 hours of contact time, powdered activated carbon effected at best 15- to 20 percent removal of 1,1,1-trichloroethane (influent concentration 18 ug/L) (31,42).

Figure 6 illustrates some of the USEPA-DWRD results from pilot scale adsorption projects. The amount of contaminant varies as well as the type of adsorbent; however, the length of service to breakthrough for the granular activated carbon ranged from 12,000 to 15,000 m^3/m^3. Expressed as a contaminant loading, the activated carbon adsorbed from 0.02 to 7.5 mg/g. In the New Jersey study, the activated carbon receiving aerated water (average 1,1,1-trichloroethane concentration reduced from 237 ug/L to 23 ug/L by aeration) produced an effluent with no detectable 1,1,1-trichloroethane during the 58 week-long study. This resulted in an empirical loading of at least 1.9 mg/g and a length of service greater than 32,000 m^3/m^3.

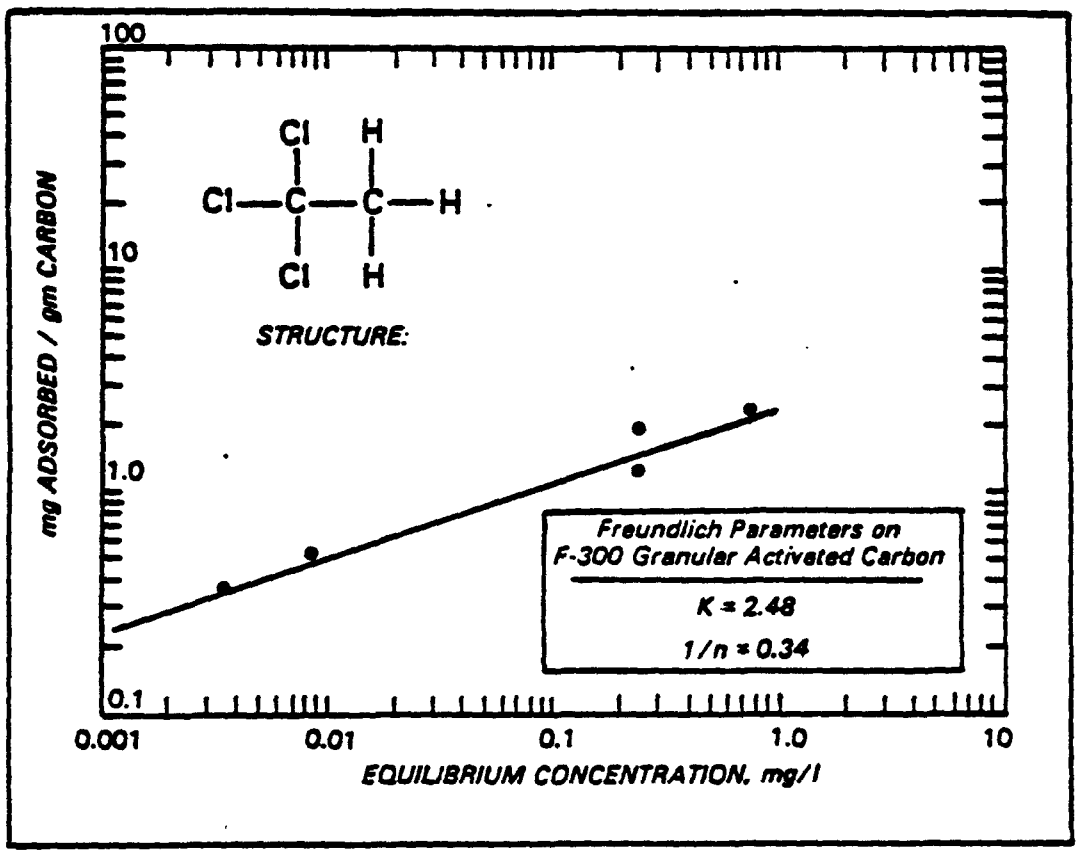
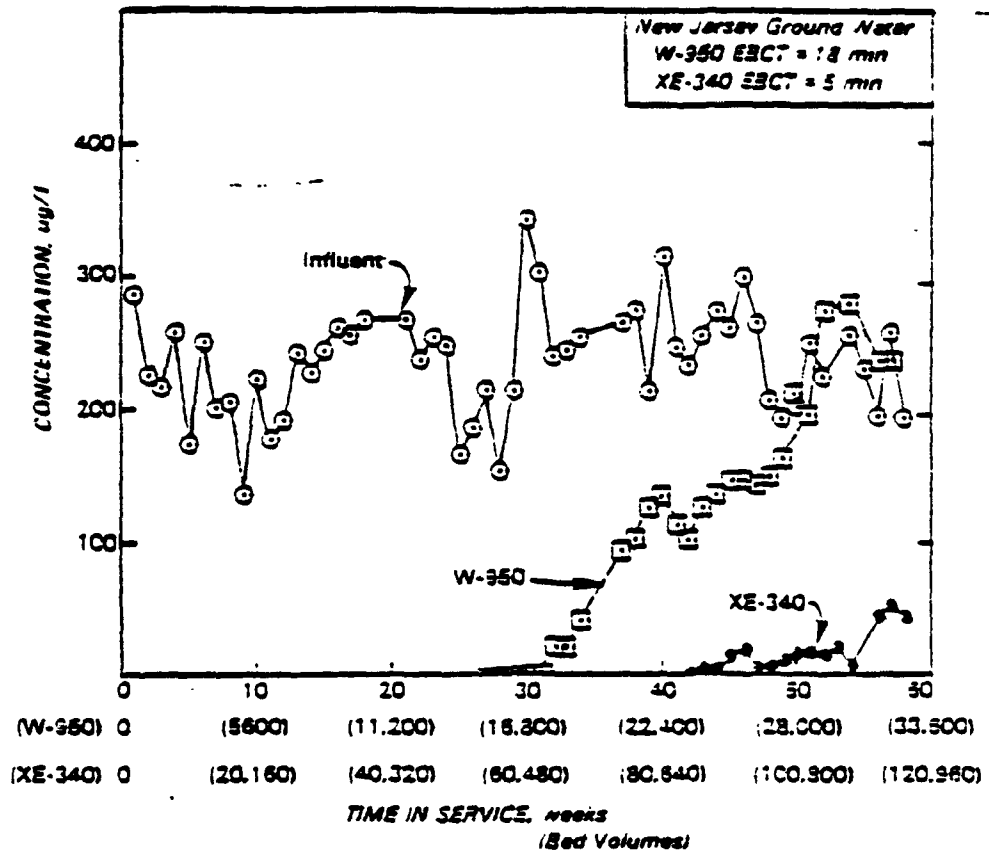


Figure 5. *Adsorption Isotherm for 1,1,1-Trichloroethane. Reference 30.*



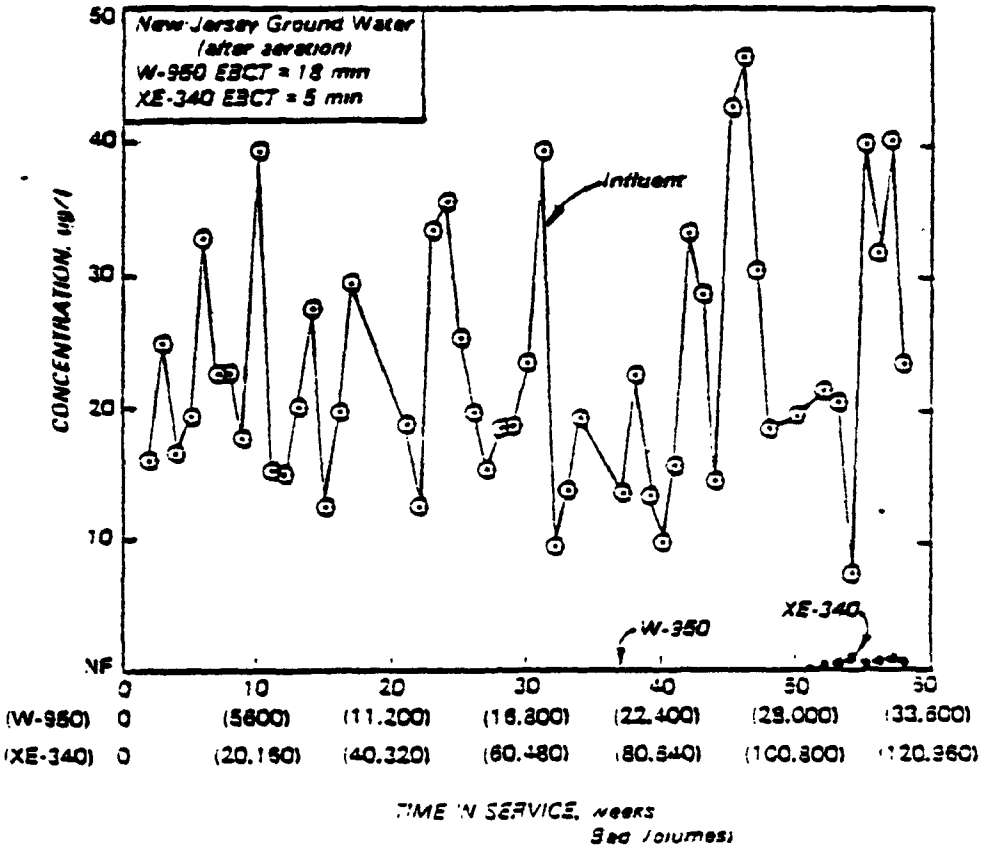
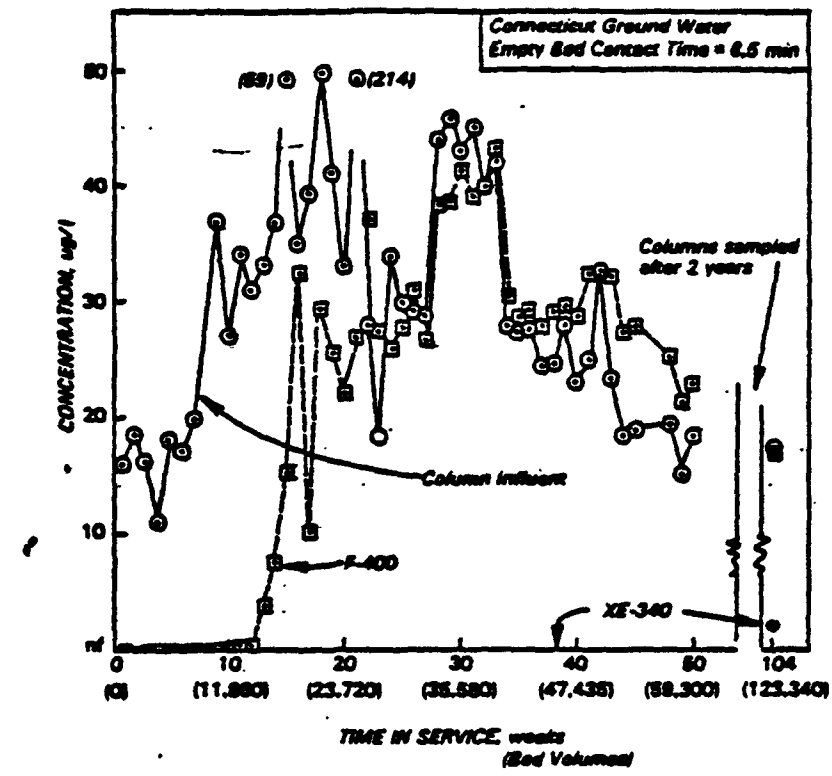


Figure 8. *Removal of 1,1,1-Trichloroethane on Granular Activated Carbon and Polymeric Resin.*



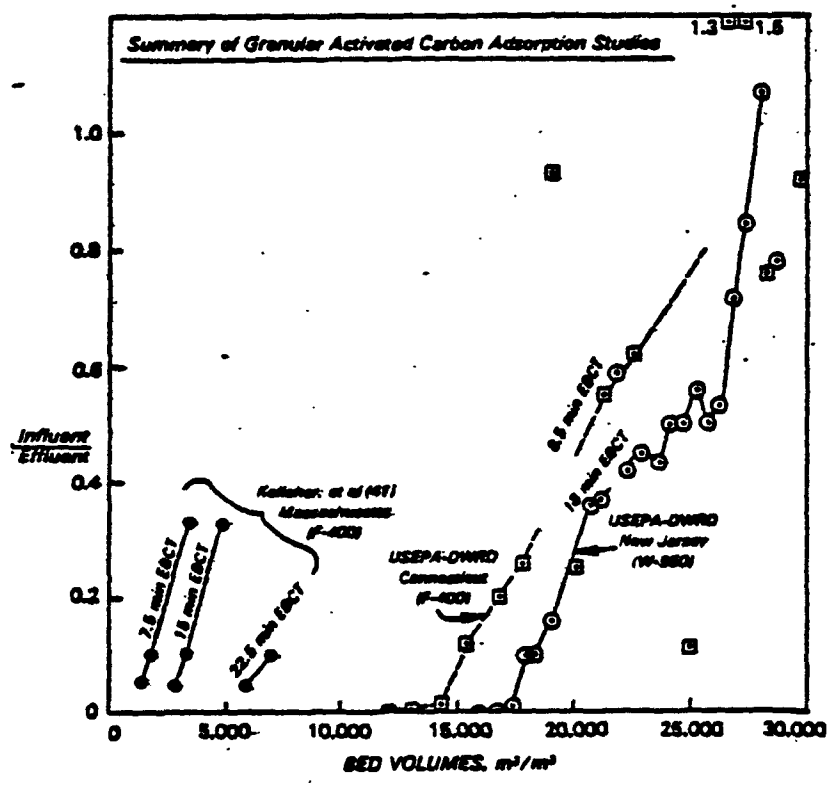


Figure 6. Cont'd.

Kalleher, et al. (41) conducted a sorption experiments at a contaminated well site in Massachusetts. They used four 10 cm (4 in) diameter glass columns, each containing 60 cm (2 ft) of Filtrasorb® 400 granular activated carbon, for a total adsorbent depth of 2.5 m (8 ft). These were operated in series to assess the effects of contact time. Time to breakthrough was not reported. The loadings to reach 5 ug/L of 1,1,1-trichloroethane in the effluent from an applied 100 ug/L concentration, were 0.26 mg/g, 0.51 mg/g, and 0.74 mg/g for contact times of 7.5 min, 15 min, and 22.5 min, respectively. These results are included in the summary portion of Figure 6. The total organic carbon (TOC) concentration was over 2 mg/L in the Massachusetts water yet less than 0.5 mg/L in the Connecticut and New Hampshire water. This may account for differences in performance.

Neeley and Isacoff (32) and Isacoff and Bittner (43) compared Ambersorb® XE-340 resin to Filtrasorb® 400 granular activated carbon for removing 1,1,1-trichloroethane from a New Jersey well water. The experiment was conducted using 5 cm long columns (containing 15 cc of adsorbent) and water shipped to their laboratory from the contaminated well. At 270 liters per minute per cubic meter (2 gpm/ft^3) loading rate (3.7 min empty bed contact time), 1,1,1-trichloroethane (average applied concentration of 450 ug/L) broke through both adsorbents between 5,000 and 6,000 m^3/m^3. This produces a loading of approximately 1.7 mg/g.

A difference in adsorbent behavior was seen after contaminant breakthrough. The granular activated carbon steadily became exhausted while the resin continued to remove a large percentage of the solvent. Rather than having a incisive slope like the granular activated carbon, the

slope of the breakthrough curve for the resin is gradual. Using the same contaminated source in New Jersey, the USEPA-DWRD found with its pilot scale operation (Figure 4), that XE-340® removed 1,1,1-trichloroethane (average applied concentration of 237 ug/L) for almost 111,000 m^3/m^3. Why the service life found in the field study was so much longer than the service life predicted from the Rohm and Haas laboratory study cannot be explained.

In the USEPA-DWRD New Jersey study, a column containing Ambersorb® XE-340 but receiving aerated water (See Figure 4) with an average 1,1,1-trichloroethane concentration of 23 ug/L, had no detectable quantities of the solvent in the effluent after 58 weeks, corresponding to a loading of greater than 120,000 m^3/m^3.

In an earlier USEPA-DWRD project in Connecticut, a column containing Ambersorb® XE-340 (9-min empty bed contact time) was sampled weekly for one year then resampled one year later. Breakthrough was evident at the end of the first year (56,000 m^3/m^3), but the adsorbent was not exhausted even at the end of the second year.

Boiling

Lataille (34) found that depending on the depth of water in the pan, 1 to 20 percent of the initial 1,1,1-trichloroethane concentration remained after 5 minutes of boiling. Similarly, personnel in the Rhode Island State Health Laboratories (44) found an average of 2 percent of the starting 1,1,1-trichloroethane concentration remained after 5 minutes of boiling contaminated drinking water samples (Table 7).

TABLE 7. REMOVAL OF 1,1,1-TRICHLOROETHANE DRINKING FROM WATER BY BOILING

Water Sample	Time of boiling, --min.	Concentration, ug/L			
Lexington, MA*	0	680	1350	2700	1900
Tap water "spiked"	(before heating)				
with 1,1,1-trichloroethane	5	8	23	35	5[a],27[b],360[c]
Contaminated	0	37**			
Drinking Water	(before heating)				
in Rhode Island	5	1**			

* After Lataille (34)
a. Water depth = 2 cm
b. Water depth = 5 cm
c. Water depth = 11 cm

**Average of 12 tests with water having 1,1,1-trichloroethane concentrations ranging from 2 to 166 ug/L. After Reference 44.

CARBON TETRACHLORIDE

CCl_4

Molecular Weight: 153.8

Solubility: 800 mg/L @ 25°C (15,16,17)

Threshold Odor Concentration:*

Vapor Pressure: 91.3 mm Hg (16)
113 mm Hg (15)

Boiling Point: 76°C

Henry's Law Constant: 1.2 (15,16)
30.2 10^{-3} $\frac{atm\text{-}m^3}{mole}$ (17)

Other Names: (20,21,59)

Tetrachloromethane, perchloromethane; Necatorina; Benzinoform; methane tetrachloride; methane, tetrachloro-; Necatorine; ENT 4,705; Halon 104; Carbon chloride; Carbona; Flukoids; R10; Tetrafinol; Tetraform; Tetrasol; Univerm; Vermoestricid

Carbon tetrachloride was once a popular household solvent, a familar dry cleaning agent and a charging agent for fire extinguishers. Since 1970, however, carbon tetrachloride has been banned from all use in consumer goods in the United States, and in 1978, it was banned as an aerosol propellant (46). Currently, its principal use is in the manufacture of fluorocarbons used as refrigerants and to a lesser degree in grain fumigants. This solvent is a known contaminant in chlorine produced by the graphite-anode method (1) and chlorinated drinking water can become contaminated with carbon tetrachloride from this source (2,47,48). The American Water Works Association (AWWA) is rewriting chlorine specifications, and this will perhaps minimize carbon tetrachloride contamination resulting from chlorination.

Aeration and Adsorption

Incidental to a study on trihalomethanes, USEPA-DWRD detected carbon tetrachloride in the Ohio River and in the City of Cincinnati drinking water in 1976 and 1977 (Figure 7). Between July, 1976 and February 1977 the

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*Keller (45) conducted a series of six tests and got two positive responses from seven panel members at the 400 ug/L concentration of carbon tetrachloride in water.

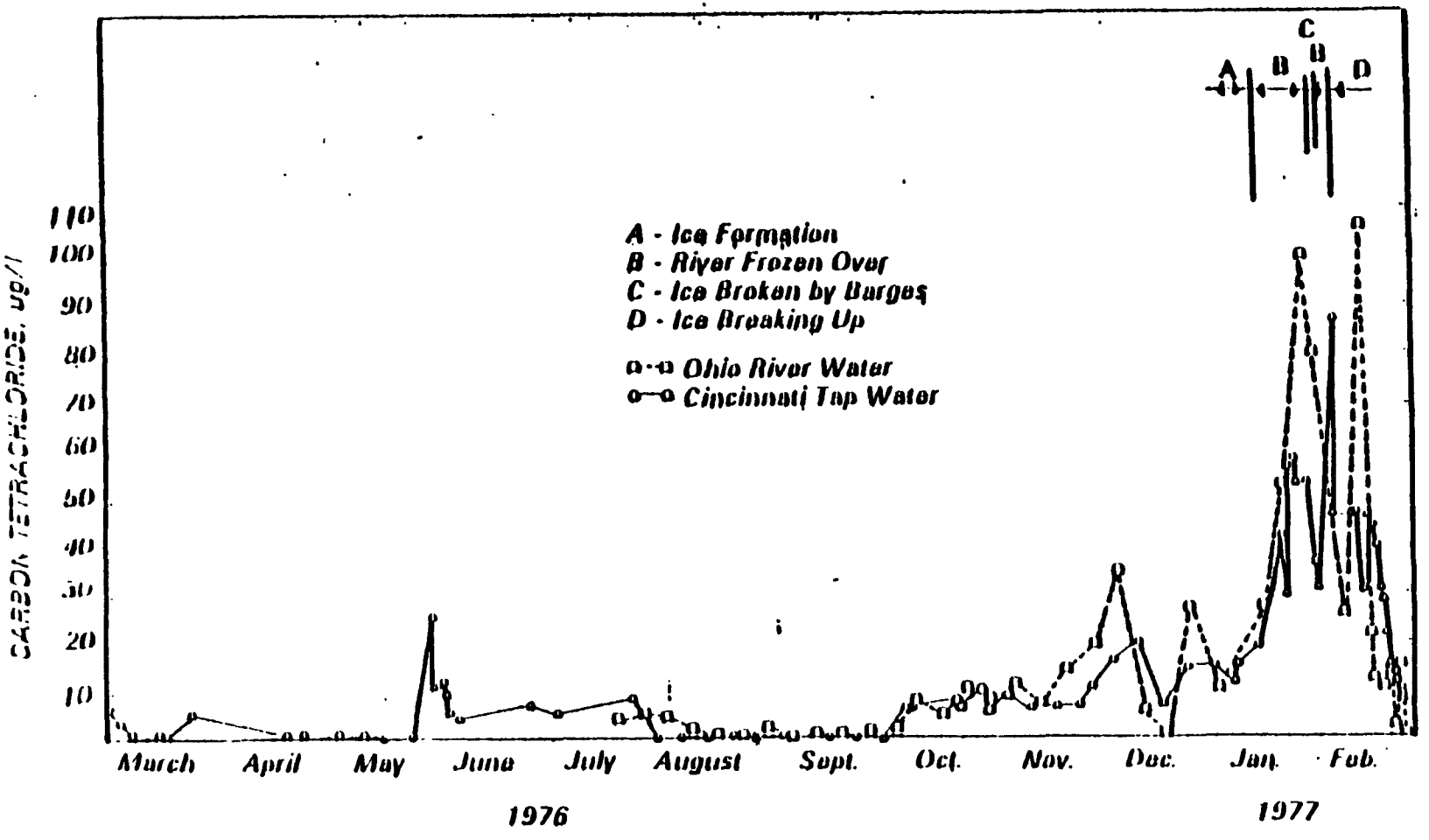

Figure 7. Carbon Tetrachloride in Raw and Treated Water at Cincinnati, Ohio

concentration of this contaminant in the untreated water was 16.3 ug/L and in the treated water, 16.0 ug/L, indicating no net removal resulted from powdered activated carbon addition (2 to 4 mg/L), coagulation, settling, and filtration. Laboratory studies by the USEPA-DWRD that showed aeration with the diffused air aerator described on page 5 and also in Table 1, (4:1 air-to-water ratio) could remove 91 percent of the carbon tetrachloride (13) and powdered activated carbon was largely ineffective, as doses up to 30 mg/L removed only about 10 percent of this contaminant. Lykins and DeMarco (49) reviewed the treatment data generated by another water utility using the Ohio River during this period and concluded that consistent removals of carbon tetrachloride were not obtained with powdered activated carbon, as differences could have been attributed to analytical variation.

Dobbs and Cohen (30) and Weber (50) have developed adsorption isotherms for carbon tetrachloride using different protocols and different types of granular activated carbon (Figure 8). From these isotherm studies, it has been determined that the calculated capacity for carbon tetrachloride on activated carbon, for an equilibrium concentration of 100 ug/L, is between 1.6 mg/g and 7.0 mg/g. It is not known whether this range reflects true differences in adsorbents or simply differences in isotherm technique.

Symons (51) reported on the behavior of carbon tetrachloride in water applied to pilot scale adsorbers containing Filtrasorb® 400 granular activated carbon. Two adsorbers, one with 5 min and the other with 10-min empty bed contact times, had been exposed to Cincinnati, Ohio tap water for 18 weeks when carbon tetrachloride was detected in the influent water. The

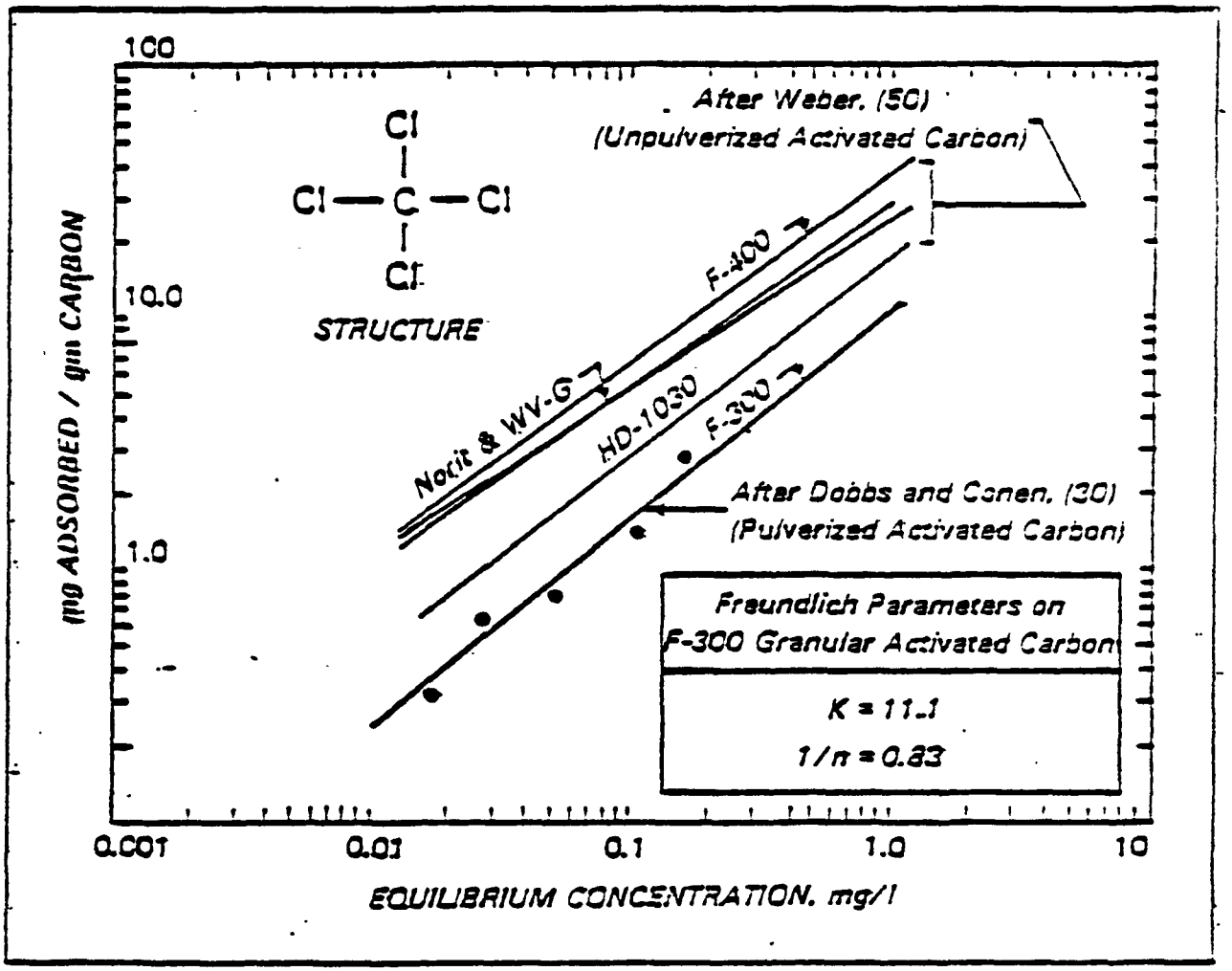

Figure 8. *Adsorption Isotherms for Carbon Tetrachloride*

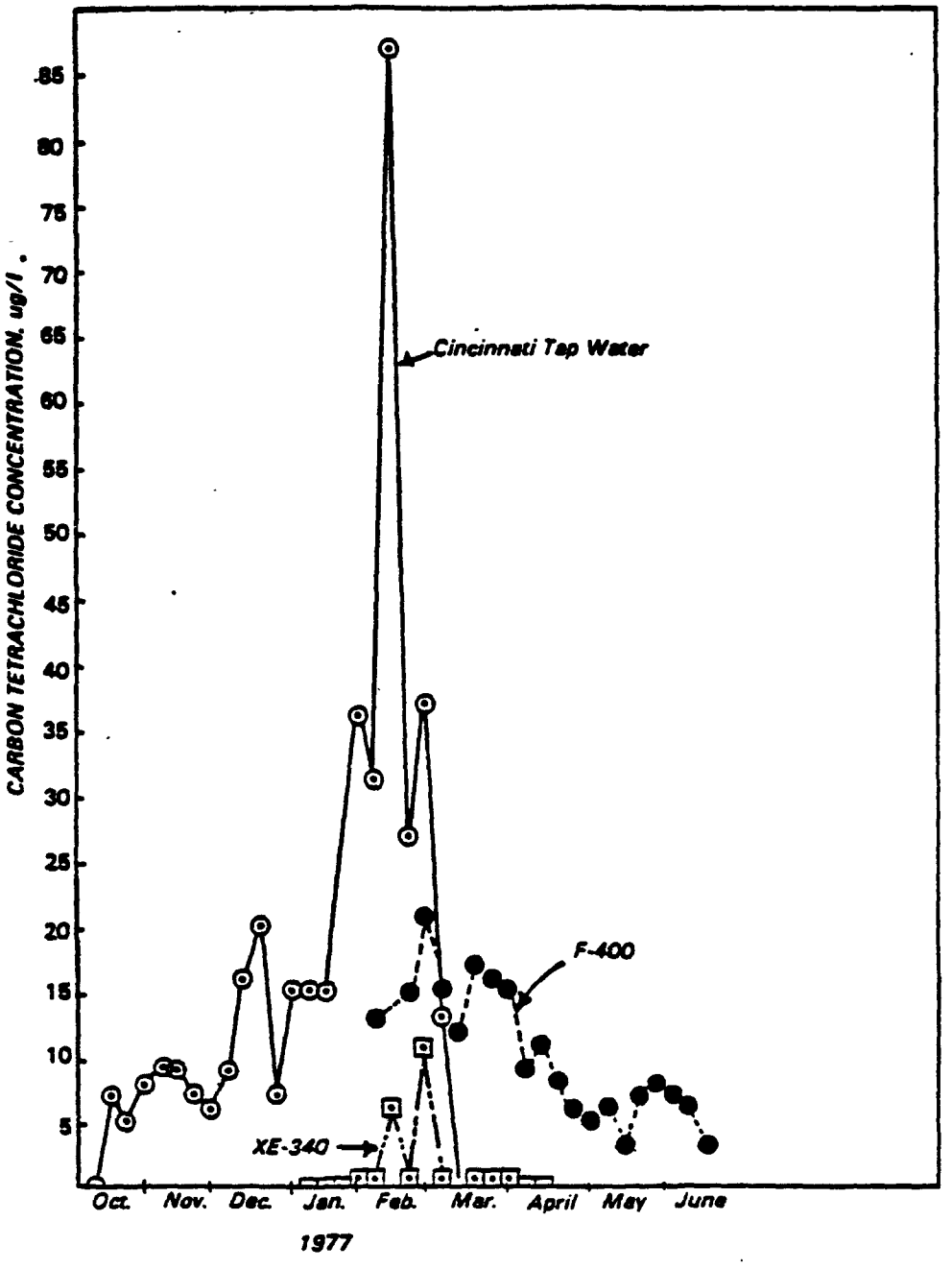

Figure 9. *Desorption of Carbon Tetrachloride from Granular Activated Carbon and Polymeric Resin*

mean concentration of the contaminant in the water was 12 ug/L, which was removed to less than 0.1 ug/L for 3 weeks by the activated carbon with 5 min contact time and between 14 and 16 weeks by the activated carbon with 10 min contact time. This corresponds to an empirical loading range of approximately 6,000 and 14,000 m^3/m^3, respectively.

In the Fall, 1976, three granular activated carbons manufactured in France were also being exposed to tap water in the USEPA-DWRD laboratory in Cincinnati. Two of the materials, PICA-A and PICA-B, behaved similarly to the Filtrasorb®400, but the third, PICA-C, had no capacity for carbon tetrachloride. Further, PICA-C had no capacity for total organic carbon or for trihalomethanes (31), leading the investigators to suspect the material was either poorly activated or not activated at all.

Symons, et al. (13) reported Ambersorb® XE-340 removed carbon tetrachloride from Cincinnati, Ohio drinking water for about the same length of time as the granular activated carbon did. Although the length of service to breakthrough was similar to that for granular activated carbon, the shape of the adsorption and desorption curves were quite different. For activated carbon, desorption is evident when influent concentrations of the contaminant decline. The resin, on the other hand, shows some desorption but much less than the granular activated carbon (Figure 9).

Boiling

Table 8 lists some results of boiling water contaminated by carbon tetrachloride. About 1 percent or less remains after 5 minutes of vigorous boiling.

TABLE 8. REMOVAL OF CARBON TETRACHLORIDE FROM DRINKING WATER BY BOILING

SAMPLE	Time of Boiling, min	Concentration, ug/L
USEPA-DWRD Cincinnati, Ohio (tap water)	0 (before heating)	30
	5	<0.1
Rhode Island State Health Department (44) (tap water)	0 (before heating)	188
	5	2

Cis-1,2-DICHLOROETHYLENE

CHCl = ClCH

Molecular Weight: 96.9 | Solubility: 3500 mg/L @ 25°C (15)

Threshold Odor Concentration: Not Reported | Vapor Pressure: 206 mm Hg (15)

Boiling Point: 60.3°C | Henry's Law Constant: 0.31 (15)

Other Names: (20,21)

cis-acetylene dichloride; cis-1,2-dichloroethene; NCI-C51581

This isomer of dichloroethylene is used as a solvent and a fermentation retardant (20).

Aeration

The engineering firm, NKRE, (26) aerated well water containing 13 ug/L to 118 ug/L (average 58 ug/L) of cis-1,2-dichloroethylene and found the average removal was 58 percent at an air-to-water ratio of 5:1. The removal could be increased to 85 percent at a 30:1 air-to-water ratio. In a USEPA-DWRD aeration study in New Jersey, 80 percent removal of this contaminant was observed at an air-to-water ratio of 4:1 and 10 min contact time. The diffused-air aeration devices used in both the above studies are described in Table 1, page 6.

Adsorption

An adsorption isotherm could not be found for cis-1,2-dichloroethylene; however, Dobbs and Cohen (30) developed that information for the other isomer, trans-1,2-dichloroethylene. That data is presented in Figure 10. Assuming the two isomers behave similarily on activated carbon, the estimated adsorption capacity for the solvent at an equilibrium concentration of 100 ug/L is 0.9 mg/g. The empirical results from two USEPA-DWRD studies in New England (Figure 11) compare favorably with those predicted by this isotherm data. For example, at one utility in New Hampshire, the cis-1,2-dichloroethaylene

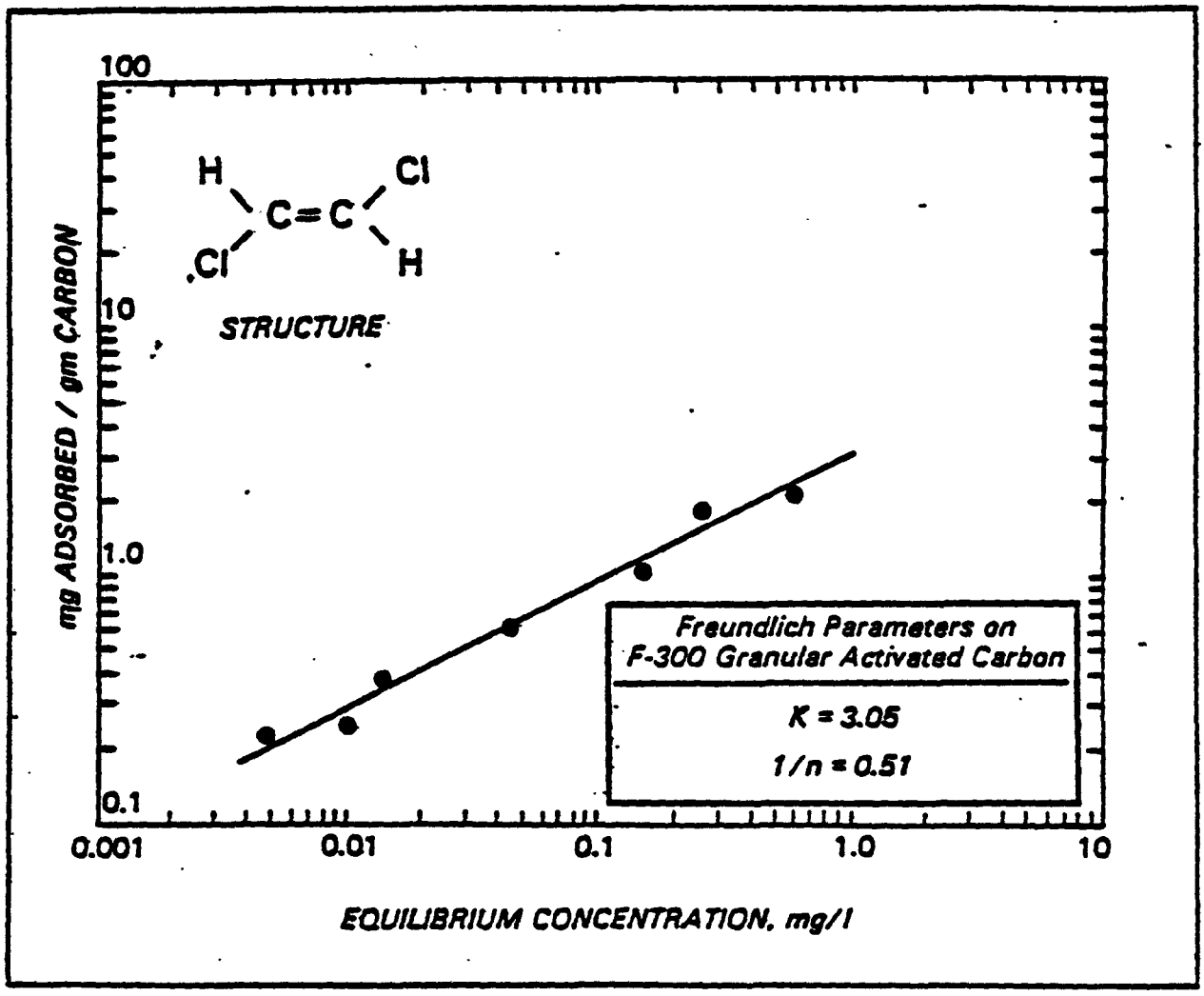

Figure 10. *Adsorption Isotherm for Trans-1,2-Dichloroethylene. Reference 30.*

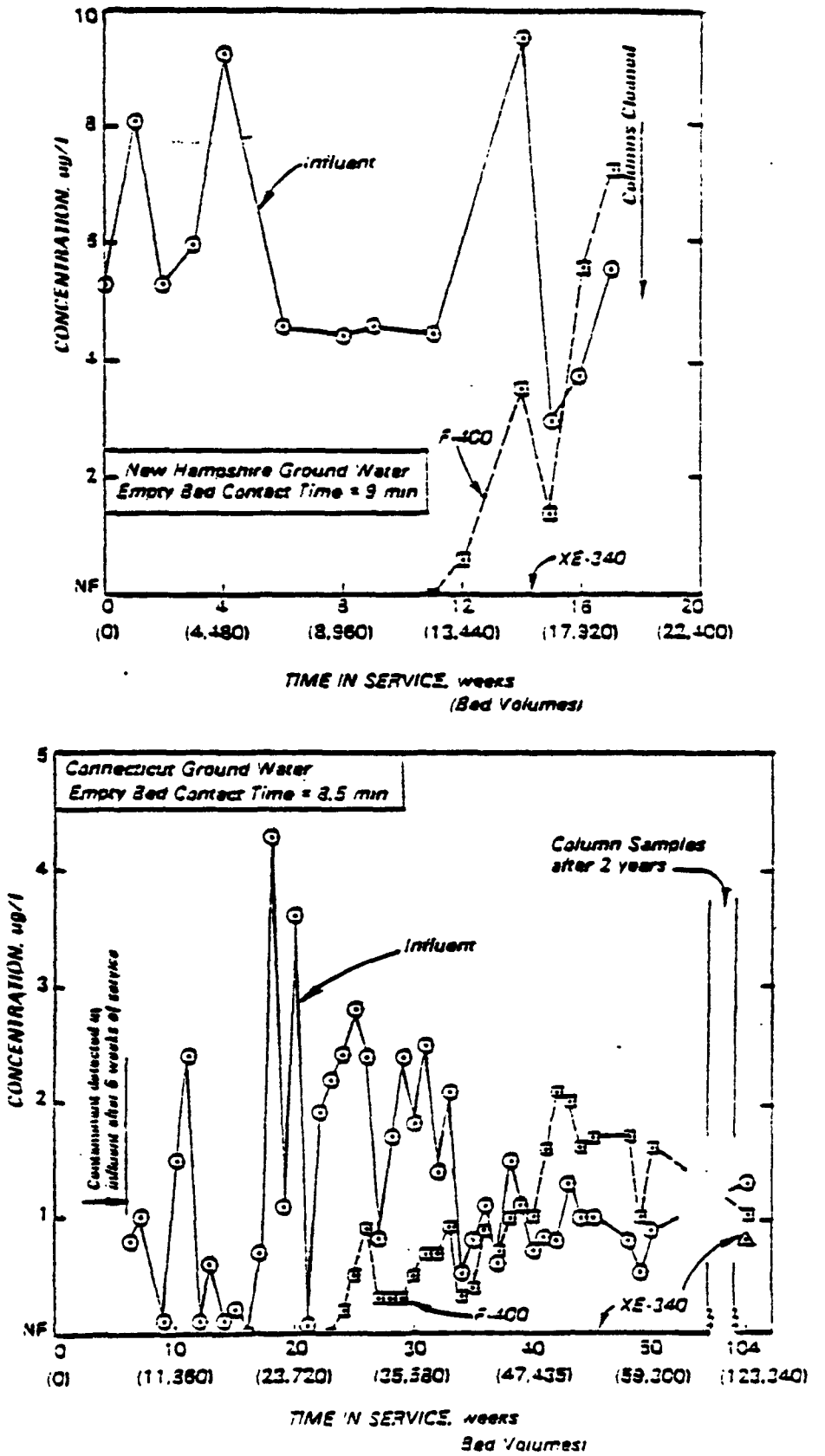

Figure 11. *Removal of Cis-1,2-Dichloroethylene by Adsorption on Granular Activated Carbon and Polymeric Resin.*

averaged 6 ug/L in the water applied to the pilot scale adsorber and the capacity for the activated carbon at exhaustion was identical to the predicted value, 0.2 mg/g. At the other site in Connecticut, the average concentration of cis-1,2-dichloroethylene was 2 ug/L, and the predicted and actual capacities were both 0.1 mg/g for the activated carbon. Companion adsorbers containing Ambersorb® XE-340 resin maintained an effluent concentration of cis-1,2-dichloroethaylene below detection for more than one year but less than 2 years (> 5.4 mg/g loading) at the Connecticut site.

Wood and DeMarco (35) evaluated Filtrasorb® 400 granular activated carbon, Ambersorb® XE-340 resin, and Amberlite® IRA-904 anion exchange resin on the organic laden groundwater in Miami, Florida. Cis-1,2-dichloroethylene was one of the major contaminants in the untreated water and its concentration remained unchanged after lime softening and filtration. Pilot scale adsorbers [2.5 cm (1 in) diameter glass columns] were placed on flow streams of raw, lime softened, and chlorinated filtered water. In the untreated (raw) water, the average concentration of cis-1,2-dichloroethylene was 25 ug/L, and this was detected in the effluent from the activated carbon between 2 and 3 weeks (0.3 mg/g loading). The XE-340 lasted approximately 9 weeks (0.7 mg/g loading), and the anion exchange resin did not remove any of the contaminant. The effects of placing the adsorbents at other locations within the treatment plant are shown in Table 9. The XE-340 performed better on the raw water than on the treated water, which may indicate how the high pH of lime softening affects capacity. NKRE (26) reported a uniform loading to breakthrough on XE-340 for a 2 and 4 min contact time. For some unexplained reason, however, the loading declined when a longer contact time (7.5 min) was used (Table 9).

TABLE 9. REMOVAL OF Cis-1,2-DICHLOROETHYLENE BY ADSORPTION

Adsorbent	Average Influent Concentration ug/L	Bed Depth, m (ft)	Empty Bed Contact Time, min	Service to Breakthrough* Time, days	Bed Volumes m³/m³	Loading kg/kg
		[Miami, FL (33)]				
Filtrasorb® 400 on raw water	25	0.8 (2.5)	6	18	4,300	0.3
Filtrasorb® 400 on filtered water	18	0.8 (2.5)	6	18	4,300	0.2
		1.5 (5)	12	39	7,100	0.3
		2.3 (7.5)	18	101	8,000	0.4
		3.1 (10)	25	>122	>7,000	>0.3
Ambersorb® XE-340 on raw water	25	0.8 (2.5)	6	60	14,400	0.7
Ambersorb® XE-340 on lime softened water	22	0.8 (2.5)	6	30	7,200	0.3
Ambersorb® XE-340 filtered water	16	0.8 (2.5)	6	48	11,500	0.4
Amberlite® IRA-904	17	0.8 (2.5)	6	Not effective		
		1.5 (5)	12	Not effective		
		[Glen Cove, NY (25)]				
Ambersorb® XE-340	40	0.3 (1)	2	48	37,200	1.7
		0.6 (2)	4	102	39,500	1.9
		1.2 (4)	7.5	102	19,700	0.9

* 0.1 ug/L or more in effluent

Boiling

Two samples of well water from Pennsylvania, having cis-1,2-dichloroethylene as one of the contaminants, were boiled for varying times by the USEPA-DWRD in Cincinnati and then analyzed. The results, given in Table 10, show 5 min of vigorous boiling reduced the contaminant level to 5 ug/L or less.

TABLE 10. REMOVAL OF Cis-1,2-DICHLOROETHYLENE FROM WATER* BY BOILING

Time of Boiling, min.	Concentration, ug/L	
	Sample 1	Sample 2
0 (before heating)	739	153
1	168	43
2	51	34
3	31	34
5	14	20
10	<1	5

*Contaminanted well water from Pennsylvania. Study by USEPA, Drinking Water Research Division, Cincinnati, OH, 1979. Water depth approximately 8 cm.

VINYL CHLORIDE

$CH_2 = CHCl$

Molecular Weight: 62.5

Threshold Odor Concentration: Not Reported

Boiling Point: -14°C

Solubility: 60 mg/L @ 10°C (15,16)

Vapor Pressure: 2660 mm Hg (16)

Henry's Law Constant: 30 (15); 301 (16)

$6.4 \frac{atm\text{-}m^3}{mole}$ (29)

Other Names: (20, 21, 59)

Chloroethylene; Chloroethene; Chlorethene; Ethylene, Chloro-; Ethylene monochloride; Monochloroethene; monochloroethylene; VCM; Vinyl C monomer

Vinyl chloride is commonly produced by reacting chlorine gas with ethylene ($CH_2 = CH_2$) (52). Billions of kilograms of this solvent are used annually in the United States to produce polyvinyl chloride (PVC), the most widely used ingredient for manufacturing plastics throughout the world (60). In 1978, Dressman and McFarren (61) conducted pilot plant tests on PVC pipe. They sampled five water distribution systems that used PVC pipe and found vinyl chloride concentrations in the water ranged from 0.7 to 55 ug/L. They concluded the vinyl chloride contamination levels were related to the vinyl chloride monomer residual in the pipe, and whether or not the water flowed continuously or sat idle for long periods. The authors pointed out, however, that producers of PVC pipe claimed that changes recently made in the manufacturing process lowered residual monomer in the pipe and thus lessened vinyl chloride expected to leach into drinking water from new PVC pipe. If vinyl chloride therefore, is detected only in the distribution system (absent in the raw water), piping materials may be the source.

Special precautions are necessary to sample and analyze for vinyl chloride because of its low boiling point (high volatility). Unlike trichloroethylene, for example, vinyl chloride would escape detection in a

routine analysis for trihalomethanes. For this reason, little definitive occurrence or treatment information exists on this contaminant in drinking water. Furthermore, few laboratories are equipped for experimentation with carcinogens, so treatment information will probably have to be developed at sites where vinyl chloride is detected.

One such site is a groundwater location in Southern Florida. Vinyl chloride was detected intermittently in this source and the average concentration reduction for this contaminant through the lime softening basins and filters was 25 to 52 percent (35). These losses were, likely, to the atmosphere around the open basins. Finished water from the treatment plant was routed to four pilot-scale granular activated carbon columns connected in series. Each column contained 76-cm (30-in) of Filtrasorb® 400 activated carbon and the empty bed contact time was approximately 6 minutes per column. Vinyl chloride concentrations in the influent ranged from below-detection to 19 ug/L, and adsorption on the activated carbon was erratic. For example, to maintain an effluent concentration of vinyl chloride below 0.5 ug/L, the estimated activated carbon loading was 810-, 1250-, 2760-, and 2050 m^3/m^3 for empty bed contact times of 6-, 12-, 19-, and 25 minutes, respectively (35, 51). Similarly, vinyl chloide was reported to be poorly removed on Ambersorb XE-340 synthetic resin (51). Because of its high volatility, vinyl chloride should effectively be removed by aeration.

1,2-DICHLOROETHANE

CH_2ClCH_2Cl

Molecular Weight: 99

Threshold Odor Concentration: 2000 mg/L (18,19)

Boiling Point: 83°C

Solubility: 8700 mg/L @ 25°C (15,16)

Vapor Pressure: 82 mm Hg (15,16)

Henry's Law Constant: 0.05 (15,16)
1.10×10^{-3} $\frac{atm\text{-}m^3}{mole}$ (17)

Other names: (20,21,59)

1,2-dichlorethane; Borer Sol; Brocide; Destraxol Borer-Sol; Dichloremulsion; Di-Chloro-Mulsion; dichloroethane; Alpha, beta-Dichloroethane; Dichloroethylene; Dutch liquid; EDC; ENT 1,656; ethane dichloride; ethylene chloride; ethylene dichloride; gylcol dichloride; NCI-C00511; Acetylene dichloride; Dioform

1,2-Dichloroethane is used as a solvent for fats, oils, waxes, gums, and resins (20).

Aeration

This contaminant is not as easily removed from water by aeration as the previously discussed solvents. For example, Symons, et al. (13) reported an air-to-water ratio of 4:1 removed only 40 percent of the 1,2-dichloroethane from contaminated well water in New Jersey.

Adsorption

Dobbs and Cohen (30) developed an adsorption isotherm (Figure 12) for 1,2-dichloroethane on Filtrasorb® 300 granular activated carbon. From that data, the estimated capacity at an equilibrium concentration of 100 ug/L is approximately 0.5 mg/g. In a USEPA-DWRD study in New Jersey, Witcarb® 950 granular activated carbon maintained an effluent concentration of 1,2-dichloroethane below 0.1 ug/L (influent concentration averaged 1.4 ug/L) for 31 weeks which yields a loading of approximately 0.1 mg/g (17,400 m^3/m^3) to breakthrough. Ambersorb® XE-340 resin showed breakthrough after 54 weeks of service, a loading of approximately 0.3 mg/g (108,360 m^3/m^3).

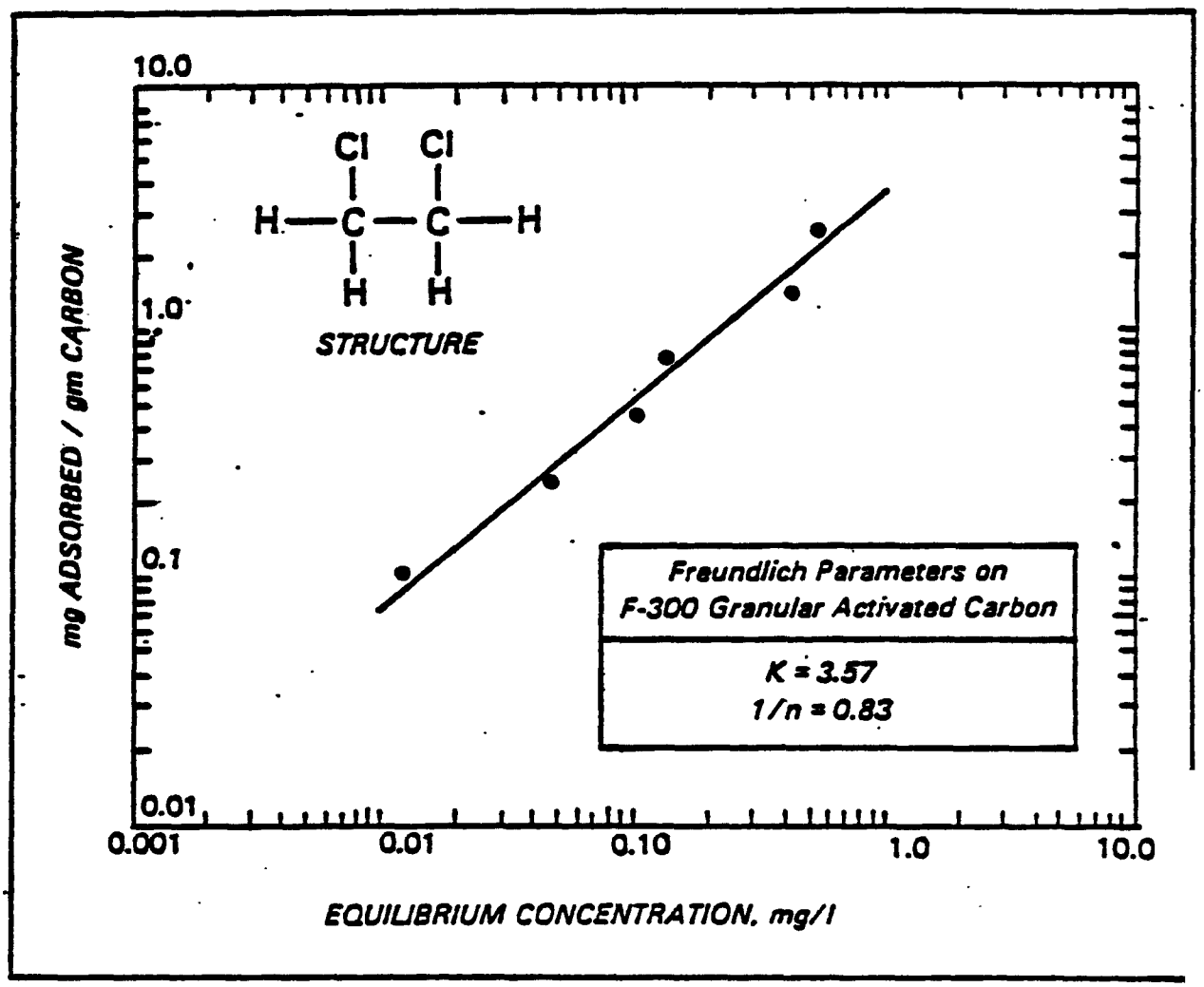

Figure 12. *Adsorption Isotherm for 1,2 -Dichloroethane. Reference 30.*

In a study by DeMarco, et al. (24), and DeMarco and Brodtman (53) in Louisiana, 1,2-dichloroethane (average concentration of 3 ug/L) was not removed by conventional coagulation and filtration but was removed to less than 0.1 ug/L for 39 days (1725 m^3/m^3) through a full scale adsorber containing 76-cm (30-in) of Westvaco WV-G granular activated carbon (20-min EBCT).

DISCUSSION AND SUMMARY

Trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethane, carbon tetrachloride, cis-1,2-dichloroethylene, and 1,2-dichloroethane are solvents found in drinking water. Some of their properties are shown in Table 11. Because of their volatility, they are seldom detected in high concentrations in surface water except during periods when rivers, susceptible to contamination, have an ice cover. Ground waters in the eastern United States (along the Atlantic Coast and particularly in New England) and in California are increasingly showing contamination by these solvents. The scope of this problem is likely to grow as monitoring improves.

These contaminants do not occur naturally nor are they produced as significant chlorination by-products during disinfection. Carbon tetrachloride can be a contaminant in chlorine; however, pending improvements in chlorine specifications may help eliminate that source. Tetrachloroethylene can be leached from polyvinyl-toluene lined asbestos cement pipe; trichloroethylene has been traced to certain adhesives used to join reservoir liners; and, vinyl chloride has been shown to leach from PVC pipe manufactured prior to 1977. All of these possible sources should be examined if solvent contamination is discovered only in the distribution system. The occurrence of these contaminants in the source water can generally be related to a near-by practice such as degreasing and ground discharge of wastes.

TABLE 11. COMPARATIVE DATA FOR TRICHLOROETHYLENE AND RELATED SOLVENTS

Name / Parameter	- chloroethylene			- chloroethane		Carbon Tetrachloride	Vinyl Chloride
	Tri-	Tetra-	Cis-1,2-di	1,1,1-tri-	1,2-di-		
Molecular Weight, g/mole	132	166	97	133	99	154	62
Boiling Point, °C							
Atmospheric	86.7	121	60	74.1	83.5	76.7	-14
Azeotropic (w/H_2O)	73.2 (55)	88.5 (37)	Not Reported	65 (55)	71.6 (37,55)	66.8 (55)	Not reported
Solubility, mg/L	1000 (16) 1100 (15,17)	150 (16,17) 140 (15)	3500 (15)	4400 (16) 5497 (17)	8700 (15,16)	800 (15,16,17)	60 (15,16)
Vapor Pressure, mm Hg (15,16)	74	18.6	206	100	82	91.3	2660
Henry's Law Constant							
$\frac{\text{conc. (air)}}{\text{conc. (water)}}$	0.48 (16) 0.49 (15)	1.1 (16) 1.2 (15)	0.31 (15)	0.17 (16) 1.2 (15)	0.05 (15,16)	1.2 (15,16)	50 (15) 301 (16)
$\frac{\text{atm-m}^3}{\text{mole}}$ (17)	11.7×10^{-3}	28.7×10^{-3}	Not Reported	4.92×10^{-3}	1.10×10^{-3}	30.2×10^{-3}	
Threshold Odor Concentration, ug/L	500 (18,19)	300 (18)	Not Reported	Not Reported	2000 (18,19)	*(45)	Not Reported
Parachor (54)	212.8	250.0	175.6	223.9	186.6	220.0	211.3
Molar Refraction (54)	30.42	35.21	20.71	24.95	21.18	26.30	23.85

*Test inconclusive. Two of seven panel members reported detection at a CCl_4 concentration of 400 ug/L.

USEPA-DWRD has found several of these solvents present when a groundwater is found to be contaminated. For example, trichloroethylene or tetrachloroethylene may be present in the highest concentrations, but lesser quantities of related solvents are also present. One reason for this might be related to solvent purity. In the manufacturing of these solvents, the end-product depends on the temperature, degree of acidification, and chlorination, so a commercial grade solvent might have varying amounts of several related compounds, Figure 13. Another reason for the presence of a variety of solvents in one location might be biological degradation of a parent compound in the ground. When solvent contamination is suspected, a thorough analysis for volatile organics should be made so the most effective treatment method can be selected.

Laboratory and field experimentation have shown air stripping can be a successful means of lowering the concentration of most of these contaminants in drinking water. In an EPA-DWRD experiment, tap water samples spiked with trichloroethlene and tetrachloroethylene alone, and a combination of the two solvents were aerated. No significant difference was observed in the efficiency of removal of the individual solvents, whether they were alone or combined. This is important because mixtures of solvents exist in contaminated water and even though the effectiveness of the process varies for each solvent, aerating to remove one specific contaminant will also reduce the concentrations of the others. A typical example of this is given in Table 12. Assuming aeration is employed to remove tetrachloroethylene, the principal target along with concentrations of the other solvents are reduced. In this illustration, if the concentrations are simply added, the water contains approximately 460 ug/L of volatile organics before aeration and 40 ug/L afterwards, for about 92 percent overall removal efficiency.

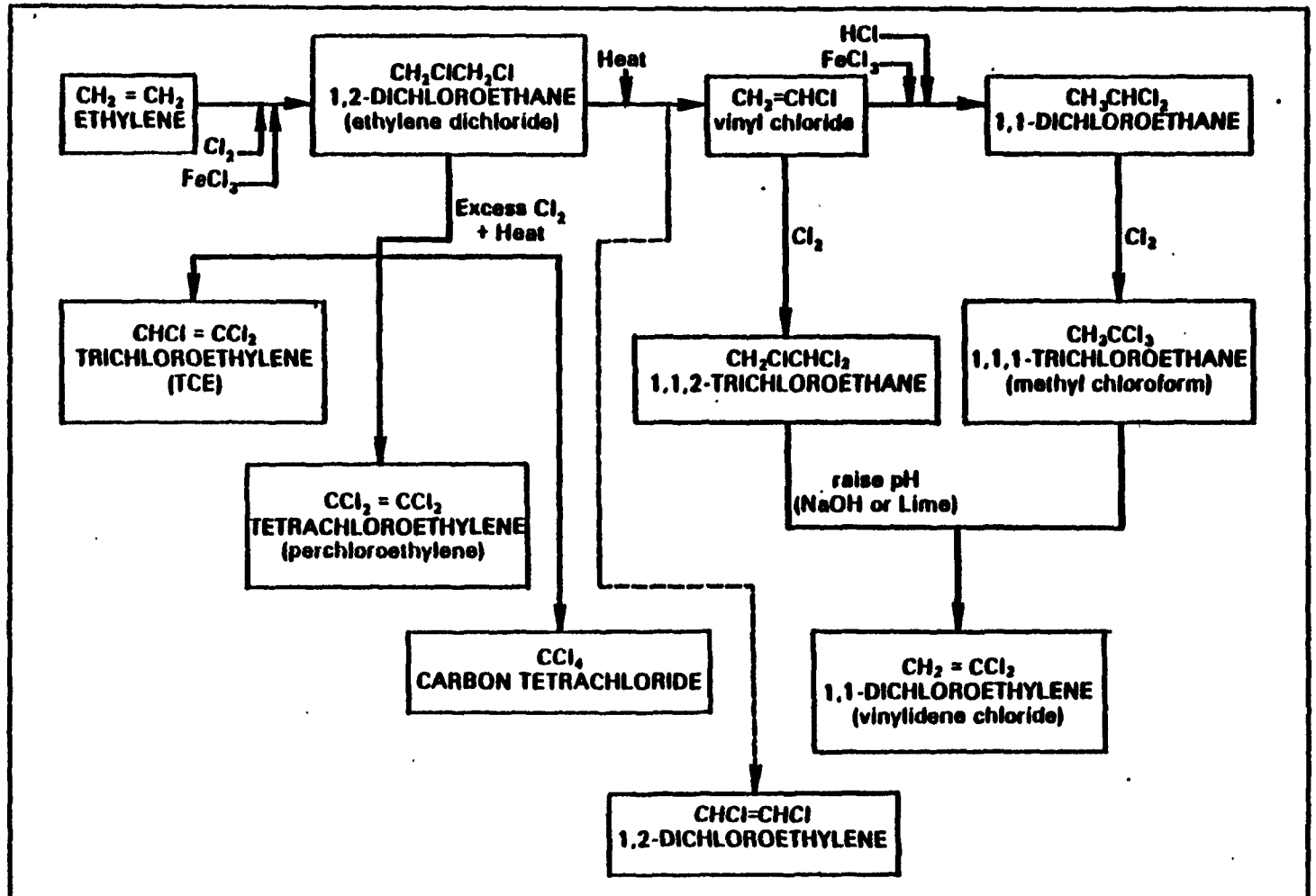

Figure 13. *Simplified Example of Manufacturing Process for Industrial Solvents. Reference* 23

TABLE 12. EFFECTS OF AERATION ON A SOLVENT CONTAMINATED GROUNDWATER*

Contaminant	Avg. concentration, ug/L Before Aeration	After Aeration**	Percent Removal	Henry's Law Constant
1,1-Dichloroethylene	122	4	97	6.3 (15)
1,1,1-Trichloroethane	237	23	90	1.2 (15)
Tetrachloroethylene	94	9	90	1.1 (15,16
Trichloroethylene	3	0.4	87	0.5 (15,16
cis-1,2-Dichloroethylene	0.5	<0.1	>80	0.31 (15)
1,1-Dichloroethane	6	1	83	0.24 (15)
1,2-Dichloroethane	1.4	0.8	42	0.05 (15,1

*USEPA-DWRD study in New Jersey
**Diffused-air aeration, 10 min contact; 4:1 (vol to vol) air to water; Area to Volume = $0.8m^{-1}$

Henry's Law constant is useful in estimating whether or not aeration should be considered (29), and Figures 14, 15 and 16, and Table 13 compare empirical data with a theoretical optimum removal.* Singley, et al. (56) have recently concluded that the mass transfer coefficient for volatile compounds is important in judging a priori the effectiveness of aeration, and that these coefficients are needed for designing full-scale stripping columns and have to be developed on-site. Future USEPA-DWRD aeration studies will include development of design information.

There is a question of whether or not the off-gasses create a problem with aeration. In one USEPA-DWRD sponsored aeration project (26), the principal investigator sampled for volatile solvents in the off-gasses near the top of the aerator and identified trichloroethylene, tetrachloroethylene, 1,1,1-trichloreothene, and 1,2-dichloroethane. The mean concentrations were 201 , 85 , 30 , and 22 ug/L, respectively. This air sampling program is continuing but the likelyhood of creating an air pollution problem by aerating solvent contimanted drinking water is remote given existing air quality standards.

Adsorption also has varying degrees of effectiveness. Figure 17 summarizes the isotherm data developed by Dobbs and Cohen (30) and, for purposes of illustration, adsorption capacities for two different concentrations of each solvent are shown in Table 14. For perspective, the capacities for chloroform and bromoform are also shown. Note, cis-1,2-dichloroethylene isotherm data were not available, but assuming it might behave like the other isomer, the trans-1,2-dichloroethylene information was included. An isotherm for vinyl chloride has not been reported.

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*This optimum removal curve was developed using the reciprocal of the Henry's Law constants given in Reference 16. An explanation of this concept is given in Reference 57.

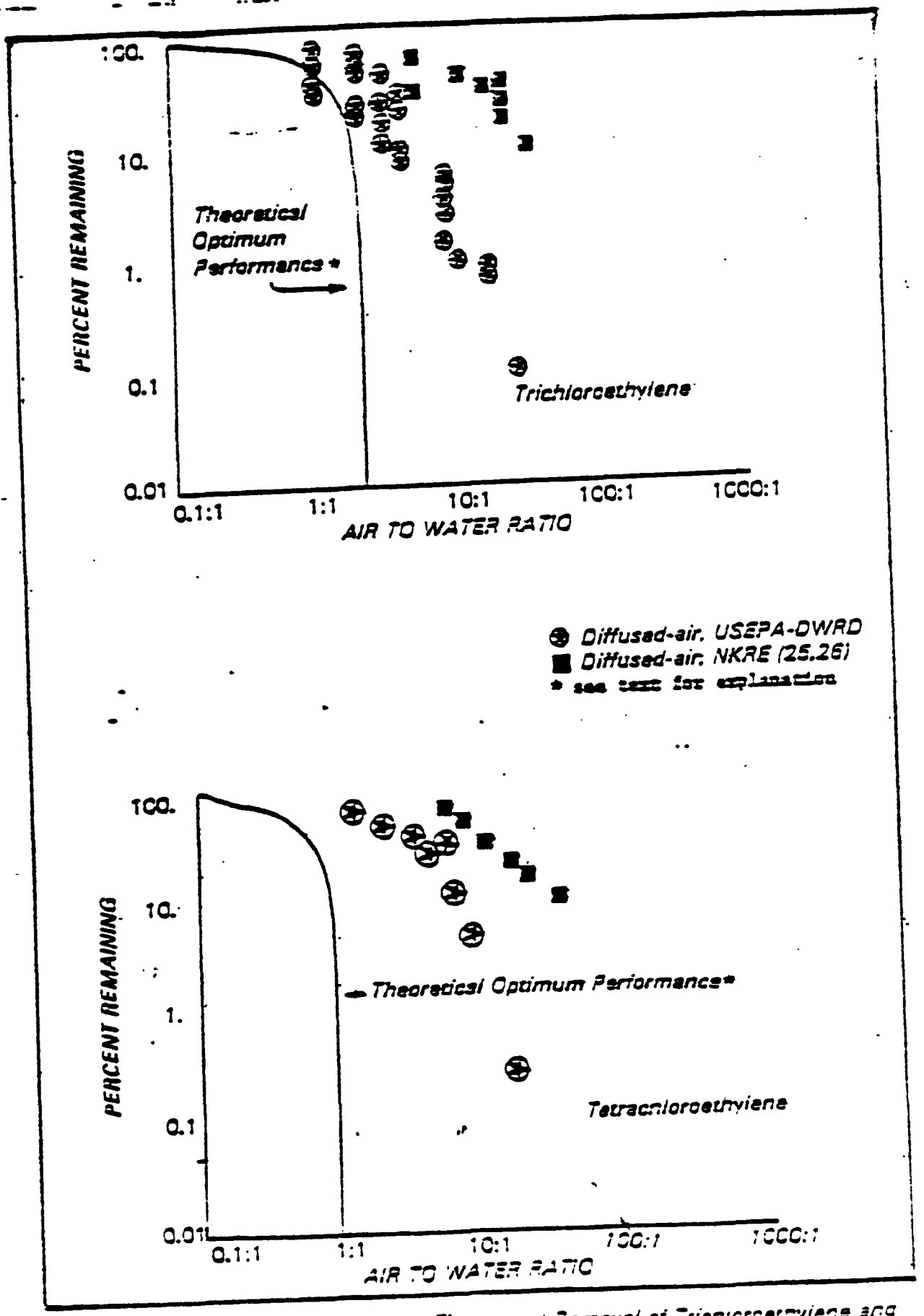

Figure 14. Comparison of Actual and Theoretical Removal of Trichloroethylene and Tetrachloroethylene from Drinking Water by Aeration.

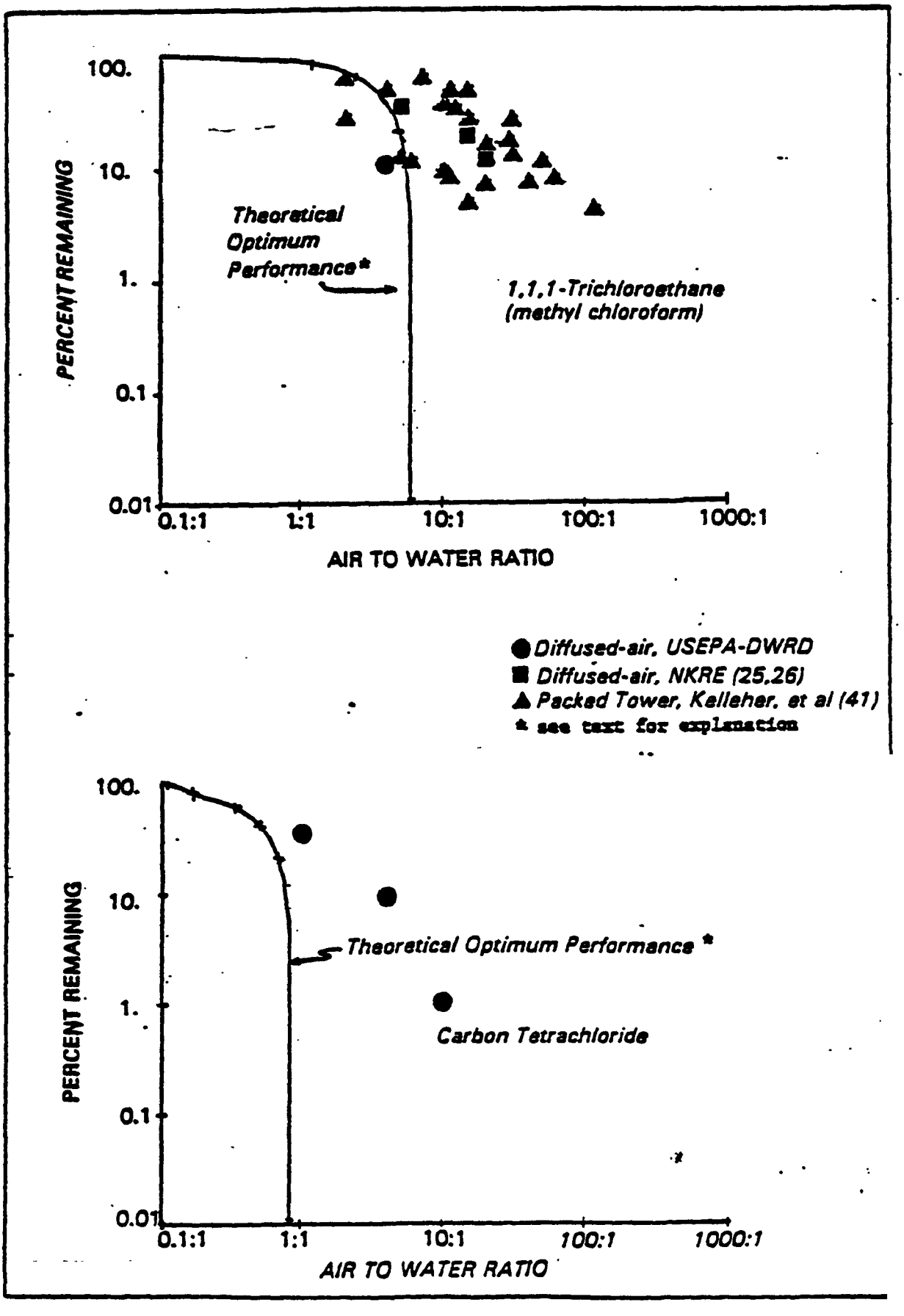

Figure 15. *Comparison of Actual and Theoretical Removal of 1,1,1-Trichloroethane and Carbon Tetrachloride from Drinking Water by Aeration.*

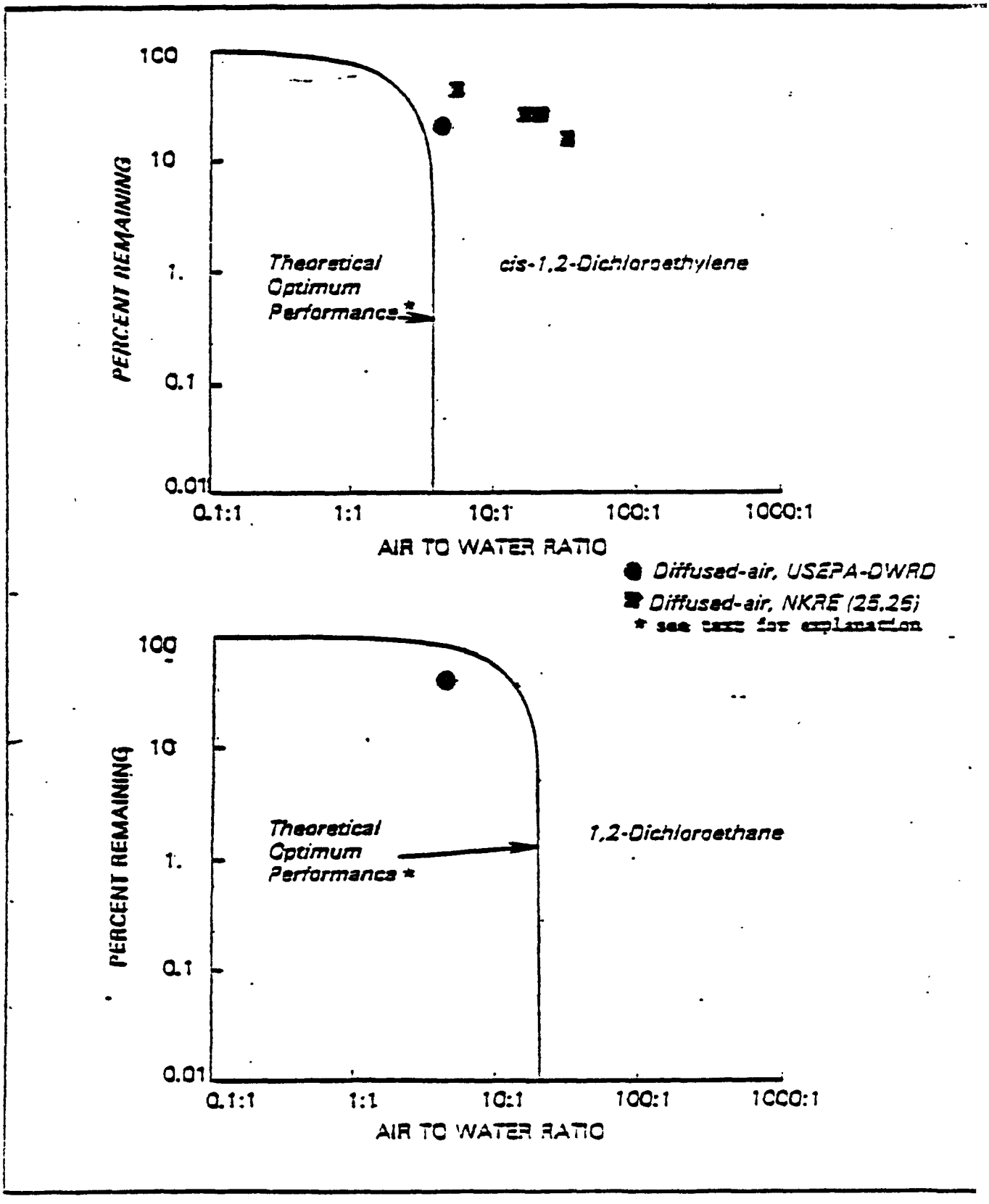

Figure 16. Comparison of Actual and Theoretical Removal of cis-1,2-Dichloroethylene and 1,2-Dichloroethane from Drinking Water by Aeration.

TABLE 13. ESTIMATED AIR TO WATER RATIOS NECESSARY TO ACHIEVE DESIRED TREATMENT, SUMMARY

	Inf. Conc. ug/L	Effluent Concentration, ug/L: 0.1			1			10			50			100		
		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
Trichloroethylene	1000	2:1	40-136:1	76:1	2:1	25-100:1	54:1	2:1	10-66:1	32:1	2:1	4-44:1	17:1	2:1	3-34:1	11:1
	100	2:1	25-100:1	54:1	2:1	10-66:1	32:1	2:1	3-34:1	11:1	<1:1	1-10:1	1:1	<1:1	-	-
	10	2:1	10-66:1	32:1	2:1	3-34:1	11:1	-	-	-	-	-	-	-	-	-
	1	2:1	3-34:1	11:1	-	-	-	-	-	-	-	-	-	-	-	-
Tetrachloroethylene	1000	1:1	25-320:1	96:1	1:1	17-150:1	72:1	<1:1	11-65:1	43:1	<1:1	8-36:1	26:1	<1:1	6-30:1	18:1
	100	1:1	17-150:1	72:1	1:1	11-65:1	43:1	<1:1	6-30:1	18:1	<1:1	2-7:1	1:1	-	-	-
	10	1:1	11-65:1	43:1	1:1	6-30:1	18:1	-	-	-	-	-	-	-	-	-
	1	1:1	6-30:1	18:1	-	-	-	-	-	-	-	-	-	-	-	-
1,1,1-Trichloroethane	1000	6:1	68-600:1	198:1	6:1	21-260:1	90:1	6:1	10-120:1	35:1	6:1	5-65:1	16:1	6:1	4-52:1	8:1
	100	6:1	21-260:1	90:1	6:1	10-120:1	35:1	6:1	4-52:1	8:1	4:1	1-15:1	1:1	-	-	-
	10	6:1	10-120:1	35:1	6:1	4-52:1	8:1	-	-	-	-	-	-	-	-	-
	1	6:1	4-52:1	8:1	-	-	-	-	-	-	-	-	-	-	-	-
Carbon Tetrachloride	1000	1:1	-	19:1	1:1	-	15:1	1:1	-	10:1	1:1	-	6:1	<1:1	-	4:1
	100	1:1	-	15:1	1:1	-	10:1	1:1	-	6:1	<1:1	-	1:1	-	-	-
	10	1:1	-	10:1	1:1	-	6:1	-	-	-	-	-	-	-	-	-
	1	1:1	-	6:1	-	-	-	-	-	-	-	-	-	-	-	-
Cis-1,2-Dichloroethylene	1000	4:1	14-152:1	104:1	9:1	10-113:1	77:1	4:1	8-76:1	52:1	4:1	3-50:1	34:1	4:1	4-38:1	26:1
	100	4:1	10-113:1	77:1	4:1	8-76:1	52:1	4:1	4-38:1	26:1	2:1	2-10:1	4:1	-	-	-
	10	4:1	8-76:1	52:1	3:1	4-38:1	26:1	-	-	-	-	-	-	-	-	-
	1	3:1	4-38:1	26:1	-	-	-	-	-	-	-	-	-	-	-	-
1,2-Dichloroethane	1000	20:1	-	56:1	20:1	-	42:1	28:1	-	28:1	20:1	-	18:1	-	-	14:1
	100	20:1	-	42:1	20:1	-	28:1	18:1	-	14:1	10:1	-	-	-	-	-
	10	20:1	-	28:1	18:1	-	14:1	-	-	-	-	-	-	-	-	-
	1	18:1	-	14:1	-	-	-	-	-	-	-	-	-	-	-	-

a = Theoretical optimum air to water ratio based on the reciprocal of the Henry's Law Constants given in Reference 16. An explanation of this concept is given in Reference 57. For vinyl chloride, this optimum value is <<0.1:1.

b = Range of air to water ratios extrapolated from actual experimentation. This is estimated by developing an envelope around the data in Figures 14, 15, and 16.

c = Average air to water ratio calculated from "b".

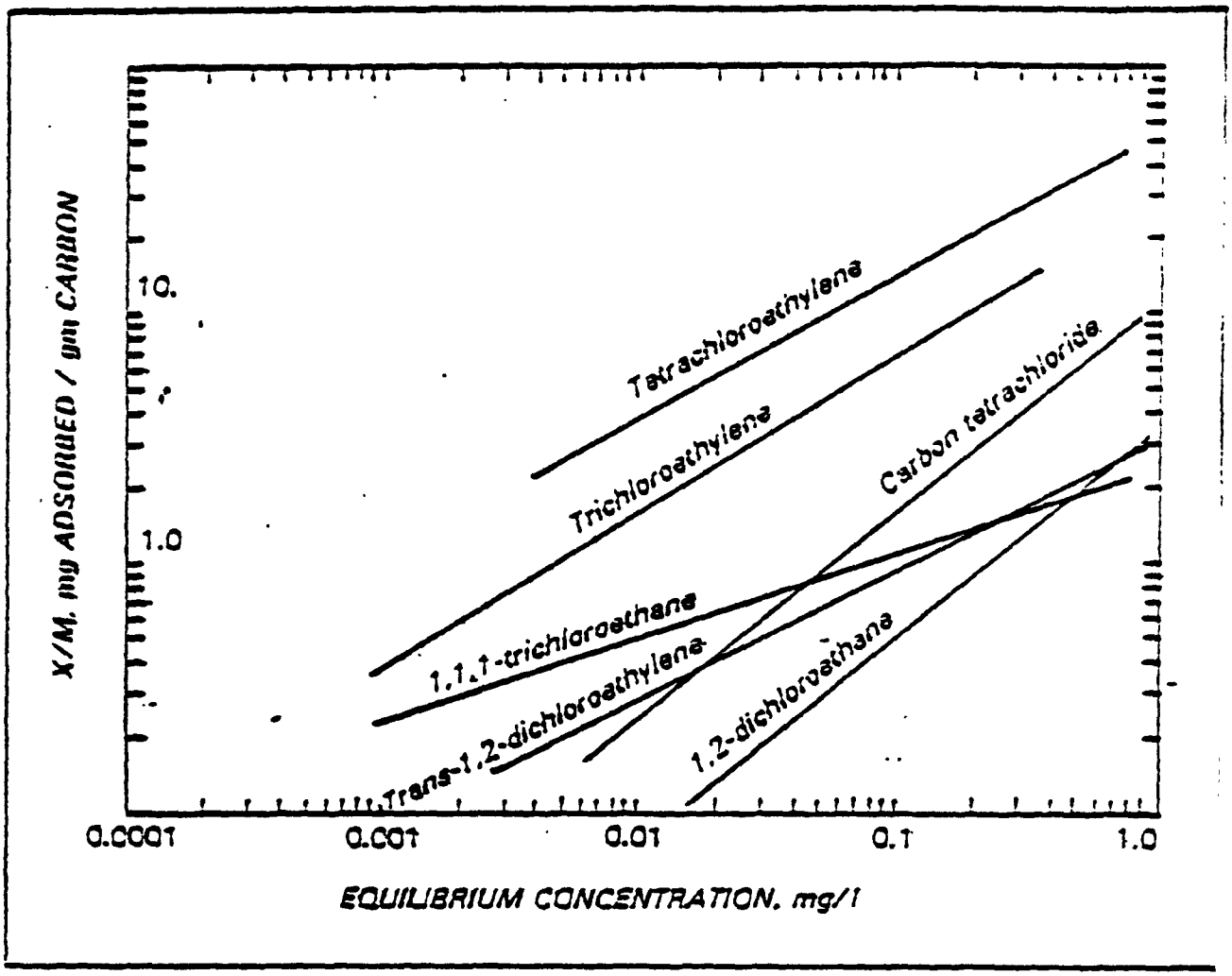

Figure 17. *Comparison of Adsorption Isotherms. Reference 30.*

TABLE 14. ACTIVATED CARBON EQUILIBRIUM ADSORPTION CAPACITITES* FOR TRICHLOROETHYLENE AND RELATED SOLVENTS

Contaminant	Adsorption Capacity, mg/g	
	Equilibrium Concentration 1000 ug/L	Equilibrium Concentration 100 ug/L
TRICHLOROETHYLENE	28	7
TETRACHLOROETHYLENE	51	14
1,1,1-TRICHLOROETHANE	2	1
CARBON TETRACHLORIDE	10	2
TRANS-1,2-DICHLOROETHYLENE**	3	1
1,2-DICHLOROETHANE	4	<1
CHLOROFORM†	3	<1
BROMOFORM†	20	6

*Taken from Dobbs and Cohen, 1980
**Cis-1,2-Dichloroethylene data not available.
†Added for perspective
Vinyl chloride adsorption capacity data not available.

The following technique was used to estimate carbon usage for the contaminant concentrations shown in Table 16. First, two ratios were established for each contaminant; a) that between capacity at exhaustion observed from field studies divided by theoretical capacity determined from isotherm data, and b) that between capacity at actual breakthrough and capacity at exhaustion (Table 15). Isotherm capacities at the given contaminant concentrations (1000, 100, 10, and 1 ug/L) were then multiplied by ratio "a" to give an estimated activated carbon usage to exhaustion, and that value was then divided by ratio "b" to give an estimated activated carbon usage to breakthrough. By plotting these two values on semilog paper, carbon usage for intermediate effluent concentrations was estimated from the graph.

For example, assume a pilot-scale study on a water containing an average concentration of 1,1,1-trichloroethane of 210 ug/L showed the activated carbon usage to breakthrough (0.1 ug/L) was 7,400 m^3/m^3 (2,250 gal/lb) and to exhaustion, 13,200 m^3/m^3 (4,000 gal/lb). This yields an exhaustion-to-breakthrough ratio of 13,200/7,400 or 1.8. From the isotherm data in Reference 30, the equilibrium capacity (X/M) is 1.46 mg/g, which corresponds to a theoretical activated carbon usage of 2,750 m^3/m^3 (830 gal/lb). This yields an actual-to-theoretical activated carbon usage ratio of 13,200/2,750 or 4.8. Thus, for a given influent concentration of 1,000 ug/L, the estimated activated carbon usage to exhaustion would be 4,800 m^3/m^3 (1,450 gal/lb = 300 gal/lb x 4.8) and to breakthrough, 2,670 m^3/m^3 (800 gal/lb = 1,450/1.8). The activated carbon usage for intermediate effluent concentrations can then be determined from Figure 18. The range of estimated carbon usage shown in Table 16 is extremely wide for certain contaminant concentrations, so on-site pilot scale experimentation would be prudent if treatment

TABLE 15. ADSORPTION OF TRICHLOROETHYLENE AND RELATED SOLVENTS BY GRANULAR ACTIVATED CARBON, SUMMARY

	Avg. Conc., ug/L	Bed Depth, m(ft)	EBCT, min.	Loading, m^3/m^3 Breakthrough 0.1 ug/L (except as noted)	Loading, m^3/m^3 Exhaustion (inf = eff)	Capacity, m^3/m^3 (a)	Reference
Trichloroethylene	177	0.8 (2.5)	9	>20,160	>20,160	21,300	EPA-DWRD
	4	0.8 (2.5)	8.5	>60,900 but <123,340	>123,340	99,900	"
	1*	0.8 (2.5)	18	>32,500	>32,500	106,560	"
	0.4**	0.8 (2.5)	18	>32,500	>32,500	199,800	"
Tetrachloroethylene	1400	0.8 (2.5)	9	12,300	33,100	17,500	EPA-DWRD
	94*	0.8 (2.5)	18	>32,500	>32,500	57,400	"
	9**	0.8 (2.5)	18	>32,500	>32,500	162,800	"
	4	0.8 (2.5)	8.5	>60,900 but <123,340	>123,340	237,600	"
	1	0.8 (2.5)	9	>20,160	>20,160	475,200	"
1,1,1-Trichloroethane	100	0.6 (2)	7.5	1,300†	not reported	3,800	(41)
		1.2 (4)	15	2,700†	not reported	3,800	"
		1.8 (6)	22.5	3,900†	not reported	3,800	"
	237*	0.8 (2.5)	18	15,700	30,800	2,600	EPA-DWRD
	23**	0.8 (2.5)	18	>32,500	>32,500	12,000	"
	38	0.8 (2.5)	8.5	11,800	26,000	9,400	"
	1	0.8 (2.5)	9	16,400	22,500	94,400	"
Carbon Tetrachloride	12	0.8 (2.5)	10	14,000	25,000	9,400	(31)
		0.8 (2.5)	5	6,050	not reported	9,400	"
Cis-1,2-Dichloroethylene††	18	0.8 (2.5)	6	4,100	13,800	9,400	(35)
		1.5 (5)	12	7,100	14,300	9,400	"
		2.3 (7.5)	18	8,100	13,700	9,400	"
	6	0.8 (2.5)	9	14,200	19,000	13,300	EPA-DWRD
	2	0.8 (2.5)	8.5	29,600	48,600	26,000	"
Vinyl Chloride	7	0.8 (2.5)	6	810	2,400	Isotherm	(35)
		1.5 (5)	12	1,250	-	not reported	"
		2.3 (7.5)	18	2,800	-		"
		3.1 (10)	25	2,050	5,011		"
1,2-Dichloroethane	8	0.8 (2.5)	20	1,700	8,640	3,500	(33)
	1.4*	0.8 (2.5)	18	17,400	45,900	5,700	EPA-DWRD
	0.8**	0.8 (2.5)	18	>32,500	>32,500	5,000	"
	2	0.9 (3)	11	3,300	9,160	4,000	(24)
		1.8 (6)	22	3,400	7,850	4,000	"
		2.7 (9)	33	4,150	>7,000	4,000	"
		3.6 (12)	44	>7,000	>7,000	4,000	"
		0.8 (2.5)	17.5	2,500	7,450	4,000	"
		0.7 (2.4)	17	2,500	7,450	4,000	"

(a) Estimated by Freundlich isotherms (30)
* Adsorption of unaerated water; ** Adsorption after 10 min aeration @ 4:1 (vol to vol) air to water
† 5 ug/L in effluent
†† Isotherm capacities based on trans-1,-2-dichloroethylene

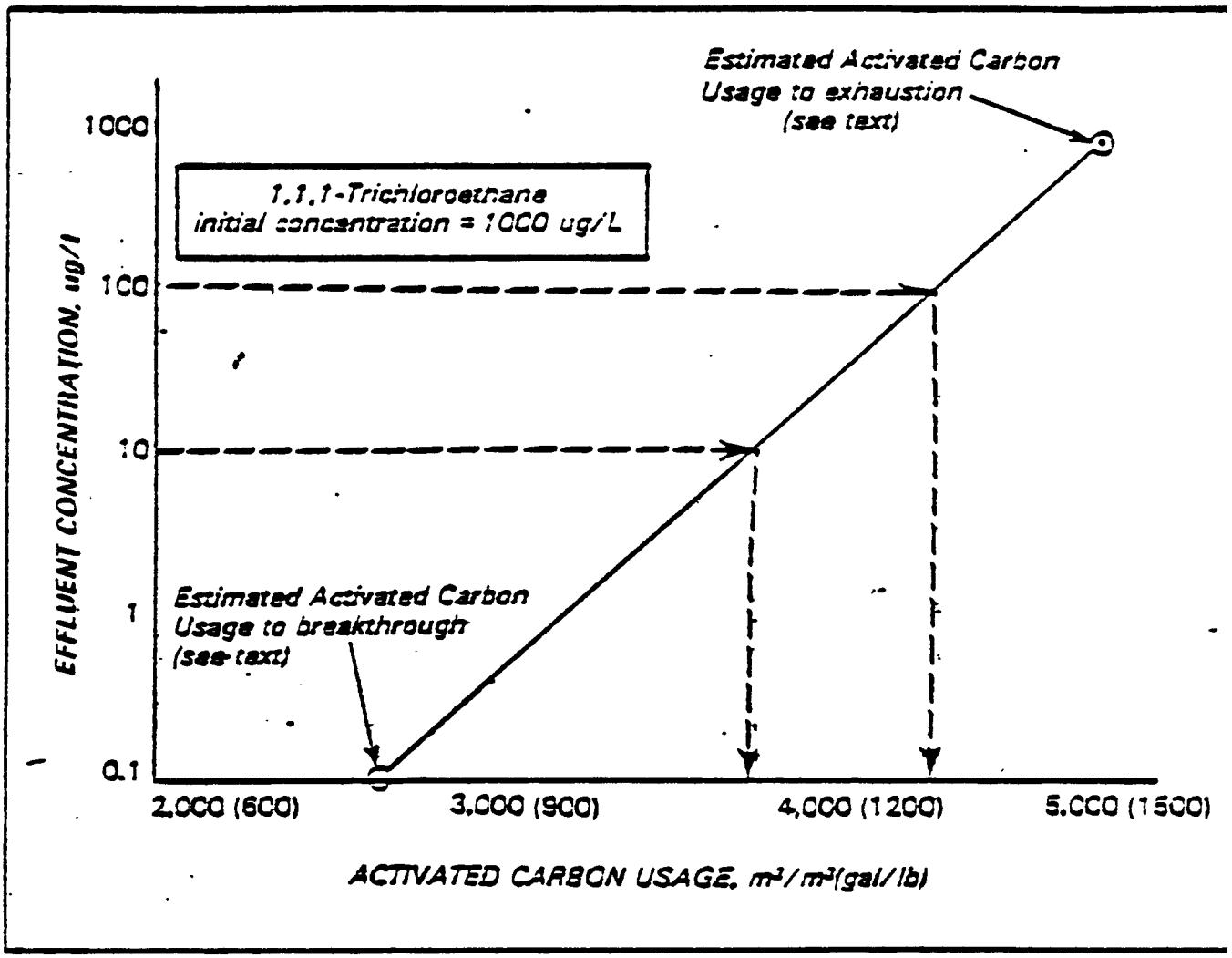

Figure 18. *Estimating Activated Carbon Usage to Achieve Target Effluent Qualities*

TABLE 16. ESTIMATED CARBON USAGE NECESSARY TO ACHIEVE DESIRED TREATMENT, SUMMARY

	Inf. Conc.	Desired Effluent Concentration, ug/L									
		0.1		1		10		50		100	
	ug/L	a	b	a	b	a	b	a	b	a	b
Trichloro-ethylene	1000	-	5.4 (1.7)	-	7.6 (2.3)	-	9.6 (2.9)	-	11.0 (3.3)	-	11.7 (3.5)
	100	-	13.1 (4.0)	-	19.6 (5.9)	-	26.0 (7.9)	-	31.6 (9.6)	-	-
	10	-	31.4 (9.5)	-	55.0 (16.7)	-	-	-	-	-	-
	1	-	76.0 (23.0)	-	-	-	-	-	-	-	-
Tetrachloro-ethylene	1000	-	15.2 (4.6)	-	21.0 (6.4)	-	26.8 (8.1)	-	30.7 (9.3)	-	32.4 (9.8)
	100	-	41.9 (12.7)	-	63.0 (19.0)	-	83.6 (25.3)	-	97.0 (29.4)	-	-
	10	-	116.8 (35.4)	-	204.0 (61.8)	-	-	-	-	-	-
	1	-	329.3 (99.8)	-	-	-	-	-	-	-	-
1,1,1-Trichloro-ethane	1000	0.1-4.6	1.0 (0.2)	0.1-7.0	1.1 (0.3)	0.1-8.2	1.3 (0.4)	0.1-9.4	1.5 (0.5)	0.2-10.0	1.6 (0.5)
	100	0.4-21.3	3.4 (1.0)	0.5-30.3	5.1 (1.5)	0.7-46.0	7.0 (2.1)	0.8-59.5	8.2 (2.5)	-	-
	10	1.6-116.8	15.3 (4.6)	2.7-172.0	26.7 (8.0)	-	-	-	-	-	-
	1	7.9-446.2	72.2 (21.9)	-	-	-	-	-	-	-	-
Carbon Tetra-chloride	1000	-	3.2 (0.9)	-	4.5 (1.4)	-	5.6 (1.7)	-	6.4 (1.9)	-	6.8 (2.1)
	100	-	4.5 (1.4)	-	6.8 (2.1)	-	9.0 (2.7)	-	10.6 (3.2)	-	-
	10	-	6.8 (2.1)	-	11.9 (3.6)	-	-	-	-	-	-
	1	-	11.3 (3.4)	-	-	-	-	-	-	-	-
Cis-1,-2-Dicloro-ethyelene	1000	0.2-0.9	0.6 (0.2)	0.6-1.3	0.9 (0.3)	1.0-1.6	1.2 (0.4)	1.2-1.8	1.5 (0.4)	1.2-2.0	1.6 (0.5)
	100	1.8-2.8	2.3 (0.7)	2.9-4.5	3.6 (1.1)	3.7-6.0	4.7 (1.4)	4.2-7.4	5.6 (1.7)	-	-
	10	5.5-8.7	7.1 (2.2)	12.0-15.5	12.5 (3.8)	-	-	-	-	-	-
	1	17.0-27.0	22.1 (6.7)	-	-	-	-	-	-	-	-
1,2-Dichloro-ethane	1000	1.0-4.5	1.6 (0.5)	1.4-6.3	2.2 (0.7)	1.8-8.0	2.8 (0.9)	2.1-9.2	3.3 (1.0)	2.3-9.8	3.5 (1.1)
	100	1.6-6.8	2.4 (0.7)	1.8-10.4	3.3 (1.0)	3.0-13.5	4.6 (1.4)	3.8-16.0	5.7 (1.7)	-	-
	10	2.4-10.2	3.7 (1.1)	4.4-17.0	6.3 (1.9)	-	-	-	-	-	-
	1	3.0-12.8	4.6 (1.4)	-	-	-	-	-	-	-	-

a = Granular activated carbon usage range, 10^3 m^3/m^3, estimated from isotherms and empirical data on Table 15.
b = Geometric mean GAC usage, 10^3 m^3/m^3 (10^3 gal/lb)

by activated carbon adsorption is contemplated. Furthermore, competition for adsorption sites in water containing a high organic content may be the reason Wood and DeMarco (35, and Kelleher, et al. (41) observed increasing capacities with increasing contact times.

The synthetic resin, Ambersorb XE-340® looks very promising as it has a high capacity for most of these contaminants (Table 17). Whether or not it can be economically regenerated by steam is the topic of on-going research (26), and it may not be known for some time. Studies have shown the effectiveness of this resin, like activated carbon, is influenced by the quality of the applied water. Its capacity may be reduced at the high pH of lime softening (35) and when competition exists for the adsorption sites (13). The effects of applying chlorinated water to the material is not known but should be resolved if the product is approved for use on potable water.

TABLE 17. ADSORPTION OF TRICHLOROETHYLENE AND RELATED SOLVENTS BY AMBERSORB® XE-340, SUMMARY

	Avg. Conc, ug/L	Bed depth, m(ft)	Empty Bed Contact time, min	Loading to 0.1 ug/L breakthrough, m^3/m^3	Reference
Trichloroethylene	215	0.3(1)	2	83,700	26
	210	0.6(2)	4	78,600	26
	210	1.2(4)	7.5	>53,300	26
	177	0.8(2.5)	9	>20,160	13
	4	0.8(2.5)	8.5	>123,340	EPA-DWRD
	3	0.2(0.8)	5	>117,000	EPA-DWRD
Tetrachloroethylene	41	0.3(1)	2	>99,900	26
	51	0.6(2)	4	78,600	26
	65	1.2(4)	7.5	>53,300	26
	70	0.3(1)	2	106,000	26
	94	0.8(2.5)	5	112,900	EPA-DWRD
	1400	0.8(2.5)	9	17,920	EPA-DWRD
	3	0.8(2.5)	8.5	>123,340	EPA-DWRD
	2	0.8(2.5)	9	>20,160	13
1,1,1-Trichloroethane	5	1.2(4)	7.5	39,300	26
	33	0.8(2.5)	9	56,000	13
	237	0.2(0.8)	5	82,600	EPA-DWRD
	23	0.2(0.8)	5	>100,800	EPA-DWRD
	1	0.8(2.5)	9	>20,160	13
Carbon Tetrachloride	19	0.8(2.5)	5	7,560	13
	19	0.8(2.5)	10	15,120	13
Cis,1,2-Dichloroethylene	40	0.3(1)	2	37,200	26
	38	0.6(2)	4	39,300	26
	40	1.2(4)	7.5	19,700	26
	40	0.3(1)	2	36,400	26
	25	0.8(2.5)	6	14,400	35
	22	0.8(2.5)	6	7,200	35
	16	0.8(2.5)	6	11,500	35
	6	0.8(2.5)	9	>20,160	13
	2	0.8(2.5)	8.5	>59,000 but <123,340	EPA-DWRD
1,2-Dichloroethane	1	0.2(0.8)	5	108,860	EPA-DWRD

ESTIMATED TREATMENT COSTS

Computer cost programs based on the Culp data (62) were used to estimate the treatment costs for removing trichloroethylene, tetrachloroethylene, 1,1,1trichloroethane, cis-1,2-dichloroethylene, carbon tetrachloride, and 1,2-dichloroethane from groundwater. No cost calculations were made for vinyl chloride removal because of the lack of treatment data for this contaminant.

The cost analysis is based on 1.3 m^3/min (500,000 gal/day) flow with the treatment system shown in Figure 19. The groundwater is treated by tower aeration, diffused air aeration, or granular activated carbon (GAC) followed by chlorination, clearwell storage, and high-lift pumping. The aeration towers are rectangular with an overall height of 3 m (10 ft) and an air supply of 137 sLm/m^2 (52 scfm/ft^2) of surface area is assumed. They have electrically driven induced-draft fans, fan stacks, and drift eliminators. The tower costs do not include supply pumps or underflow pumps. The aeration basins are rectangular with a depth of 3.5 m (12 ft). The diffused air supply system was sized for 14 sLm/m^2 (5 scfm/ft^2) of basin flow area. Adsorption consists of 3 steel contactors in series with an initial carbon supply. Carbon usage is based on 6-month throwaway at a cost of $1.50/kg ($.70/lb). Chlorination consists of a feed system (no basin) and a building for cylinder storage. A chlorine dose of 2 mg/L is assumed and the cost of chlorine is $.35/kg ($320/ton). Clearwell storage is above ground, with a capacity equal to 10 percent of the daily plant flow. The high lift pumping has a head of 12 m (40 ft). The estimated treatment cost does not include expenditures for land, slime or corrosion control, fences, off-gas handling, or carbon disposal.

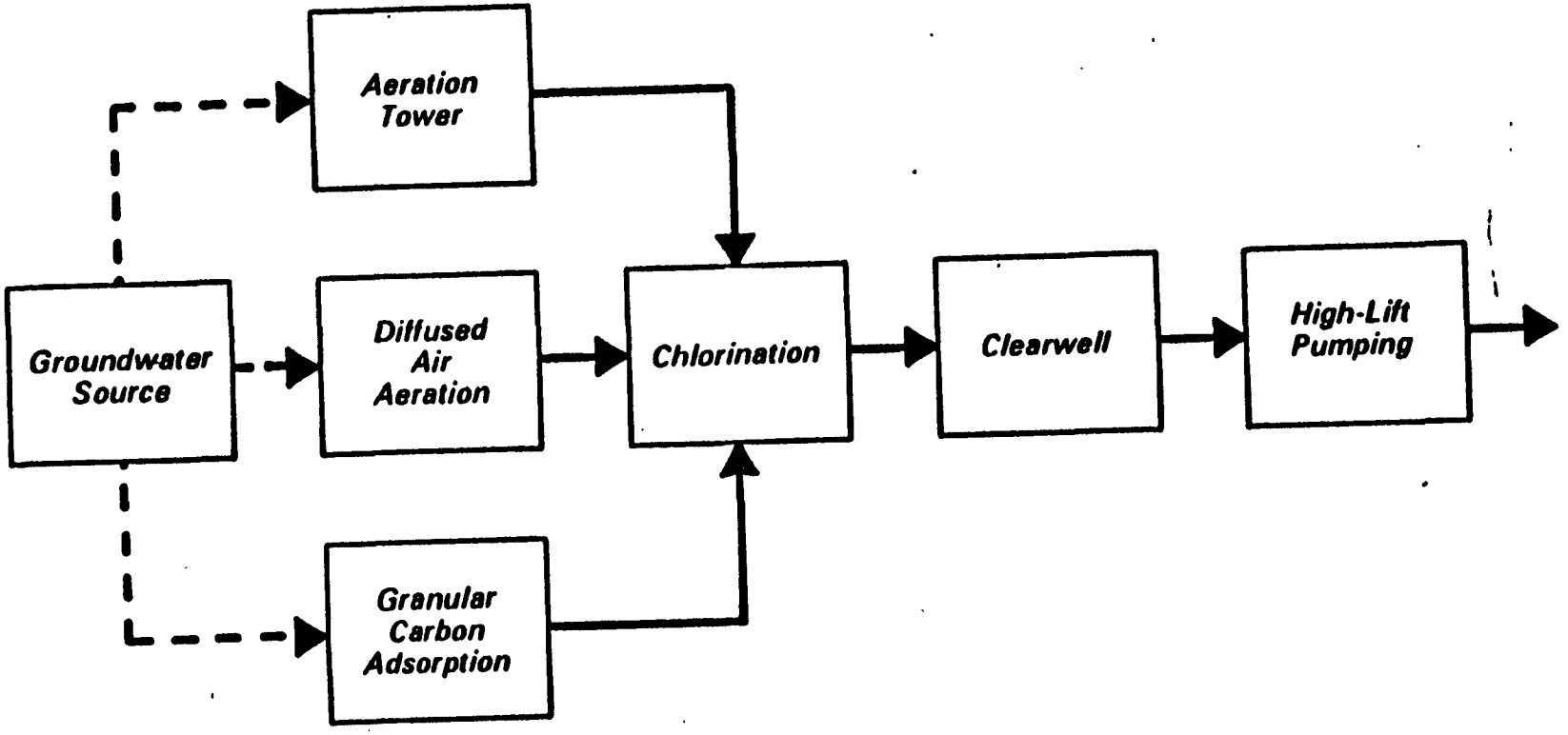

Figure 19. Water treatment system configuration for economic analysis of volatile organic contaminant removal.

Figures 20 through 25 give the total treatment cost in dollars per 1000 gallons of treated water as a function of operating flow. Each figure shows the 90 to 95 percent removal cost range in October 1980 dollars for aeration towers, aeration basins, and GAC for an influent contaminant concentration varying from 1 to 1000 ug/L. The required aeration basin and tower volumes for costing purposes were computed as a function of the mean air-to-water ratios given in Table 13. The cost bands for aeration towers are relatively narrow because little economy-of-scale exists for operating these units at such small hydraulic loadings.

The carbon requirements were the mean values given in Table 16. The adsorption cost ranges are wider than those estimated for aeration because of the influence of contaminant concentration. For example, the cost of 90 percent removal by aeration is the same whether the contaminant concentration is reduced from 1000 to 100 ug/L or from 1 to 0.1 ug/L. Adsorption capacity and activated carbon usage, however, vary with contaminant concentration; therefore, the cost of 90 percent removal by activated carbon is higher if the influent concentration is 1000 ug/L compared to 100 ug/L. The cost range for adsorption is very wide for some contaminants because of poor adsorbability. To achieve high percentages of removal for the poorly adsorbed contaminants a large amount of activated carbon is required and this increases the cost of treatment.

Figure 26 illustrates another way of presenting the cost information given in Figures 20 to 25. The total treatment cost of trichloroethylene removal is shown as a function of influent concentration at 4 levels of effluent concentration for each of the 3 treatment modes. Similar graphs could be generated for the other contaminants. Figure 27 gives the total

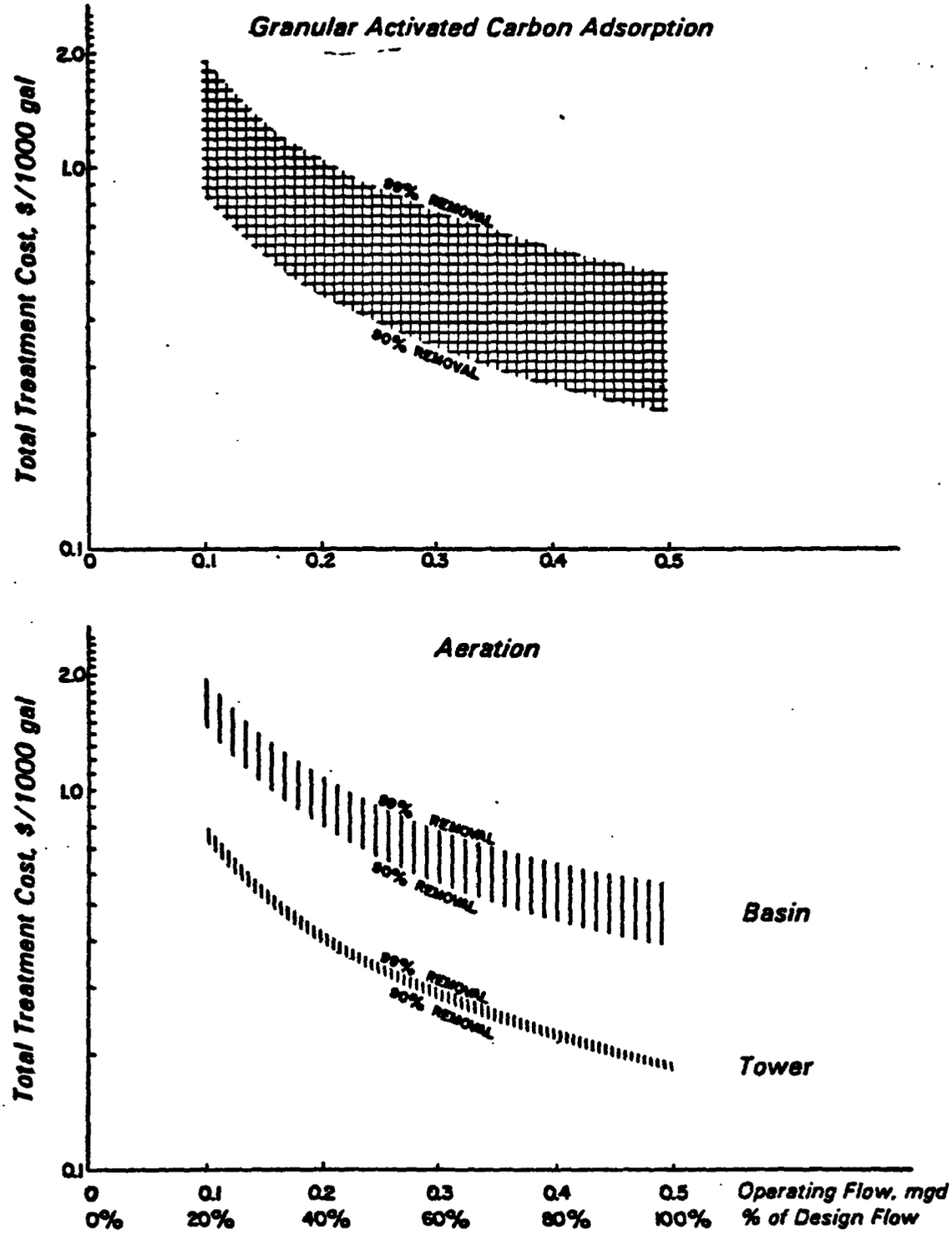

Figure 20. Cost of trichloroethylene removal (90–99%) (October 1980 dollars, influent concentration of 1–1000 µg/l, design flow of 0.5 mgd).

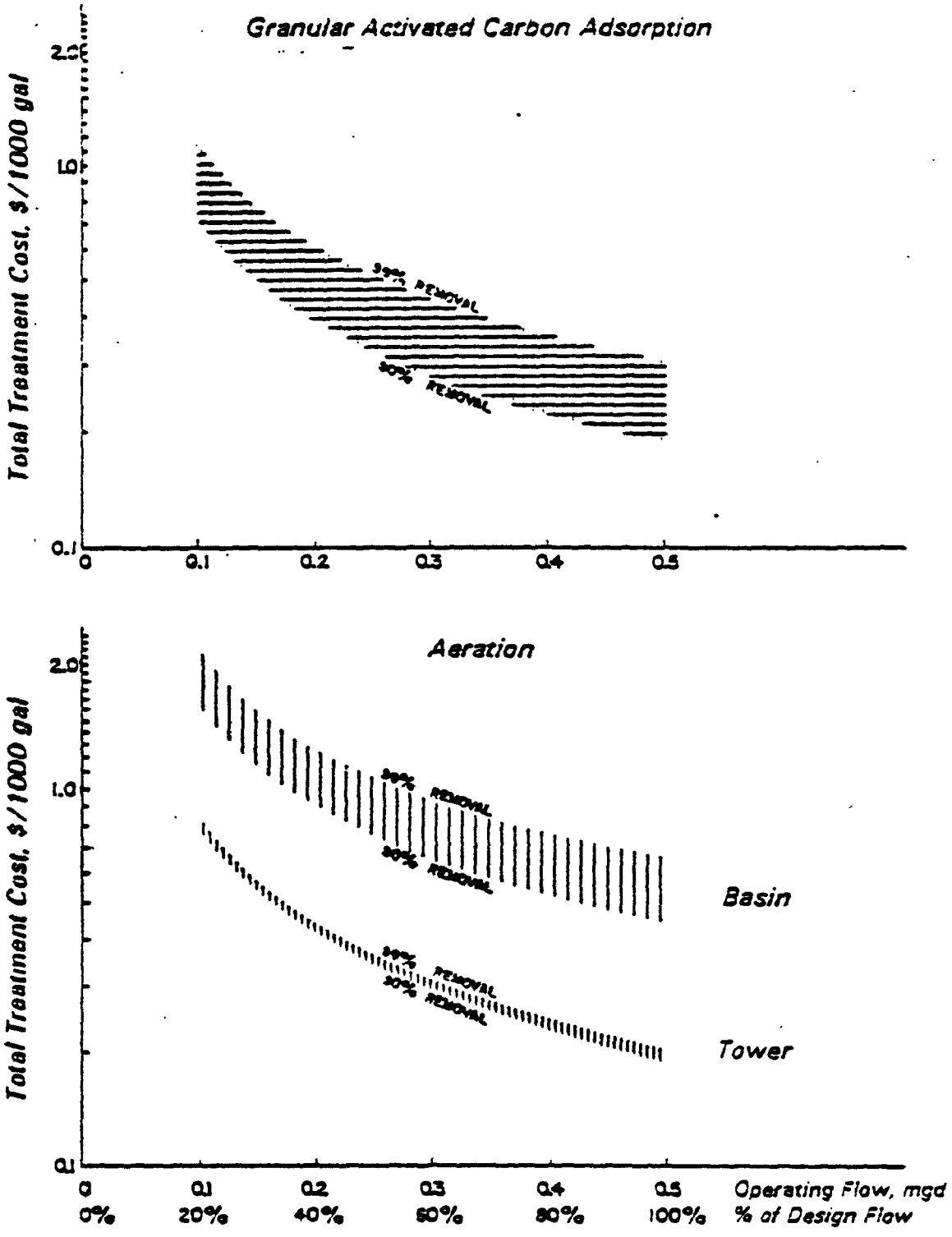

Figure 21. Cost of tetrachloroethylene removal (90–99%) (October 1980 dollars, influent concentration of 1–1000 µg/l, design flow of 0.5 mgd).

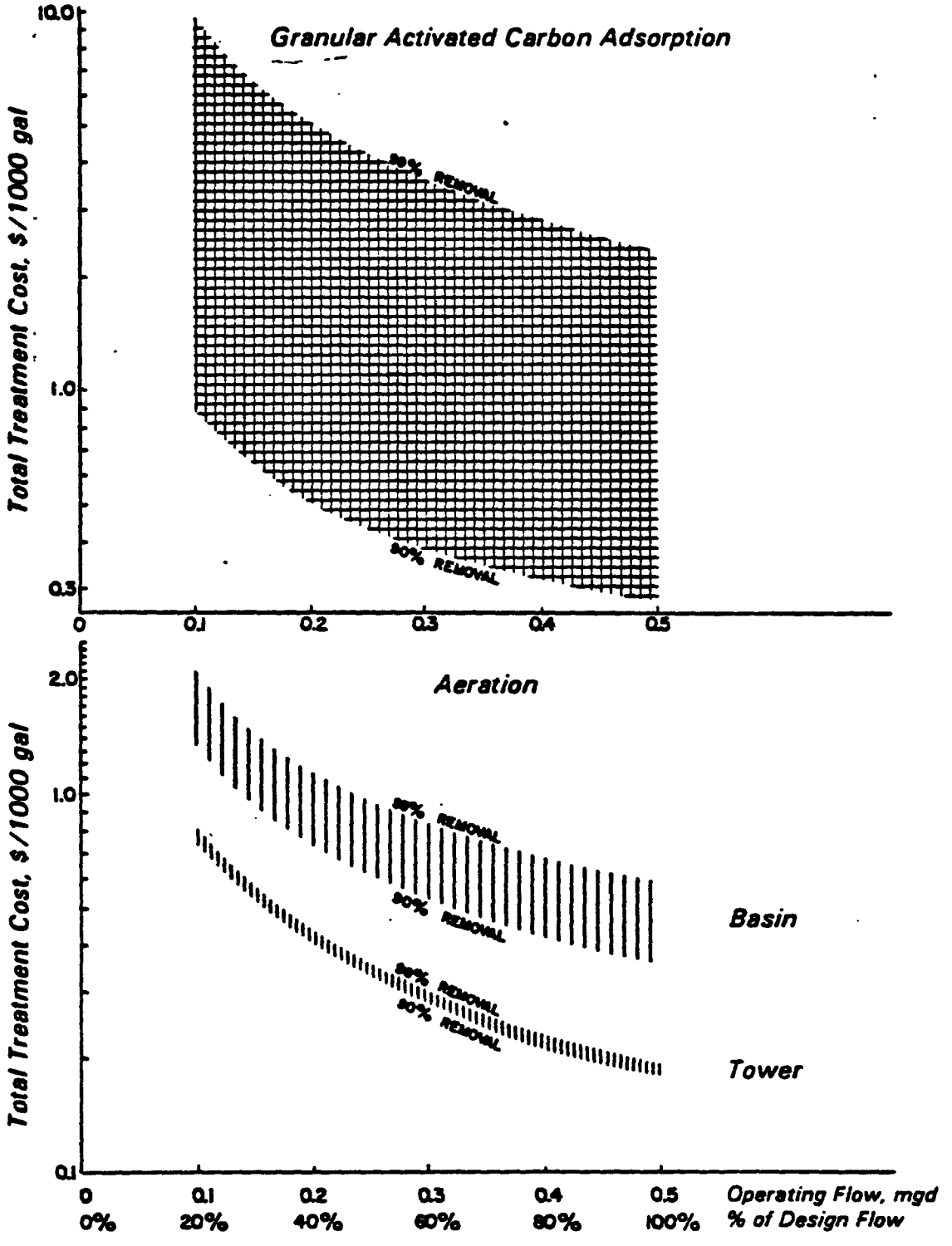

Figure 22. Cost of 1,1,1-trichloroethane removal (90–99%) (October 1980 dollars, influent concentration of 1–1000 µg/l, design flow of 0.5 mgd).

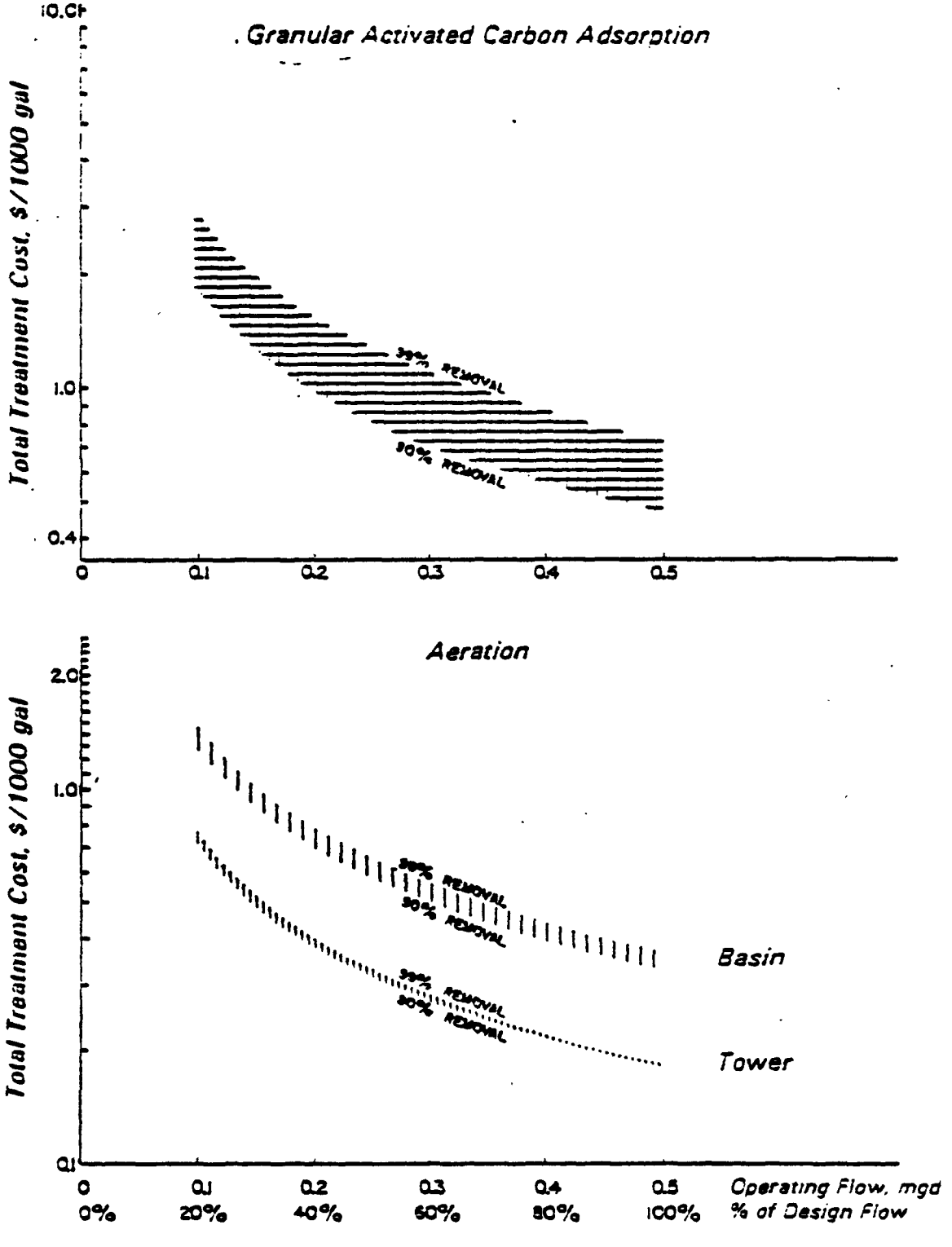

Figure 23. Cost of carbon tetrachloride removal (90-99%) (October 1980 dollars, influent concentration of 1-1000 µg/l, design flow of 0.5 mgd).

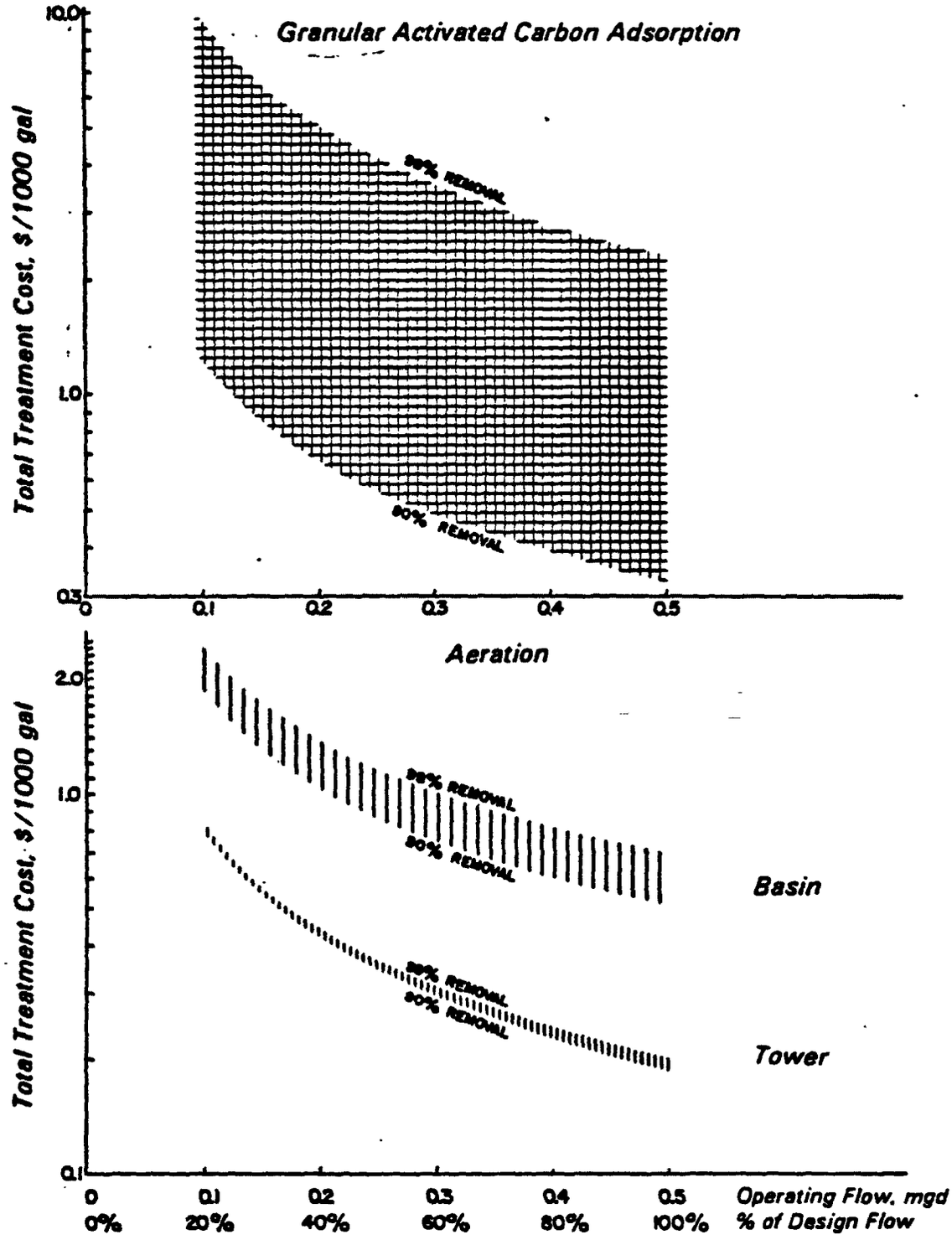

Figure 24. Cost of cis-1,2-dichloroethylene removal (90–99%) (October 1980 dollars, influent concentration of 1–1000 µg/l, design flow of 0.5 mgd).

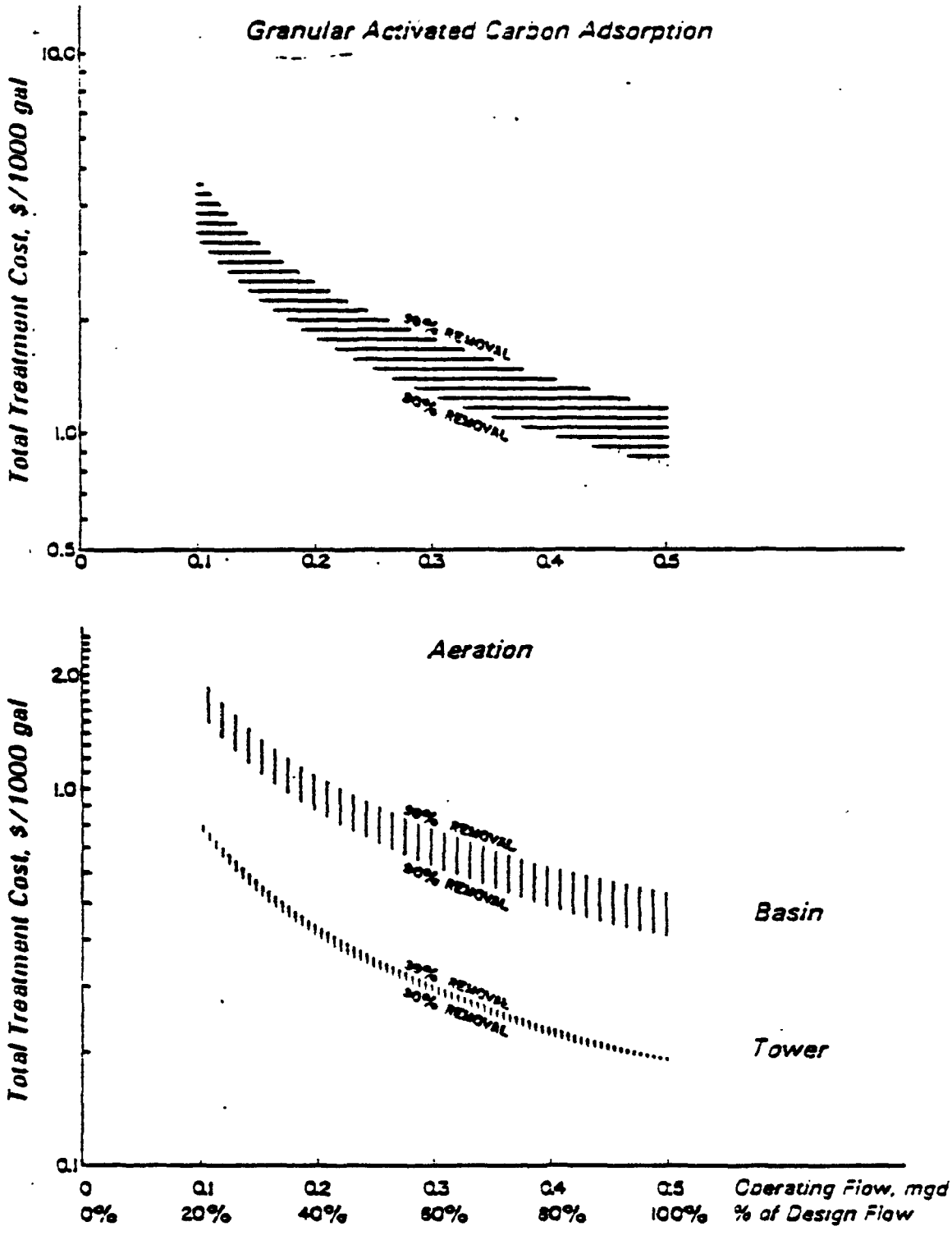

Figure 25. Cost of 1,2-dichloroethane removal (90–99%) (October 1980 dollars, influent concentration of 1–1000 ug/l, design flow of 0.5 mgd).

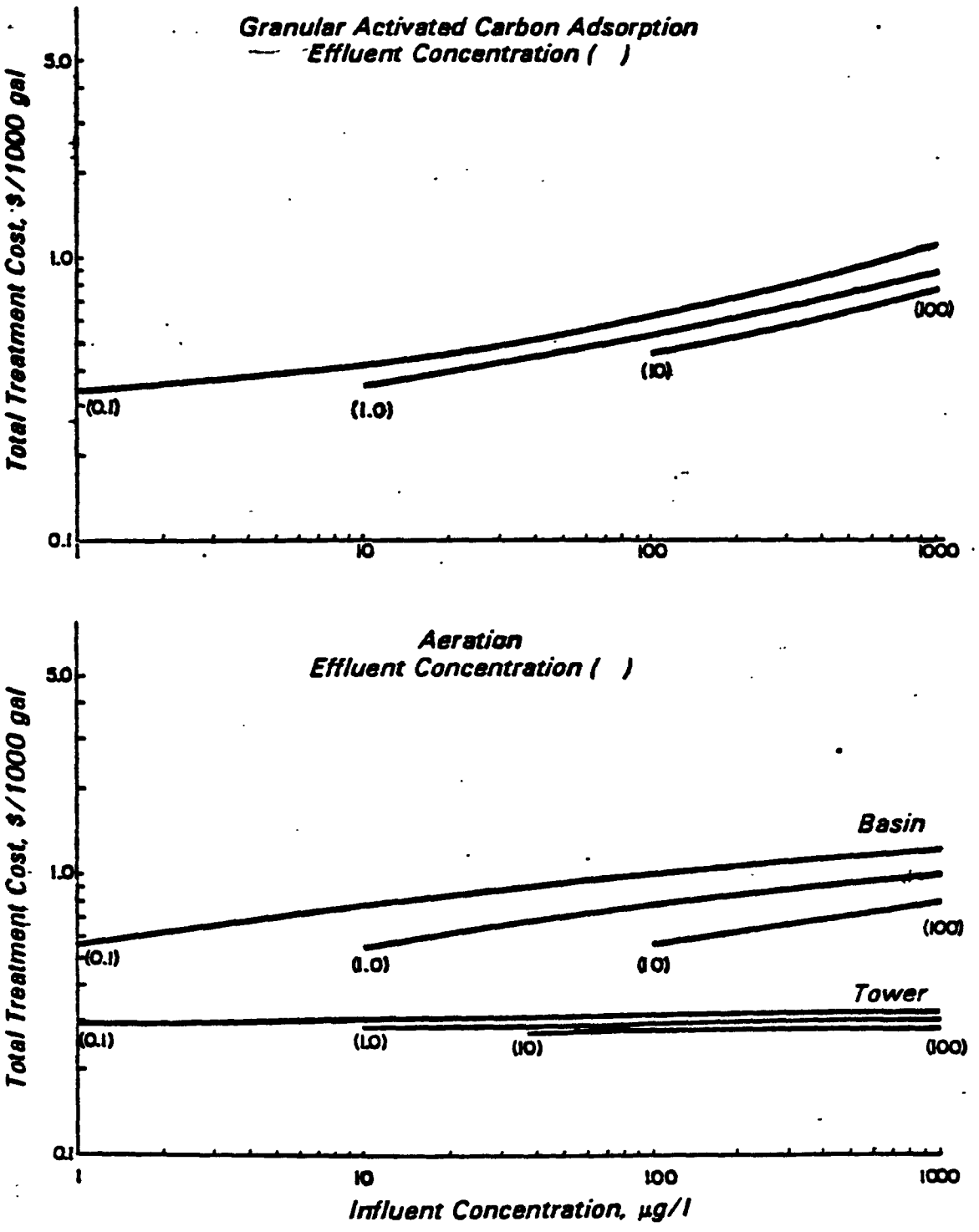

Figure 26. Cost of trichloroethylene removal (October 1980 dollars, effluent concentrations of 0.1–100 µg/l, design flow of 0.5mgd operating at 60% capacity).

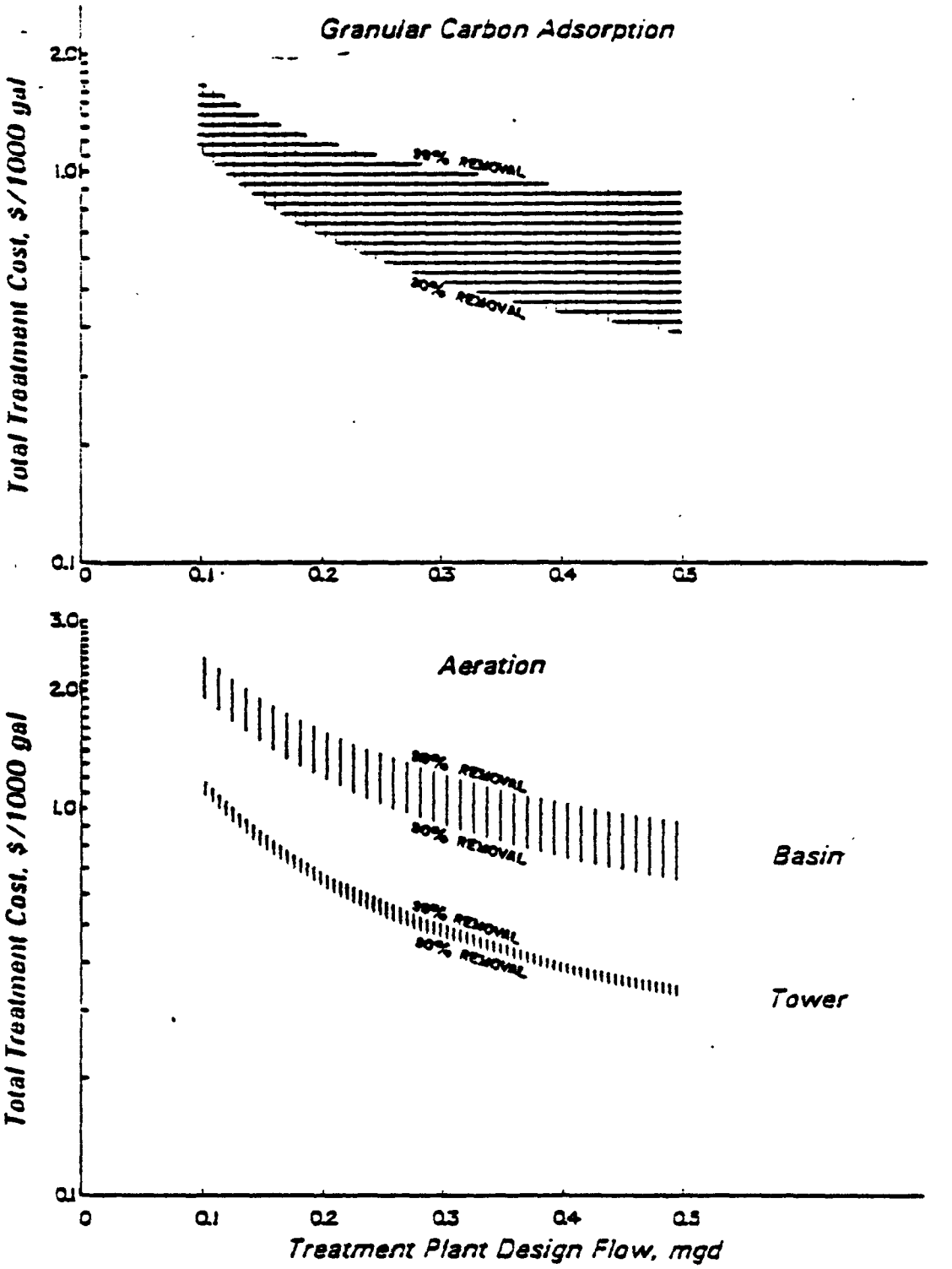

Figure 27. Cost of trichloroethylene removal (90–99%) (October 1980 dollars. Influent concentration of 1–1000 µg/l, operating flow is 50% of design flow).

treatment cost of trichloroethylene removal verus treatment plant size for each treatment type. Operating flow is 50 percent of design flow for this data with an influent concentration of 1 to 1000 ug/L. Similar cost information can be generated for the other contaminants. Note in these estimates that operating a small treatment system at less than design flow has a pronounced effect on unit costs.

As in any economic analysis, the cost data presented here are dependent on the particular design assumptions that were made for the treatment system. For example, the costs associated with both types of aeration are quite sensitive to the removal efficiencies. The cost of treatment therefore, can vary significantly depending of the design parameters selected by the cost analyst and site-specific consideraitons. For this reason, these cost estimates should be viewed as a preliminary attempt to quantify the economics of removing trichloroethylene and related solvents from drinking water.

Conclusion

Trichloroethylene and related solvents occur in both untreated and treated drinking water. In general, groundwaters rather than surface waters are more likely to have significant concentrations of these compounds. Some exceptions might be during periods when a river is frozen over and volatile organics cannot escape into the atmosphere, when upstream "spills" occur, or when products used to treat or transport the water have contaminants (2,3,5, 58 61).

These solvents can be removed by aeration, adsorption on gramular activated carbon or synthetic resins, or combinations of these processes. Aeration, for example, preceeding adsorption seems very encouraging and may be

the combination needed for treating certain problem waters. Preliminary estimates of treatment costs show significant variations between process and contaminants and amplify the need for a thorough organic analysis and site specific performance data. Vinyl chloride was not included in the economics discussion because of the lack of treatment data. Its Henry's Law constant is quite high, 301 ug/L air/ug/L water (16), so vinyl chloride should be easily removed by aeration.* At one location where vinyl chloride intermittently occurred in the drinking water, neither granular activated carbon, nor synthetic resin (XE-340) effectively removed this contaminant (13, 31).

Boiling can be effective for removing these solvents but it requires at least 5-minutes of vigorous boiling in a shallow pan. Table 18 lists the treatment processes and their relative effectiveness for removing or reducing the concentrations of these volatile organics.

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*Vinyl chloride was one of several volatile organics included in a recent study where contaminants were "spiked" in drinking water, then passed through a pilot scale aeration tower. Vinyl chloride was the contaminant most efficiently removed. (DeMarco, J., P. Wood, F. Curtis, and R. Lang, "Aeration of Halogenated Organics". Paper in preparation).

TABLE 18. RELATIVE EFFECTIVENESS OF TREATMENT

	AERATION			ADSORPTION			BOILING
				Granular Activated Carbon		XE-340	
	Predicted by Henry's Law Constant (16)	USEPA-DWRD Experience	Summary of Studies*	Predicted by Isotherm data (30)	Summary of Studies*		
Trichloroethylene	4	2	1	2	1	1	5
Tetrachloroethylene	3	1	2	1	2	2	1
1,1,1-Trichloroethane	6	5	4	6	5	5	4
Carbon Tetrachloride	2	3	-	3	3	6	3
Cis-1,2-Dichloroethylene	5	4	3	5	6	4	2
Vinyl chloride	1	-	-	-	-	-	-
1,2-Dichloroethane	7	6	-	4	4	3	-

*Performance summary averaged from two or more studies
1 = Best performance
6 = Poorest performance

ACKNOWLEDGEMENT

The cooperation and assistance provided by water utility and regulatory personnel in the states of Connecticut, New Hampshire, Rhode Island, New Jersey, and Pennsylvania is greatly appreciated.

Special recognition is expressed to Mr. Charles D. Larson, USEPA, Region I, Boston, MA and Mr. Melvin Haupman, USEPA, Region II, New York, NY for their help in conducting our field studies.

The efforts of Ms Patricia Pierson for typing this manuscript and Dr. James M. Symons, Mr. Alan A. Stevens, Mr. Gordon G. Robeck, Mr. Walter A. Feige, Dr. Robert M. Clark, Mr. James Westrick, and Mr. Thomas Thorton for providing valuable editorial and technical comments are acknowledged.

REFERENCES

1. Federal Register "Control of Organic Chemical Contaminants in Drinking Water", Vol. 43. No. 28, p. 5759 (Feb. 9, 1978).

2. Cairo, P. R., R. G. Lee, B. S. Aptowicz, and W. M. Blankenship. "Is Your Chlorine Safe to Drink?" Jour. American Water Works Association, Vol. 71, No. 8, pp.450-453 (Aug. 1979).

3. Larson, C. D., Love, O. T. and Reynolds, G. B. "Tetrachloroethylene from Lined Asbestos Cement Pipe". Presented at: Corrosion Control in Water Distribution Systems, USEPA Technology Transfer, Cincinnati, OH (May 20-22, 1980).

4. Maddox, F. D., USEPA Region V. Personal Communication, February 14, 1980 as follow-up to article entitled, "Federal Test Link Carcinogenic Chemical to Chlorine", The Cincinnati Enquirer (Dec. 16, 1979).

5. Seeger, D. R., Slocum, C. J., and Stevens, A. A., "GC/MS Analysis of Purgeable Contaminants in Source and Finished Drinking Water". Proceedings, 26th Annual Conference on Mass Spectrometry and Applied Topics, St. Louis, MO (May 28-Jun. 2, 1978).

6. Dunlap, W., "Preliminary Laboratory Study of Transport and Fate of Selected Organics in a Soil Profile". U.S. Environmental Protection Agency, Groundwater Research Center, Ada, OK (1980).

7. Roberts, P. V., Schreiner, J., and Hopkins, G. D., "Field Study of Organic Water Quality Changes During Groundwater Recharge in the Palo Alto Baylands", Presented at the Symposium on Waste Water Reuse for Groundwater Recharge, Pomona, CA (Sep. 7, 1979).

8. Chiou, C. T., Peters, L. J., and Freed, V. H., "A Physical Concept of Soil-Water Equilibria for Nonionic Organic Compounds". Science, Vo. 206, pp 831-832 (Nov. 1979).

9. Symons, J. M., T. A. Bellar, J. K. Carswell, J. DeMarco, K. L. Kropp, G. G. Robeck, D. R. Seeger, C. J. Slocum, B. L. Smith, and A. A. Stevens, "National Organics Reconnaissance Survey for Halogenated Organics in Drinking Water". JAWWA, Vol. 67, No. 11, Part I, 634-647 (Nov. 1975).

10. Jarema, R., "Plainville and Plainfield's Plight with Pollution". Connecticut State Department of Health, Hartford, CT 06115 (Jul. 1977).

11. Johnson, D., H. Kaltenthaler, P. Breault, and M. Keefe, "Chemical Contamination". The Commonwealth of Massachusetts, Special Legislative Commission on Water Supply, 14 Beacon Street, Room 201, Boston, MA 02108 (Sep. 1979).

12. Kim, N. K. and Stone, D. W., "Organic Chemicals in Drinking Water". New York State Department of Health, Albany, NY 12237 (1980).

13. Symons, J. M., J. K. Carswell, J. DeMarco, and O. T. Love, Jr., "Removal of Organic Contaminants from Drinking Water Using Techniques Other Than Granular Activated Carbon Alone — A Progress Report". In: Proceedings, Practical Application of Adsorption Techniques in Drinking Water, EPA/NATO, Challenges of Modern Society, Reston, VA (1979) (In Press).

14. Crane, A. M. and Freeman, A. F., "Water Softening and Conditioning Equipment: A Potential Source of Water Contamination". EPA-600/3-77-107, ORD, Environmental Research Laboratory, Gulf Breeze, FL (Mar. 1977).

15. Dilling, W. L., "Interphase Transfer Processes. II. Evaporation Rates of Chloro Methanes, Ethanes, Ethylenes, Propanes, and Propylenes from Dilute Aqueous Solutions. Comparisons with Theoretical Predictions". Environmental Science and Technology, Vol. 11, No. 4, pp. 405-405 (Apr. 1977).

16. U. S. Environmental Protection Agency., "Innovative and Alternative Technology Assessment Manual (Draft)". EPA-430/9-78-009, Office of Research and Development, MERL, Cincinnati, OH (1978).

17. Warner, P. H., Cohen, J. M., and Ireland, J. C. "Determination of Henry's Law Constants of Selected Priority Pollutants" USEPA Office of Research and Development, MERL, Cincinnati, OH (Apr. 1980).

18. Zoeteman, B. C. J., "Threshold Odour Concentrations in Water of Chemical Substances". R.I.D.-Medeleling 74-3, National Institute Water, Leidschendam, The Netherlands (1974).

19. Stahl, W. H., "Compilation of Odor and Taste Threshold Values Data". American Society for Testing Materials Data Series DS48 (05-048000-36) ASTM, 1916 Race Street, Philadelphia, PA 19103 (May 1973).

20. The Merck Index. Merck & Co., Inc., Rahway, NJ (9th Edition, 1976).

21. NIOSH Registry of Toxic Effects of Chemical Substances Vol. II, U. S. Department of Health Education and Welfare, Public Health Service, CDC, National Institute of Occupational Safety and Health, Cincinnati, OH 45226 (Sep. 1977).

22. "Preliminary Study of Selected Potential Environmental Contaminants — Optical Brighteners, Methyl chloroform, Trichloroethylene, Tetrachloroethylene, Ion Exchange Resins". EPA 560/2-75-002 (PB 243-910) Office of Toxic Substances, Washington, D. C. 20460 (Jul. 1975).

23. Kirk-Othmer Encyclopedia of Chemical Technology, Volume 5, John Wiley & Sons, New York (3rd Edition, p 671, 1979).

24. DeMarco, J., N. V. Brodtmann, Jr., H. Russell, and G. Wood, "A Comparative Study of Granular Activated Carbon in Plant Scale Operations". Presented at 98th Annual AWWA National Conference, Atlantic City, NJ (1978). (unpublished).

25. Nebolsine Kohlman Ruggiero Engineers, P.C., "Technical Memorandum Well Water Study Testing for the Removal of Organic Contaminants" Office of the Mayor, City of Glen Cove, NY (Apr. 1973).

26. Nebolsine Kohlman Ruggiero Engineers, P.C., "Removal of Organic Contaminants from Drinking Water Supply at Glen Cove, NY." Interim Report on USEPA Agreement No. CR806355-01, Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (Jul. 1980).

27. Joyce, M., "Smyrna, Delaware Solves a Water Problem". Journal of Environmental Health, Vol. 42, No. 2. pp. 72-74 (Sep./Oct. 1979). See also - Joyce, M., "Smyrna, Delaware Solves a Water Problem". Water and Sewage Works (Mar. 1980).

28. Argo, D. G., "Control of Organic Chemical Contaminants in Drinking Water". Proceedings: Control of Organic Chemical Contaminants in Drinking Water, Public Technology, Inc./U. S. Environmental Protection Agency Seminar (1978). (In Press)

29. McCarty, P. L., K. H. Sutherland, J. Graydon, and M. Reinhard, "Volatile Organic Contaminants Removal by Air Stripping". Proceedings: AWWA Seminar. "Controlling Organics in Drinking Water", 99th Annual National AWWA Conference, San Francisco, CA (Jun. 1979).

30. Dobbs, R. A. and Cohen, J. M. "Carbon Adsorption Isotherms for Toxic Organics". EPA 600/880-023 Office of Research and Development, MERL, Wastewater Treatment Division, Cincinnati, Ohio 45268 (Apr. 1980).

31. Singley, J. E., Beaudet, B. A., and Ervin, A. L. "Use of Powdered Activated Carbon for Removal of Specific Organic Compounds" Proceedings, AWWA Seminar, "Controlling Organics in Drinking Water", 99th Annual National AWWA Conference, San Francisco, CA (Jun. 1979).

32. Neely, J. W. and Isacoff, E. G., "Regenerability of Ambersorb XE-340", Presented at New Jersey AWWA Section Meeting, Atlantic City, NJ (Sep. 19, 1979).

33. Love, O. T. Jr., "Boiling to Remove Trichloroethylene". U.S. Enivornmental Protection Agency. Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (Nov. 27, 1979). (Mimeo)

34. Lataille, M., "The Effect of Boiling on Water Contaminated with Chlorinated Solvents". U. S. Environmental Protection Agency, Region I. Lexington, MA (Dec. 4, 1979). (Mimeo)

35. Wood, P. R. and DeMarco, J., "Effectiveness of Various Adsorbents in Removing Organic Compounds from Water" - Part I - removing Purgeable Halogenated Organics". Presented at "Activated Carbon Adsorption of Organics from the Aqueous Phase" - 176th ACS Meeting, Miami Beach, FL (Sep. 10-15, 1978).

36. Glaze, W. H., G. R. Peyton, F. Y. Huang, J. L. Burleson, and P. C. Jones, "Oxidation of Water Supply Refractory Species by Ozone with Ultraviolet Radiation". Final Report, EPA R-804640, Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (1980). (Draft under review for publication).

37. Azeotropic Data-II. No. 35, Advances in Chemistry Series, (R. F. Gould, editor), American Chemical Society, Washington, D. C. (1962).

38. Fleisher, M. B. and MacKay, S. L., "Assessment of the Impact of Organic Solvent Cesspool Cleaners and Drain Openers on Nassau County Drinking Water Supplies". Nassau County Department of Health, 240 Old Country Road, Mineola, NY (Dec. 1977).

39. Byer, E. G., USEPA Region III, Water Supply Branch, Private Communication, (Nov. 8, 1979).

40. Stevens, A. A., D. R. Seeger, J. DeMarco, and L. Moore. "Removal of Higher Molecular Weight Organic Compounds by the Granular Activated Carbon Adsorption Unit Process". Proceedings, Practical Applications of Adsorption Techniques in Drinking Water, EPA/NATO, Challenges of Modern Society, Reston, VA (1979). (In Press)

41. Kelleher, D. L., Stover, E. L., and Sullivan, M. "Investivation of Volatile Organics Removal". Presented At New England Water Works Association Meeting, Randolph, MA (Jan. 17, 1980).

42. Ervin, A. L., and Singley, J. E., "Alternative Powdered Activated Carbon Study", Report prepared for the City of North Miami Beach, Florida, Project No. 79-206-003 by Environmental Science and Engineering, Inc., Gainsville, FL (Sep. 1979).

43. Isacoff, E. G. and Bittner, J. A., "Resin Adsorbent Takes on Chloroorganics from Well Water", Water and Sewage Works, pp. 41-42 (Aug. 1979).

44. Combs, W. S. "Removal of Chlorinated Solvents from Water by Boiling", State of Rhode Island and Providence Plantations, Department of Health, Cannon Building, Providence, RI (Feb. 5, 1980). (Mimeo)

45. Keller, P. A. "Threshold Odor Concentration for Carbon Tetrachloride in Drinking Water". U.S. Environmental Protection Agency, Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (1977). (unpublished)

46. Federal Register, "Certain Fluorocarbons (CHLOROFLUOROCARBONS) in Food, Food Additive, Drug, Animal Food, Animal Drug, Cosmetic, and Medical Device Products as Propellants in Self-Pressurized Containers", Vol. 43, No. 53, pp. 11301 (Mar. 17, 1978).

47. Lykins, B. W., "Summary of Short-Term Experimental Modes of Operation — Evansville, Indiana". (Draft) Interim Report, EPA Grant No. R804902, Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (May 1979). (Unpublished)

48. Evansville Courier, "High Carbon Tet Found in Water Used April 19", Evansville, Indiana, (May 18, 1978).

49. Lykins, B. W. and DeMarco, J. "An Overview of the Use of Powdered Activated Carbon for Removal of Trace Organics in Drinking Water" U. S. Environmental Protection Agency, Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (1980). (Draft)

50. Weber, W. W., "Effectiveness of Activated Carbon for Removal of Toxic and/or Carcinogenic Compounds from Drinking Water". Final Report EPA R8044367-30-01, Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (Mar. 1980).

51. Symons, J. M., "Interim Treatment Guide for Controlling Organic Contaminants in Drinking Water Using Granular Activated Carbon". U.S. Environmental Protection Agency, Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH. (Jan. 1978).

52. Rosenzweig, M. D., "Vinyl Chloride Process Has Wide Range of By-Products", Chemical Engineering, pp. 105-107 (Oct. 18, 1971).

53. DeMarco J. and Brodtmann, N. V. "Prediction of Full Scale Plant Performance from Pilot Columns". Proceedings, Practical Application of Adsorption Techniques in Drinking Water, EPA/NATO, Challenges of Modern Society, Reston, VA (1979). (In Press)

54. Kittsley, S. L., Physical Chemistry. Barnes and Noble, Inc., New York, pp. 36-38 (2nd ed., 1967).

55. DCI Solvent Data Sheet. DCI Corporation, 5752 W. 79th Street, Indianapolis, IN 46278.

56. Singley, J. E., A. L. Ervin, M. A. Mangone, J. M. Allen, and H. H. Land, Trace Organics Removal by Air Stripping, prepared for: American Water Works Association Research Foundation, Denver, CO (May 1980).

57. Symons, J. M., A. A. Stevens, O. T. Love, Jr., and J. DeMarco, "Treatment Techniques for Controlling Trihalomethanes in Drinking Water". U. S. Environmental Protection Agency, Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (In Press).

58. Ohio River Valley Water Sanitation Commission, "Water Treatment Process Modifications for Trihalomethane Control and Organic Substances in the Ohio River". Final Report EPA-600/2-80-028. Office of Research and Development, MERL, Drinking Water Research Division, Cincinnati, OH (Mar. 1980).

59. Merrick, E. T., H. Ketcham, L. J. Murphy, Jr., and K. Slike, "EPA Chemical Activities Status Report", First Edition, EPA 560/13-79-003, Toxic Integration Information Series, USEPA Washington, D. C. (Apr. 1979).

60. Vinyl Chloride Ambient Water Quality Criteria. EPA 440/5-80-078. Criteria and Standards Division, Office of Water Planning and Standards, U. S. EPA Washingto, D. C. (1980).

61. Dressman, R. C. and McFarren, E. F., "Determination of Vinyl Chloride Migration from Polyvinyl Chloride Pipe into Water Using Improved Gas Chromatographic Methodology" JAWWA, Vol. 70, No. 1, pg. 29 (Jan. 1978).