5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

Tetrachloroethylene is a volatile organic compound that is widely distributed in the environment. It is released to the environment via industrial emissions, and it is released from building and consumer products. Releases are primarily to the atmosphere, but the compound is also released to surface water and land in sewage sludges and in other liquid and solid waste, where its high vapor pressure and Henry's law constant usually result in its rapid volatilization to the atmosphere. Tetrachloroethylene has relatively low solubility in water and has medium-to-high mobility in soil, thus its residence time in surface environments is not expected to be more than a few days. However, it persists in the atmosphere for several months and may also persist in groundwater for several months or more. Because of its pervasiveness and ability to persist under certain conditions, the potential for human exposure may be substantial. It should be noted that the amount of tetrachloroethylene measured by chemical analysis is not necessarily the amount that is bioavailable.

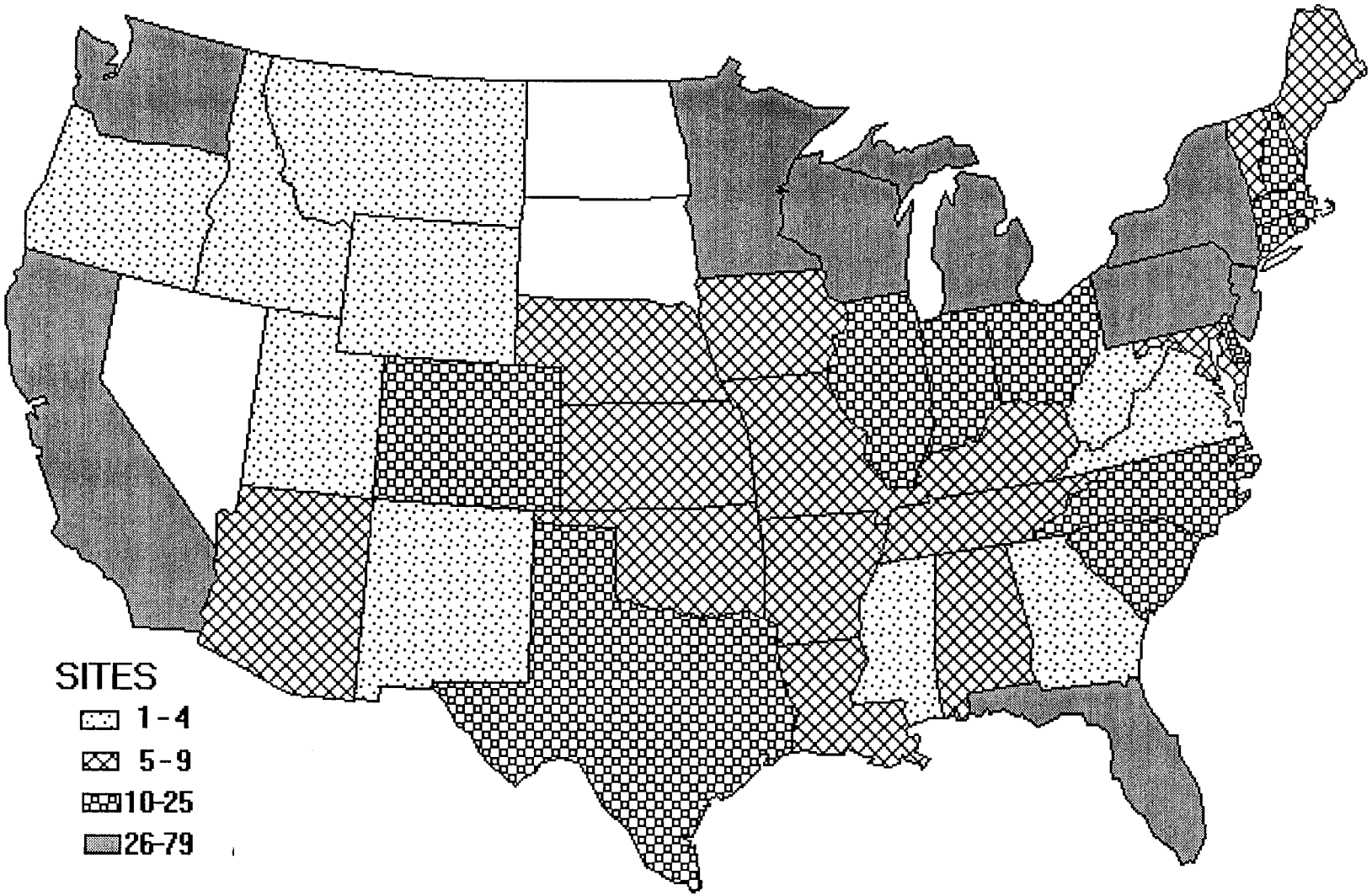
Tetrachloroethylene has been found in at least 771 of the 1,430 current or former EPA National Priorities List (NPL) hazardous waste sites (HazDat 1996). However, the number of sites evaluated for tetrachloroethylene is not known. The frequency of these sites can be seen in Figure 5-l. Of these sites, 767 are located in the United States and 4 are located in the Commonwealth of Puerto Rico (not shown).

5.2 RELEASES TO THE ENVIRONMENT

5.2.1 Air

According to the Toxics Release Inventory (TRI), an annual compilation of information bn the release of toxic chemicals by manufacturing and processing facilities, an estimated total of at least 11.2 million pounds of tetrachloroethylene was released to the air in the United States in 1993 (TRI93 1995). This accounts for about 99% of all tetrachloroethylene released to the environment and is a reduction from a level of 32.2 million pounds which was reported in 1988 (TRI88 1990). The number

FIGURE 5-1 FREQUENCY OF NPL SITES WITH TETRACHLOROETHYLENE CONTAMINATION*



*Derived from HAZDAT 1996

of reporting facilities in each state and the ranges within which individual facilities reported their releases are shown in Table 5-1. The TRI data listed in Table 5-l should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list.

It has been estimated that 80-90% of the tetrachloroethylene used annually in the United States is released to the environment, particularly to the atmosphere (EPA 1982a; Singh et al. 1979). Most releases of tetrachloroethylene during its use are directly to the atmosphere (EPA 1987b). A major portion of the atmospheric releases are attributed to evaporative losses in the dry cleaning industry (EPA 1982a). Other atmospheric emissions occur from metal degreasing uses, production of fluorocarbons and other chemicals, textile industry uses, and miscellaneous solvent-associated applications (EPA 1982a; Weant and McCormick 1984).

Environmental releases of tetrachloroethylene also occur at sites of its manufacture and at sites of production of other chlorohydrocarbons (such as ethylene dichloride and methylene chloride) in which tetrachloroethylene is formed as a by-product (Weant and McCormick 1984). Tetrachloroethylene emissions to the atmosphere may occur at sites used in disposing the chemical (EPA 1985d), including incineration facilities for municipal and hazardous waste (Oppelt 1987). Tetrachloroethylene can also be released to the atmosphere from the ocean where it is produced by some macroalgae (Abrahamsson et al. 1995).

5.2.2 Water

According to TRI, an estimated total of at least 23,000 pounds of tetrachloroethylene was released to water from manufacturing and processing facilities in the United States in 1988 (TRI88 1990). The level reported in 1993 was 10,152 pounds, about 0.09% of the total release to the environment (TRI93 1995). The number of reporting facilities in each state and the ranges within which individual facilities reported their releases are shown in Table 5-l. The TRI data listed in Table 5-l should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list.

A variety of industries that use tetrachloroethylene (such as metal degreasing and dry cleaning) generate aqueous wastes containing the compound which end up at waste treatment facilities (Weant and McCormick 1984). Aeration processes at waste treatment facilities strip much of the

Table 5-1. Releases to the Environment from Facilities That Manufacture or Process Tetrachloroethylene

State[b]	Number of facilities	Range of reported amounts released in pounds per year[a]						
		Air	Water	Land	Underground injection	Total environment[c]	POTW transfer	Off-site waste transfer
AL	5	1-24500	0	0-1	0	2-24500	0-20412	0-84
AR	4	5-110259	0	0	0	5-110259	0	0-8621
AZ	2	5850-18900	0	0	0	5850-18900	0-5	250-5600
CA	63	0-396721	0-5	0-10	0	0-396721	0-250	0-164700
CO	2	6000-14500	0	0	0	6000-14500	0	1600-4000
CT	16	1200-149000	0-200	0	0	1221-149000	0-5	0-125348
FL	11	59-67050	0	0	0	59-67050	0-1	0-19600
GA	12	0-122200	0	0	0	0-122200	0-250	0-27800
IA	7	0-266000	0-540	0	0	0-266540	0	0-73901
IL	35	0-97041	0-1	0	0	0-97041	0-5	0-117146
IN	26	3-179077	0-23	0	0	3-179077	0	0-84223
KS	8	1-632630	0-5	0	0-15041	1-632635	0-250	0-76260
KY	10	18-142550	0-22	0	0	18-142550	0-750	0-123331
LA	16	0-621100	0-5048	0-5	0	0-622200	0-5	0-1566936
MA	7	4-71800	0	0	0	4-71800	0	4-66171
MD	2	15400-85268	0	0	0	15400-85268	0	1400-4331
ME	1	1527	0	0	0	1527	0	0
MI	10	385-33811	0-2	0	0	385-33813	0-750	0-47005
MN	11	996-132646	0	0	0	996-132646	0-5	0-15550
MO	12	321-17296	0	0	0	321-17296	0-37	0-22935
MS	5	2-10250	0-1	0	0	2-10250	0-5	0-95000
MT	2	1800-3105	0	0	0	1800-3105	0	0
NC	20	0-154224	0	0-2916	0	0-154224	0-28602	0-32700
NE	4	4-158300	0	0	0	4-158300	0	0-8740
NH	4	7300-21500	0	0	0	7300-21500	0-5	1080-12100
NJ	6	0-46799	0	0	0	0-46799	0-5	0-37211
NY	20	0-86000	0-540	0	0	0-86000	0-230	0-1140610
OH	48	155-228891	0-250	0	0	155-228892	0-250	0-123400

Table 5-1. Releases to the Environment from Facilities That Manufacture or Process Tetrachloroethylene

State[b]	Number of facilities	Range of reported amounts released in pounds per year[a]						
		Air	Water	Land	Underground injection	Total environment[c]	POTW transfer	Off-site waste transfer
OK	8	3500-95700	0	0	0	3500-95700	0-5	0-25549
OR	1	23264	0	0	0	23264	0	27005
PA	18	0-52600	0-5	0	0	0-52600	0	0-52758
PR	2	33-500	0	0	0	33-500	0	0
SC	12	16-69666	0-520	0	0	16-69666	0-5	0-193136
TN	8	10-98900	0	0	0	10-98900	0-432	0-5001
TX	25	0-70520	0-1500	0-750	0	0-70520	0	0-1069519
UT	3	250-10600	0	0	0	250-10600	0	250-8160
VA	7	28-23017	0	0	0	28-23017	0-5	0-85000
VT	1	1605	0	0	0	1605	0	55800
WA	1	28564	0	0	0	28564	0	25188
WI	12	5-46755	0	0-3620	0	5-46755	0-10	0-324080
WY	1	0	0	0	0	0	0	34

Source: TRI93 1995

[a] Data in TRI are maximum amounts released by each facility.
[b] Post office state abbreviations used
[c] The sum of all releases of the chemical to air, land, water, and underground injection wells by a given facility

POTW = publicly owned treatment works

tetrachloroethylene from the water and release it into the atmosphere as a result of the high volatility of this chemical (Lurker et al. 1982).

Dumping of industrial waste products into the St. Clair River/Lake St. Clair/Detroit River system in Canada and Michigan resulted in tetrachloroethylene concentrations up to 473 ng/L (0.473 ppb) in surface water samples from Lake St. Clair (Kaiser and Comba 1986). Disposal of secondary sewage effluent by rapid infiltration into the subsurface resulted in contamination of groundwater in Massachusetts with several volatile organic compounds including tetrachloroethylene, which reached levels as high as 980 ppb (Barber et al. 1988). Tetrachloroethylene in untreated well water located near a dry cleaning plant in Japan reached levels of 27,000 μg/L (27,000 ppb) (Kido et al. 1989). Tetrachloroethylene may also be emitted to groundwater from landfill leaching (Dewalle and Chian 1981; Kosson et al. 1985; Reinhard et al. 1984; Sabel and Clark 1984; Schultz and Kjeldsen 1986) as well as from pits and lagoons used for storage, treatment, and disposal of liquid wastes (Barbash and Roberts 1986).

5.2.3 Soil

According to TRI, an estimated total of at least 106,000 pounds of tetrachloroethylene was released to land from manufacturing and processing facilities in the United States in 1988 (TRI88 1990) prior to the federal ban on land disposal of tetrachloroethylene (see Section 4.4). The amount released in 1993 was at least 8,027 pounds, about 0.07% of the total released to the environment (TRI93 1995). The number of reporting facilities in each state and the ranges within which individual facilities reported their releases are shown in Table 5-l. The TRI data listed in Table 5-l should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list.

Many of the processes in which tetrachloroethylene is used as a solvent involve recycling the compound by various methods (EPA 1991a). These recycling methods produce tetrachloroethylene-containing sludges and dirty filters that have been landfilled in the past. Contamination of soil can occur through leaching of tetrachloroethylene from these disposal sites (Kosson et al. 1985; Schultz and Kjeldsen 1986). Leaking of tetrachloroethylene from underground storage tanks can also result in the contamination of soil.

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5.3 ENVIRONMENTAL FATE

5.3.1 Transport and Partitioning

The predicted degradation half-life of tetrachloroethylene in the atmosphere indicates that long-range global transport is likely (Class and Ballschmiter 1986). Indeed, monitoring data have demonstrated that tetrachloroethylene is present in the atmosphere worldwide and at locations far removed from anthropogenic emission sources (see Section 5.4.1).

Tetrachloroethylene has been detected in a number of rainwater samples collected in the United States and elsewhere (see Section 5.4.2). However, the relatively low water solubility of tetrachloroethylene suggests that wet deposition as a result of scavenging by rainwater occurs very slowly compared to other volatile chlorinated hydrocarbons. For example, concentrations of the more water soluble l,l,l-trichloroethane fell to below detection limits during a 12-hour rain event, while concentrations of tetrachloroethylene fell only slightly during the same time period (Jung et al. 1992). Dry deposition does not appear to be a significant removal process (Cupitt 1987), although substantial evaporation from dry surfaces can be predicted from the high vapor pressure.

Laboratory studies have demonstrated that tetrachloroethylene volatilizes rapidly from water (Chodola et al. 1989; Dilling 1977; Dilling et al. 1975; Okouchi 1986; Roberts and Dandliker 1983; Zytner et al. 1989b). One study found that only 2.7% of the initial mass of tetrachloroethylene remained in stagnant water with a surface-to-volume ratio of 81 m^2/m^3 after 4.5 hours (Zytner et al. 1989b). Dilling et al. (1975) reported the experimental half-life with respect to volatilization of 1 mg/L tetrachloroethylene from water to be an average of 26 minutes at approximately 2°C in an open container. This behavior is consistent with its high Henry's law constant and first-order kinetics. Other factors which influence volatilization rates are ambient temperature, water movement and depth, associated air movement, and surface-to-volume ratio. In laboratory models using beakers of stagnant water, the rate of tetrachloroethylene volatilization was found to increase with increasing surface-to-volume ratio (Chodola et al. 1989; Zytner et al. 1989b). Data from these models also demonstrated that volatilization from water was independent of concentration.

The volatilization half-life of tetrachloroethylene from a rapidly moving, shallow river (1 meter deep, flowing 1 meter/second with a wind velocity of 3 meters/second) has been estimated to be 4.2 hours

(Thomas 1982). Measured volatilization half-lives in a mesocosm, which simulated the Narragansett Bay in Rhode Island during winter, spring, and summer, ranged from 12 days in winter conditions to 25 days in spring conditions (Wakeham et al. 1983). Measurements of tetrachloroethylene levels in Lake Zurich, Switzerland, indicated that volatilization is the dominant removal process in surface waters (Schwarzenbach et al. 1979).

Laboratory studies modeling soil systems have demonstrated that volatilization rates for tetrachloroethylene from soil are much less than those from water (Park et al. 1988; Zytner et al. 1989b). Volatilization rates from soil, like water, appear to be related to surface-to-volume ratio (Zytner et al. 1989b). However, the authors of these studies also found a direct relationship between the concentration of the chemical in soil and rate of volatilization, which contrasts with results seen in water, probably because concentration gradients are a more significant factor in soils than in uniformly mixed water (Zytner et al. 1989b). Soil type also influenced the volatilization rate in this study, with the rate in a high organic carbon top soil greatly reduced compared to that of a low organic carbon, sandy loam. Contrasting results were seen in another study, which found that soil type had no effect on rate of volatilization (Park et al. 1988). However, this may simply be a reflection of the fact that the differences between soils used in this study, particularly organic carbon content, were not very great. Park et al. (1988) found that 20% of the applied tetrachloroethylene was volatilized 168 hours after treatment. In general, it can be said that losses of tetrachloroethylene from soil resulting from volatilization seem to be between l0- and l00-fold slower than from water, depending on soil type which directly affects the amount of sorption (Park et al. 1988; Zytner et al. 1989b).

Sorption of organic compounds to soil has been found to be most reliably predicted when related to the organic carbon content of the soil (Kenaga 1980; Urano and Murata 1985; Zytner et al. 1989a). Experimentally measured soil sorption coefficients based on organic carbon content (K_{OC}) for tetrachloroethylene range from 177 to 534 (Seip et al. 1986; Zytner et al. 1989a). These values are indicative of medium-to-high mobility in soil (Kenaga 1980; Swann et al. 1983). Others have also shown that tetrachloroethylene is highly mobile in sandy soil (Wilson et al. 1981). Another study comparing predicted and observed sorption on clay and organic soils suggested that sorption/desorption to inorganic mineral surfaces may also play a role, and the reactions generally follow reversible pseudo first-order kinetics (Doust and Huang 1992). The movement of tetrachloroethylene in soil has been confirmed by band-infiltration systems in the Netherlands, where tetrachloroethylene has been reported to leach rapidly into groundwater (Piet et al. 1981).

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Several models for describing the transport of volatile chlorinated hydrocarbons in soils have been developed, often by fitting one or more parameters to experimental data. One model which determined all parameters *a priori* and included transfer between solid, liquid, and gas phases found that the Henry's law constant was the primary determinant of transport behavior in a wet, nonsorbing aggregated medium, suggesting that volatilization and movement in the gas phase accounts for a large portion of tetrachloroethylene movement in soils (Gimmi et al. 1993).

A considerable number of monitoring studies have detected tetrachloroethylene in groundwater (see Section 5.4.2), which is further evidence of its mobility in soil. Tetrachloroethylene was observed to leach rapidly into groundwater near sewage treatment plants in Switzerland (Schwarzenbach et al. 1983). No evidence of biological transformation of tetrachloroethylene in groundwater was found in this study. Accurate prediction of tetrachloroethylene transport in groundwater is complicated by the sorption effect of organic and inorganic solids (Doust and Huang 1992). Analysis of groundwater in Massachusetts contaminated with tetrachloroethylene indicated that movement of the chemical was not retarded by sorption to sediment (Barber et al. 1988), although this phenomenon may be site specific. Contrasting data from an experiment in a sand aquifer indicated that the movement of tetrachloroethylene through the aquifer was significantly retarded and the retardation was attributed to sorption (Roberts et al. 1986).

Experimentally measured bioconcentration factors (BCFs), which provide an indication of the tendency of a chemical to partition to the fatty tissue of organisms, have been found to range between 10 and 100 for tetrachloroethylene in fish (Kawasaki 1980; Kenaga 1980; Neely et al. 1974; Veith et al. 1980). Barrows et al. (1980) estimated a value of 49 for bluegill sunfish. Somewhat lower BCFs were determined by Saisho et al. (1994) for blue mussel (25.7) and killifish (13.4). These numbers are suggestive of a low tendency to bioconcentrate.

Monitoring data on tetrachloroethylene concentrations in seawater and associated aquatic organisms are in agreement with the experimental BCF data. Concentrations of tetrachloroethylene (dry weight basis) detected in fish (eel, cod, coalfish, dogfish) from the relatively unpolluted Irish Sea ranged from below detection limits to 43 ppb (Dickson and Riley 1976). Levels of 1-41 ppb (wet weight) in liver tissue, and up to 11 ppb (wet weight) in other tissue, were found in various species of fish collected off the coast of Great Britain near several organochlorine plants (Pearson and McConnell 1975).

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Clams and oysters from Lake Pontchartrain near New Orleans had tetrachloroethylene levels averaging up to 10 ppb (wet weight) (Ferrario et al. 1985).

To assess bioaccumulation in the environment, the level of tetrachloroethylene in the tissues of a wide range of organisms was determined (Pearson and McConnell 1975). Species were chosen to represent several trophic levels in the marine environment. The maximum overall increase in concentration between sea water and the tissues of animals at the top of food chains, such as fish liver, sea bird eggs, and sea seal blubber, was less than loo-fold for tetrachloroethylene. Biomagnification in the aquatic food chain does not appear to be important (Pearson and McConnell 1975). Bioaccumulation in plants may be indicated by the presence of tetrachloroethylene in fruits and vegetables (see Section 5.4.4), but care must be used in interpreting these studies because it is often unclear whether accumulation took place during growth or at some point after harvesting.

5.3.2 Transformation and Degradation

5.3.2.1 Air

The dominant transformation process for tetrachloroethylene in the atmosphere is a reaction with photochemically produced hydroxyl radicals (Singh et al. 1982). Using the recommended rate constant for this reaction ($1.67x10^{-13}$ cm^3/molecule-second) and a typical atmospheric hydroxyl (OH) radical concentration of $5x10^5$ molecules/cm^3 (Atkinson 1985), the half-life is calculated at about 96 days. Class and Ballschmiter (1986) state this half-life as about 70 days. An atmospheric lifetime of 119-251 days was calculated by Cupitt (1987), assuming removal by reaction with hydroxyl radicals and using a range of temperatures, rates, and hydroxyl ion concentrations. It should be noted that the half-lives determined by assuming first-order kinetics represent the calculated time for loss of the first 50% of tetrachloroethylene; the time required for the loss of the remaining 50% may not follow firstorder kinetics and may be substantially longer.

The reaction of volatile chlorinated hydrocarbons with OH radicals is temperature dependent and is thus expected to proceed more rapidly in the summer months. The degradation products of this reaction include phosgene, chloroacetylchlorides, formic acid, carbon monoxide, carbon tetrachloride, and hydrochloric acid (Gay et al. 1976; Itoh et al. 1994; Kirchner et al. 1990; Singh et al. 1975).

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Reaction of tetrachloroethylene with ozone in the atmosphere is too slow to be an effective agent in tetrachloroethylene removal (Atkinson and Carter 1984; Cupitt 1987).

EPA considers the photochemical reactivity of tetrachloroethylene leading to the production of ambient ozone to be negligible (EPA 1996a). Therefore, tetrachloroethylene has been added to the list of compounds excluded from the definition of volatile organic compounds for purposes of preparing state implementation plans to attain the national ambient air quality standards for ozone.

5.3.2.2 Water

Existing evidence indicates that tetrachloroethylene does not readily transform in water. Mass balance experiments in a sand aquifer showed that the amount of tetrachloroethylene recovered at the end of migration through the aquifer was essentially the same as that added (Roberts et al. 1986). Studies of photolysis and hydrolysis conducted by Chodola et al. (1989) demonstrated that photolysis did not contribute substantially to the transformation of tetrachloroethylene. Chemical hydrolysis appeared to occur only at elevated temperature in a high pH (9.2) environment, and even then, at a very slow rate.

Results from experiments conducted at high pH and temperature were extrapolated to pH 7 and 25°C (Jeffers et al. 1989), and the estimated half-life was $9.9x10^8$ years, which suggests that hydrolysis does not occur under normal environmental conditions. In contrast, estimates of the hydrolysis half-life of tetrachloroethylene under corresponding conditions were cited in other studies as about 9 months (Dilling et al. 1975) and 6 years (Pearson and McConnell 1975). It is not clear why there is such a large difference between these values; however, errors inherent in the extrapolation method used in the first approach (Jeffers et al. 1989) and the presence of transformation factors other than chemical hydrolysis, such as microbial degradation, in the second approach (Dilling et al. 1975; Pearson and McConnell 1975) may account for the discrepancy in the estimates of half-lives.

In natural waters, biodegradation may be the most important transformation process. Various biodegradation screening tests and laboratory studies have shown tetrachloroethylene to be resistant to biotransformation or biodegraded only slowly (Bouwer and McCarty 1982; Bouwer et al. 1981; Wakeham et al. 1983). Other screening studies have noted more rapid biodegradation; however, these studies used microbes that had to be adapted to tetrachloroethylene (Parsons et al. 1984, 1985; Tabak et al. 1981). Microbial degradation products of tetrachloroethylene in groundwater have been reported

to include primarily trichloroethylene and small amounts of cis- and trans-dichloroethylene (Parsons et al. 1984, 1985; Smith and Dragun 1984). Biotransformation was strongly indicated as a factor in the degradation of tetrachloroethylene in a case of soil and groundwater pollution (Milde et al. 1988). The only ethylenes at the source of pollution were tetrachloroethylene and trichloroethylene; however, substantial amounts of known metabolites of these two compounds (dichloroethylene, vinyl chloride, and ethylene) were found at points far from the source. Data from laboratory studies by the same group supported the study authors' contention that degradation was due to reductive dehalogenation by microorganisms. Further evidence that tetrachloroethylene can be completely degraded to ethylene by microorganisms was provided by Freedman and Gossett (1989). Their experiments indicated that this transformation can occur under methanogenic conditions. Reductive dehalogenation and further degradation to carbon dioxide by methanogens have also been demonstrated (Vogel and McCarty 1985).

Since neither biodegradation nor hydrolysis occurs at a rapid rate, most tetrachloroethylene present in surface waters can be expected to volatilize into the atmosphere. However, because tetrachloroethylene is denser than water and only slightly soluble in water, that which is not immediately volatilized may be expected to sink and thus be removed from contact with the surface (Doust and Huang 1992). Volatilization will therefore not be a viable process for this fraction of tetrachloroethylene, which may instead be rapidly transported into groundwater by leaching through fissures rather than matrix pores (Chilton et al. 1990). The sinking of tetrachloroethylene into groundwater also makes cleanup difficult.

There is evidence that slow biodegradation of tetrachloroethylene occurs under anaerobic conditions with acclimated microorganisms (Bouwer and McCarty 1984; Wilson et al. 1983b), suggesting that a slow transformation by biodegradation may occur in subsurface waters. Analysis of pore water from the principal aquifer in England referred to as "the Chalk," which has low carbon content and rapid groundwater flow in fissures, detected the presence of tetrachloroethylene at concentrations ranging from 0.05 to 40 mg/L at a depth of 50 meters (Lawrence et al. 1990). Given the slow rate of biodegradation, it is probable that tetrachloroethylene will persist for decades in the Chalk.

5.3.2.3 Sediment and Soil

Biodegradation of tetrachloroethylene in soil appears to occur only under specific conditions, and then only to a limited degree. When subsurface soil samples containing toluene-degrading bacteria were collected from a floodplain in Oklahoma and incubated with tetrachloroethylene, no detectable degradation occurred (Wilson et al. 1983a). Most evidence for transformation in soil comes directly from data on contaminated aquifers and the soils and sediments associated with them. Based on this indirect evidence, tetrachloroethylene is probably degraded to some extent in anaerobic soil environments (Freedman and Gossett 1989; Milde et al. 1988; Parsons et al. 1984, 1985; Wakeham et al. 1983). There is evidence that during the first 2 months of soil contamination, tetrachloroethylene (l00-1,000 μg/l00 g soil) may inhibit microbial and fungal activity as measured by ATP content of the soil (Kanazawa and Filip 1987). However, the same study authors observed an increase in anaerobic and specialized aerobic bacteria, which might indicate an opportunistic response to a suitable substrate by these microorganisms.

Anaerobic incubations of tetrachloroethylene with soils collected from lotus, rice, and vegetable fields in Japan resulted in biodegradation rates which varied with soil type, temperature, and initial concentration of tetrachloroethylene (Yagi et al. 1992). The decline in tetrachloroethylene concentration over 42 days was accompanied by an increase in the concentration of trichloroethylene, implicating this compound as a major metabolite. In an anaerobic column operated under methanogenie conditions, 100% transformation of injected tetrachloroethylene and trichloroethylene to vinyl chloride was obtained after 10 days (Vogel and McCarty 1985).

5.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

5.4.1 Air

A compilation of available U.S. ambient air monitoring data for tetrachloroethylene prior to 1981 has been published (Brodzinsky and Singh 1982). This compilation, which includes more than 2,500 monitoring points, reported mean tetrachloroethylene concentrations of 0.16 ppb in rural and remote areas, 0.79 ppb in urban and suburban areas, and 1.3 ppb in areas near emission sources. A similar compilation listed measured average concentrations ranging from 0 ppb (Grand Canyon, Arizona) to 31 ppb (the Boundbrook/Rahway/Edison/Passaic area of New Jersey) (EPA 1985d). Data

from ambient air monitoring studies in Canada have shown tetrachloroethylene concentrations of 0.03-0.73 ppb in urban locations and 0.03-0.06 ppb in a rural location (CEPA 1993).

Data from ambient air monitoring studies in the United States have shown tetrachloroethylene concentrations of 400-2,100 ng/m^3 (0.0584l.31 ppb) in Portland, Oregon, in 1984 (Ligocki et al. 1985), 5.2 μglm^3 (0.77 ppb) in Philadelphia, Pennsylvania, in 1983-1984 (Sullivan et al. 1985), 0.24-0.46 ppb in three New Jersey cities during the summer of 1981 and the winter of 1982 (Harkov et al. 1984), and 0.29-0.59 ppb in seven cities (Houston, Texas; St. Louis, Missouri; Denver, Colorado; Riverside, California; Staten Island, New York; Pittsburgh, Pennsylvania; and Chicago, Illinois) in 1980-1981 (Singh et al. 1982). A Total Exposure Assessment Methodology (TEAM) study of three industrialized areas (Bayonne/Elizabeth, New Jersey; Los Angeles, California; and Antioch/Pittsburg, California) detected levels ranging from 0.24 to 9.0 μg/m^3 (0.035-1.33 ppb) (Hartwell et al. 1987). In these studies, levels were found to vary between the fall/winter season and the spring/summer season, with fall/winter levels usually higher. This is consistent with the observation that higher temperatures increase the rate of reaction with hydroxyl radicals and subsequent degradation of tetrachloroethylene (see Section 5.3.2.1).

Data gathered from several sites near Niigata, Japan, between April 1989 and March 1992 also showed elevated levels of tetrachloroethylene and other volatile chlorinated hydrocarbons in the winter (Kawata and Fujieda 1993). A rural site in this study had annual mean concentrations between 0.031 and 0.045 ppb, while four industrial sites had mean concentrations between 0.082 and 1.0 ppb. The average levels of tetrachloroethylene detected in air in the Norwegian Arctic during July 1982 and March 1983 were 0.018 and 0.038 ppb, respectively (Hov et al. 1984). Average concentrations of tetrachloroethylene in Alaskan Arctic haze between 1980 and 1982 were 0.118 ppb in winter and 0.067 ppb in summer (Khalil and Rasmussen 1983). Measurements of tetrachloroethylene completed during 1982-1989 on marine islands included concentrations of 0.021 ppb in the northern troposphere at 90-30°N, 0.007 ppb in the northern troposphere at 30-0°N, and 0.002 ppb in the southern troposphere at 0-30°S(Wiedmann et al. 1994). The sample sites were chosen with the objective of sampling large and well-mixed air masses influenced only by long-range transport.

Data collected from several locations in the city of Hamburg, Germany, showed ambient air concentrations ranging from 1.8 to 70.8 μg/m^3 (0.27-10.44 ppb) (Bruckmann et al. 1988). The highest concentrations were detected downwind of a dry cleaning facility. A monitoring study in Finland

reported levels of 0.08 and 130 μg/m^3 (0.012 and 19.17 ppb) in ambient air from an industrialized and a suburban area, respectively (Kroneld 1989a). No tetrachloroethylene was detected in samples of rural air in that study.

Some of the highest outdoor air levels of tetrachloroethylene reported are associated with waste disposal sites. Mean concentrations of tetrachloroethylene detected in ambient samples collected at seven waste sites in New Jersey ranged from 0.12 to 1.91 ppb; the maximum level found at any site was 7.24 ppb (Harkov et al. 1985). Levels between 5.0 and 5.6 μg/m^3 (0.70 ppb and 0.82 ppb) were found at a distance of 0.5-l.5 meters above the surface of a landfill known to contain halogenated volatile organic compounds in Germany (Koenig et al. 1987).

A survey of indoor air in an office building, a school, and a home for the elderly showed median levels of tetrachloroethylene between 1.7 and 4.8 μg/m^3 (0.25 and 0.71 ppb) (Hartwell et al. 1985). The level of tetrachloroethylene in the air of an indoor university laboratory was 0.002-0.005 ppm (2.0-5.0 ppb) (Nicoara et al. 1994). Analysis of indoor and outdoor air for tetrachloroethylene in six regions of the United States (Greensboro, NC; Baton Rouge/Geismar, LA; Deer Park/Pasadena, TX; Elizabeth/Bayonne, NJ; Antioch/W. Pittsburg, CA; and small communities in the Los Angeles, CA, area) during 1981-1984 showed that indoor air concentrations were generally greater than outdoor air concentrations (Pellizzari et al. 1986). Ratios of tetrachloroethylene concentrations in indoor air relative to outdoor air ranged from 1.2 to 27.

Elevated levels of tetrachloroethylene have been found in apartments above dry cleaning facilities (Schreiber et al. 1993). Tetrachloroethylene concentrations ranged from 0.04 to 8.1 ppm in six apartments above dry cleaning facilities when measurements were completed from 7 AM to 7 PM, and from 0.01 to 5.4 ppm when measured from 7 PM to 7 AM. Tetrachloroethylene concentrations were higher above facilities using transfer-type dry cleaning machines compared to dry-to-dry machines, although the highest levels were found above a facility using an old, poorly maintained dry-to-dry machine. Tetrachloroethylene concentrations in nearby apartments were <0.001-0.015 ppm during the day and <0.001-0.01 ppm at night.

5.4.2 Water

Average concentrations of 0.12-0.5 parts-per-trillion (ppt) tetrachloroethylene have been detected in the North Atlantic (Murray and Riley 1973; Pearson and McConnell 1975). Levels in open waters of the Gulf of Mexico were below the detection limit of <l ppt (Sauer 1981).

Rainwater collected in Portland, Oregon, in 1984 was found to contain tetrachloroethylene levels of 0.82-9.2 ng/L (0.82-9.2 ppt) (Ligocki et al. 1985). A March 1982 rainwater sample from Los Angeles, California, contained 21 ng/L (21 ppt) (Kawamura and Kaplan 1983). An average tetrachloroethylene concentration of 5.7 ng/L (5.7 ppt) was detected in rainwater from La Jolla, California, and levels of 2.3 and 16 ng/L (2.3 and 16 ppt) were detected in snow from southern California and Alaska, respectively (Su and Goldberg 1976). Levels up to 150 ng/L (150 ppt) were found in samples collected in rainwater in industrial cities in England (Pearson and McConnell 1975). Rainwater samples collected in Tokyo between October 1989 and September 1990 had a mean tetra-chloroethylene level of 99 ng/L (99 ppt), with higher levels in samples obtained during the winter (Jung et al. 1992).

Tetrachloroethylene has been detected in drinking water sources throughout the United States. Results from an EPA Groundwater Supply Survey of 945 water supplies from groundwater sources nationwide showed tetrachloroethylene in 79 water supplies. The median concentration of the positive samples was about 0.75 μg/L (0.75 ppb), with a maximum level of 69 μg/L (69 ppb) (Westrick et al. 1984). Tetrachloroethylene concentrations of 0.01-0.2 μg/L (0.01-0.2 ppb) were detected in drinking water from five cities in 1974 and 1975 (Cincinnati, Ohio; Miami, Florida; Grand Forks, North Dakota; Lawrence, Massachusetts; New York, New York) (Keith et al. 1976). Drinking water from wells in New York, New Jersey, and Connecticut have been found to contain tetrachloroethylene at levels of 717-1,500 ppb, although these elevated levels were in areas of considerable pollution (Burmaster 1982). Levels of 0.38-2.9 ppb were detected in tap water from homes near the contaminated Love Canal site in New York (Barkley et al. 1980). In other countries, 30 Canadian drinking water sources were found to contain tetrachloroethylene levels at <l μg/L (Otson and Williams 1982), and recent drinking water samples from Zagreb, Croatia, contained 0.36-7.80 μg/L (0.36-7.80 ppb) (Skender et al. 1993).

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A summary of U.S. groundwater analyses from both federal and state studies reported that tetrachloroethylene was detected in 14-26% of all samples analyzed (Dykson and Hess 1982). In a comparison of groundwater data from 178 CERCLA sites, tetrachloroethylene was detected in 36% of the samples and was the second most frequently detected organic groundwater contaminant in the CERCLA database (Plumb 1987). Tetrachloroethylene was detected in 179 of 421 groundwater samples in New Jersey between 1977 and 1979, at a maximum concentration of 90.6 ppb (Page 1981). Tetrachloroethylene has been detected in groundwater leachates from various landfill sites nationwide (Reinhard et al. 1984; Sabel and Clark 1984; Schultz and Kjeldsen 1986). A landfill in New Jersey contained levels up to 590 μg/L (590 ppb) in its leachate (Kosson et al. 1985). Groundwater samples taken from several locations near a sewage effluent disposal site in Massachusetts had levels as high as 980 μg/L (980 ppb) (Barber et al. 1988). A nationwide monitoring study conducted in Japan showed that tetrachloroethylene was common in water supplies of that country (Magara and Furuichi 1986). Tetrachloroethylene was detected in 27% of shallow wells and 30% of deep wells. Concentrations ranged from 0.2 to 23,000 μg/L (0.2 to 23,000 ppb) in shallow wells and from 0.2 to 150 μg/L (0.2 to 150 ppb) in deep wells.

An analysis of the EPA STORET Data Base showed that tetrachloroethylene was detected in 38% of 9,323 surface water reporting stations nationwide (Staples et al. 1985). An analysis of 1,140 samples from the Ohio River showed a similar percentage of positive detections, with detected levels usually <l ppb (Ohio River Valley Sanitation Commission 1980). Tetrachloroethylene was detected in 154 of 174 surface water samples collected in New Jersey between 1977 and 1979, with a maximum concentration of 4.5 ppb (Page 1981). Levels of 0.003-.08 μg/L (0.003-0.08 ppb) were found in the Niagara River and Lake Ontario between 1978 and 1981 (Strachan and Edwards 1984). Concentrations ranged from 0 to 473,000 ppb in the surface water of Lake St. Clair in Canada during June of 1984 (Kaiser and Comba 1986). Highest levels were detected where the St. Clair River emptied into the lake. River levels ranged from 79,000 to 182,000 ppb.

5.4.3 Sediment and Soil

Sediments from Liverpool Bay, England, were found to contain concentrations ranging from 0.03 to 6 ppm, with most detections at the lower limit (Pearson and McConnell 1975). Sediment levels from nondetectable to 0.3 ppb (wet weight) tetrachloroethylene were identified in samples from Lake Pontchartrain, near New Orleans (Ferrario et al. 1985). The detection limit of the method used in this

study was not stated. An analysis of the EPA STORET Data Base showed that tetrachloroethylene had been positively detected in 5% of 359 sediment observation stations, with median levels of <5 ng/g (5 ppb) (Staples et al. 1985). Tetrachloroethylene was qualitatively detected in the soil/sediment matrix of the Love Canal waste site near Niagara Falls, New York (Hauser and Bromberg 1982).

5.4.4 Other Environmental Media

Tetrachloroethylene has been detected in dairy products (milk, cheese, and butter) at 0.3-13 μg/kg (0.3-13 ppb), meat (English beef) at 0.9-1.0 μg/kg (0.9-1.0 ppb), oils and fats at 0.01-7 μg/kg (0.01-7 ppb), beverages (canned fruit drink, instant coffee, and tea) at 2-3 μg/kg (2-3 ppb), fruits and vegetables (potatoes, apples, pears, and tomatoes) at 0.7-2 μg/kg (0.7-2 ppb), and fresh bread at 1 μg/kg (1 ppb) (McConnell et al. 1975). Samples obtained from a food processor in Pennsylvania contained tetrachloroethylene concentrations of 0.4 ppb in plant tap water, 2.0 ppb in Chinese-style sauce, 2.2 ppb in quince jelly, 2.5 ppb in crab apple jelly, 1.6 ppb in grape jelly, and 3.6 ppb in chocolate sauce (Entz and Hollifield 1982). In another study, levels of tetrachloroethylene detected in a variety of foods ranged from 1 to 230 ng/g (l-230 ppb), with a mean of 12 ng/g (12 ppb) (Daft 1989). An analysis of intermediate grain-based foods in 1985 showed the following tetrachloroethylene levels (in ppb): corn muffin mix, 1.8; yellow corn meal, 0.0; fudge brownie mix, 2.45; dried lima beans, 0.0; lasagna noodles, 0.0; uncooked rice, 0.0; and yellow cake mix, 2.5 (Heikes and Hopper 1986). Levels of tetrachloroethylene detected in margarine from several supermarkets in the Washington, DC, area were 50 ppm in 10.7% of the products sampled (Entz and Diachenko 1988). The highest levels (500-5,000 ppb) were found in samples taken from a grocery store located near a dry cleaning shop. Additional analysis showed that the concentrations were highest on the ends of the margarine stick and decreased toward the middle. According to the study authors, these findings suggested that contamination occurred after manufacturing rather than during the manufacturing process (Entz and Diachenko 1988).

Another study showed that tetrachloroethylene can be absorbed from the atmosphere by foods and concentrated over time, so that acceptable ambient air levels may still result in food levels which exceed acceptable limits (Grob et al. 1990). The study authors estimated that, in order to limit food concentrations of tetrachloroethylene to 50 μg/kg (the maximum tolerated limit for food halocarbons in Switzerland), the level in surrounding air should not exceed 12.5 $\mu g/m^3$ (0.002 ppm). Since the

accepted levels found near emission sources are often far above this limit, foods processed or sold near these sources may routinely exceed the Swiss tolerated tetrachloroethylene concentration, thus making the setting of air emission standards problematic. It is also noteworthy that the limits recommended by Grob et al. (1990) exceed acceptable ambient air concentrations for many regions of the United States (see Chapter 7).

An analysis of six municipal solid waste samples from Hamburg, Germany, revealed levels of tetrachloroethylene ranging from undetectable to 1.41 mg/kg (1.41 ppm) (Deipser and Stegmann 1994). In a study analyzing automobile exhaust for chlorinated compounds, tetrachloroethylene was not detected (Hasanen et al. 1979).

5.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

The most important routes of exposure to tetrachloroethylene for most members of the general population are inhalation of the compound in ambient air and ingestion of contaminated drinking water. Available data indicate generally that dermal exposure is not an important route for most people. General population exposure from inhalation of ambient air varies widely depending on location. While background levels are generally in the low-ppt range in rural and remote areas, values in the high-ppt and low-ppb range are found in urban and industrial areas and areas near point sources of pollution.

Tetrachloroethylene has been detected in expired air in several comprehensive studies of humans; attempts were made to correlate the levels in breath with those in water and ambient air (Hartwell et al. 1987; Krotoszynski et al. 1979; Wallace et al. 1985, 1986a). Results suggested that expired air concentrations of tetrachloroethylene were correlated with personal exposure concentrations of the chemical. Breath levels were higher than outdoor air levels and seemed to be more closely related to indoor air levels (Wallace 1986; Wallace et al. 1985, 1986a), suggesting that indoor air is a more significant exposure source of tetrachloroethylene than outdoor air, even near major point sources such as chemical plants (Wallace 1986; Wallace et al. 1986a, 1986b, 1986c, 1986d). Wallace et al. (1989) reported air concentrations for four homes (nine samples per home) in North Carolina and found that indoor air concentrations of tetrachloroethylene in all homes were consistently higher than the outdoor concentrations.

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Indoor air of apartments where dry cleaners lived was about 0.04 ppm compared to 0.003 ppm in the apartments of the controls (Aggazzotti et al. 1994a), indicating that dry cleaners serve as a source of exposure for their families. Breath concentrations of tetrachloroethylene in dry cleaners, family members and controls were 0.65, 0.05, and 0.001 ppm, respectively (Aggazzotti et al. 1994b). A study which combines PBPK modeling with a single compartment model for a "typical" home (Thompson and Evans 1993) suggests that tetrachloroethylene levels in a home with a worker exposed to a TWA of 50 ppm for 8 hours as the only source of tetrachloroethylene could result in concentrations of 0.004-0.01 ppm. The air exchange rate in the house made a larger difference in the house air concentrations than the choice of metabolic data used in the PBPK model.

In addition to breathing contaminated air, infants can also be exposed to tetrachloroethylene in breast milk. For example, tetrachloroethylene was present at unspecified levels in seven of eight samples of mother's milk from four urban areas in the United States (Pellizzari et al. 1982). A woman in Halifax, Nova Scotia, who visited her husband daily at the dry cleaning plant where he worked, was found to have tetrachloroethylene present in her breast milk (Bagnell and Ellenberger 1977). This was discovered after her breast-fed infant developed obstructive jaundice, which was attributed to the contaminant. Using a PBPK model, Schreiber (1993) predicted that for women exposed under occupational conditions, breast milk concentrations would range from 857 to 8,440 μg/L. The exposure scenario for the low concentrations was 8 hours at about 6 ppm (exposure concentration of counter workers, pressers and seamstresses) and 16 hours at 0.004 ppm (residential background), and for the high concentration, 8 hours at 50 ppm and 16 hours at 0.004 ppm (residential background). Assuming a 7.2-kg infant ingests 700 mL of breast milk/day, the infant dose would range from 0.08 to 0.82 mg/kg/day, relative to the EPA RfD of 0.01 mg/kg/day (IRIS 1996). The infant dose estimated from background exposure (24 hours at 0.004 ppm) was 0.001 mg/kg/day (Schreiber 1993). Because of potential widespread exposure, the study author suggested that additional monitoring of breast milk levels should be completed. A second model of the lactational transfer of tetrachloroethylene has been developed using data from rats (Byczkowski and Fisher 1994, 1995). Using an exposure scenario similar to that described by Bagnell and Ellenberger (1977), investigators (Byczkowski and Fisher 1994) estimated that a l-hour exposure to 600 ppm tetrachloroethylene each day would result in an infant blood concentration of about 0.035 mg/L within 1 month of exposure. Using the same exposure scenarios as Schreiber (1993), the Byczkowski and Fisher (1995) model predicts slightly smaller doses delivered to the infant. For example, Schreiber (1993) predicted 0.08 mg/kg/day as the minimum dose to the infant for the exposure scenario for low concentrations (8 hours at 6 ppm, 16 hours at

0.004 ppm) while Byczkowski and Fisher (1995) predicted a dose of 0.032 mg/kg/day. The Schreiber (1993) model may have overestimated the dose to the infant because it assumes the infant will be exposed to the peak concentrations of tetrachloroethylene in breast milk, while the Byczkowski and Fisher (1995) model provides more insight into the changing concentrations of tetrachloroethylene in breast milk as maternal exposure changes.

Although the use of tetrachloroethylene in the dry cleaning industry makes this chemical a potential hazard for exposed workers, casual contact by the general population with dry-cleaned clothing may pose a risk as well. One study showed that the storage of newly dry-cleaned garments in a residential closet resulted in tetrachloroethylene levels of 0.5-2.9 mg/m^3 (74-428 ppb) in the closet after 1 day, followed by a rapid decline to 0.5 mg/m^3 (74 ppb) which persisted for several days (Tichenor et al. 1990). Initial "airing out" of the clothes for 4-8 hours had little effect on the resulting emissions, presumably because diffusion through the fabric, rather than surface evaporation, was rate-limiting. A study of nine homes into which 10 or fewer freshly dry-cleaned garments were introduced showed an increase in tetrachloroethylene levels in the air of seven homes (Thomas et al. 1991). The increases ranged from 2 to 30 times the levels before the introduction of the garments, and the magnitude of the increase was highly correlated with the number of garments divided by the house volume. tetrachloroethylene levels in personal breathing space and expired air of residents were also monitored and found to be generally correlated with indoor air concentrations. An investigation of different methods for reducing tetrachloroethylene retention in dry-cleaned fabrics found that, while airing at 20°C for several hours had little effect, airing at 45°C greatly reduced retention time, and thus was recommended as a way to reduce consumer exposure from garments (Guo et al. 1990).

A survey of 15 coin-operated dry cleaning establishments in Hamburg, Germany, showed indoor air concentrations of tetrachloroethylene between 3.1 and 331 mg/m^3 (457 and 48,812 ppb) and a concentration of 4.5 mg/m^3 (664 ppb) in one building 7.5 months after removal of dry cleaning machines, indicating that tetrachloroethylene may be absorbed by building materials and then slowly released into the air over time (Gulyas and Hemmerling 1990). This study also indicated that a car transporting a freshly dry-cleaned down jacket had air concentrations of 20.4 mg/m^3 (3,008 ppb) after 25 minutes and 24.8 mg/m^3 (3,657 ppb) after 108 minutes.

A survey of dry cleaning operators conducted by the International Fabricare Institute from 1980 to 1990 indicated that 1,302 operators in plants with transfer units were exposed to an average time-

weighted average of 48.4 ppm, while 1,027 operators in plants with dry-to-dry units were exposed to an average time-weighted average of 16.9 ppm (Andrasik and Cloutet 1990). An in-depth series of studies of the dry cleaning industry has been completed by the National Institute for Occupational Safety and Health (NIOSH). These studies evaluate worker exposure to tetrachloroethylene at several locations in the United States, and examine how the exposure can be controlled (Earnest 1995, 1996; Earnest and Spencer 1995; Earnest et al. 1995a, 1995b, 1995c; Spencer et al. 1995). Personal and area air samples were obtained. Results of the studies showed that the TWA concentrations of tetrachlorethylene were within the American Conference of Governmental Industrial Hygienists recommended threshold limit value of 25 ppm (ACGIH 1995). The primary exposure of the workers occurred during the loading and unloading of the dry cleaning machines.

Various consumer products have been found to contain tetrachloroethylene. These include printing ink, glues, sealants, polishes, lubricants, and silicones (ACGIH 1991) as well as paint removers; rug and upholstery cleaners; and stain, spot, and rust removers (EPA 1985d).

Contamination of drinking water supplies with tetrachloroethylene varies with location and with the drinking water source (surface water or groundwater). Generally higher levels are expected in groundwater because tetrachloroethylene volatilizes rapidly from surface water. The EPA has estimated that approximately 5.3% of the U.S. population using public water supplies is exposed to tetrachloroethylene levels above 0.5 μg/L (0.5 ppb), and 0.4% are exposed to levels above 5 μg/L (5 ppb) (EPA 1985c). Thus, assuming a 70-kg person drinking 2 L of water containing 0.5 ppb tetrachloroethylene per day, the daily intake of tetrachloroethylene is 1 ppb, or 0.014 μg/kg/day.

Showering or bathing with contaminated water can also result in tetrachloroethylene exposure. Rao and Brown (1993) describe a combined PBPK exposure model that estimates brain and blood levels of tetrachloroethylene following a 15-minute shower or 30-minute bath with water containing 1 mg tetrachloroethylene/. The PBPK model is described further in Section 2.3.5. The exposure model assumed that the shower or bath would use 100 L of water, the air volume in the shower stall or above the bath tub was 3 m^3, and the shower flow rate was 6.667 L/mmute. The exposure model was validated with data for chloroform and trichloroethylene, but not tetrachloroethylene. Using this model, Rao and Brown (1993) estimated that shower air would contain an average of 1 ppm and that the air above the bathtub would contain an average of 0.725 ppm if the water contained 1 mg tetrachloroethylene/L.

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There is some evidence that tetrachloroethylene can be produced in small amounts during the chlorination process of water treatment (Bellar et al. 1974), although no evidence exists for its formation through drinking water chlorination (Bellar et al. 1974; Westrick et al. 1984). Other studies of vinyl coated water pipes used for carrying drinking water in some parts of the northeast United States suggested that residual tetrachloroethylene from the coating process may contribute to drinking water contamination (Wakeham et al. 1980; Yuskus 1984).

General population exposure may also occur from ingestion of contaminated foods, but data are insufficient to calculate an average daily intake with a high degree of accuracy, or estimate the importance of contaminated food as a source of exposure for the general population. However, the EPA made some approximations assuming individual average daily intakes of 0.753 kg for dairy products, 0.262 kg for meat, fish, and poultry, 0.073 kg for fats and oils, and 0.128 kg for beverages. Based on average tetrachloroethylene levels reported for these foods, it was determined that a person's average daily intake of tetrachloroethylene is between 0 and 4 μg from dairy products, 0 and 1 μg from meat, fish, and poultry, 0 and 0.95 μg from fats and oils, and 0 and 0.06 μg from beverages (EPA 1985c).

Total tetrachloroethylene intake for Canadians has been estimated to range from 1.2 to 2.7 μg/kg/day (CEPA 1993). Indoor air exposure (assuming 20 hours/day) from the use of household products containing tetrachloroethylene and from recently dry-cleaned clothes accounted for 1.2-l .9 μg/kg/day. Drinking water and food consumption contributed 0.002-0.03 and 0.12-0.65 μg/kg/day, respectively. Data were not sufficient to estimate tetrachloroethylene intake from soil.

Tetrachloroethylene has been measured in the blood and urine in a sample of the general population in Italy (Brugonone et al. 1994). In rural locations, tetrachloroethylene was detected in the blood of 76% of 107 individuals tested at a mean concentration of 62 ng/L, while in 106 urban subjects it was detected in 41% at a mean concentration of 263 ng/L. Measurement of tetrachloroethylene in urine showed similar results for urban (74% positive; average 90 ng/L) and rural populations (74% positive; average 119 ng/L). In Zagreb, Croatia, tetrachloroethylene concentrations in the drinking water ranged from 210 to 7,800 ng/L, and tetrachloroethylene in blood ranged from <10 to 239 ng/L (Skender et al. 1994).

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The National Occupational Exposure Survey (NOES), conducted by NIOSH from 1981 to 1983, estimated that 688,110 workers employed at 49,025 plant sites were potentially exposed to tetrachloroethylene in the United States during this period (NOES 1990). The NOES database does not contain information on the frequency, concentration, or duration of exposure; the survey provides only estimates of workers potentially exposed to chemicals in the workplace. A NIOSH survey of 44 dry cleaning facilities showed tetrachloroethylene TWA exposures to machine operators ranging from 4.0 to 149 ppm; the geometric mean tetrachloroethylene exposures to machine operators was 22 ppm, while mean exposures to pressers, seamstresses, and front counter workers were 3.3, 3.0, and 3.1 ppm, respectively (Ludwig et al. 1983). A study of the dry cleaning industry in England indicated exposure was similar to that determined in the U.S. studies (Shipman and Whim 1980).

Workplace exposure to tetrachloroethylene has been monitored by examining venous blood concentrations of unmetabolized tetrachloroethylene and its metabolite trichloroacetic acid in workers at dry cleaning shops. The tetrachloroethylene concentrations increased greatly through the course of the workweek, while the increases in trichloroacetic acid were less dramatic (Skender et al. 1987). A limited capacity in humans for metabolizing tetrachloroethylene was also indicated by a study in which 61 workers showed a linear increase in urinary metabolite concentration as the ambient tetrachloroethylene concentration increased up to 100 ppm, beyond which point metabolite excretion leveled off (Ohtsuki et al. 1983). Another study involving 40 workers at various plants exposed to tetrachloroethylene showed a direct correlation between levels monitored in the personal breathing zone and levels of unmetabolized tetrachloroethylene in the urine (Ghittori et al. 1987).

5.6 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Various segments of the population can be exposed to levels of tetrachloroethylene significantly above normal background concentrations. Metal degreasers who use the chemical as a solvent would be expected to have high exposure. People working in the dry cleaning industries are exposed to elevated levels of tetrachloroethylene. In addition, recent evidence has suggested that people living with workers in the dry cleaning industry may be subjected to higher exposures even though their homes are far removed from the work site (Aggazzotti et al. 1994a). This study surveyed 30 such homes and showed a range of indoor tetrachloroethylene levels from 34 to 3000 $\mu g/m^3$ (5.0 to 442 ppb), which was significantly higher than that found in control homes (1-16 $\mu g/m^3$) (0.1-2.4 ppb). The tetrachloroethylene levels in alveolar air samples were likewise significantly higher in family members

of workers than in control subjects, and the higher exposures were attributed to clothing worn home from work and the expired breath of workers (Aggazzotti et al. 1994a, 1994b).

Elevated levels of tetrachloroethylene in human breath of the general public (i.e., non-occupational exposure) appear to be related to tetrachloroethylene emissions from nearby factories or from chemical waste dumps. A sample of 6 children living near a factory in the Netherlands had a mean concentration of 24 $\mu g/m^3$ (3.5 ppb) tetrachloroethylene in their breath, compared with 11 control children with a mean level of 2.8 $\mu g/m^3$ (0.4 ppb) (Monster and Smolders 1984). Nine residents of Love Canal, New York, a site of serious chemical contamination for many years, were found to have tetrachloroethylene levels ranging from 600 to 4,500 ng/m^3 (0.09-0.66 ppb) in their breath, from 0.35 to 260 ng/mL (0.35-260 ppb) in their blood, and from 120 to 690 ng/mL (120-690 ppb) in their urine (Barkley et al. 1980). This same study indicated that the participants were exposed to 120-14,000 ng/m^3 (0.02-2.06 ppb) in ambient outside air and levels of 350-2,900 ng/L (0.35-2.90 ppb) in their drinking water.

Because of its pervasiveness in the environment, the general public can be exposed to tetrachloroethylene through drinking water, air, or food, although the levels of exposure are probably far below those causing any adverse effects. Concern may be justified, however, for people who are continuously exposed to elevated levels, such as residents of some urban or industrialized areas, people living near hazardous waste sites, or people exposed at work. Short-term exposure to high levels of tetrachloroethylene may also pose risks to people using products containing the chemical in areas with inadequate ventilation. The discontinuation of tetrachloroethylene use in many medical applications and some consumer products has generally decreased the exposure risks in these situations.

An EPA TEAM (Total Exposure Assessment Methodology) study conducted in New Jersey attempted to identify factors associated with risk of higher inhalation of tetrachloroethylene (Wallace et al. 1986b). The following factors (in order of importance) were identified: employment (not otherwise specified), wood processing, visiting a dry cleaner, working at a textile plant, using pesticides, working at or being in a paint store, and being male.

5.7 ADEQUACY OF THE DATABASE

Section 104(i)(5) of CERCLA, as amended, directs the Administrator of ATSDR (in consultation with the Administrator of EPA and agencies and programs of the Public Health Service) to assess whether adequate information on the health effects of tetrachloroethylene is available. Where adequate information is not available, ATSDR, in conjunction with the NTP, is required to assure the initiation of a program of research designed to determine the health effects (and techniques for developing methods to determine such health effects) of tetrachloroethylene.

The following categories of possible data needs have been identified by a joint team of scientists from ATSDR, NTP, and EPA. They are defined as substance-specific informational needs that if met would reduce the uncertainties of human health assessment. This definition should not be interpreted to mean that all data needs discussed in this section must be filled. In the future, the identified data needs will be evaluated and prioritized, and a substance-specific research agenda will be proposed.

5.7.1 Identification of Data Needs

Physical and Chemical Properties. The physical and chemical properties of tetrachloroethylene are well characterized and allow prediction of the environmental fate of the compound (HSDB 1996; Lide 1990; Sax and Lewis 1987). Estimates of the distribution of tetrachloroethylene in the environment based on available constants (e.g., water solubility, log kow, log koc, vapor pressure) (HSDB 1996; Seip et al. 1986; Zytner et al. 1989a) are generally in good agreement with experimentally determined values. No additional studies are required at this time.

Production, Import/Export, Use, and Release and Disposal. Humans are at risk of exposure to tetrachloroethylene because of its widespread use and distribution in the environment. Production, import, and use of the chemical are known to be relatively high. Tetrachloroethylene is released to the atmosphere mainly through its use in the dry cleaning and textile processing industries, as a chemical intermediate, and in degreasing procedures (EPA 1982a; Weant and McCormick 1984). It is also released to surface water and land in sewage sludges and industrial liquid or solid waste (Schultz and Kjeldsen 1986; TRI93 1995; Weant and McCormick 1984). Tetrachloroethylene-containing material is considered a hazardous waste and its disposal is subject to regulations (see Chapter 7) (EPA 1985a, 1985c). More current data on production, use in food processing and consumer products, releases,

efficiency of disposal practices, adequacy of current disposal regulations, and the extent of recovery and recycling of tetrachloroethylene would assist in estimating human potential exposures, particularly of populations living near industrial facilities and hazardous waste sites.

According to the Emergency Planning and Community Right-to-Know Act of 1986, 42 U.S.C. Section 11023, industries are required to submit substance release and off-site transfer information to the EPA. The Toxics Release Inventory (TRI), which contains this information for 1992, became available in May of 1994. This database will be updated yearly and should provide a list of industrial production facilities and emissions.

Environmental Fate. Tetrachloroethylene partitions primarily to the atmosphere (Class and Ballschmiter 1986), where it can be transported back to land and surface water in rain (Kawamura and Kaplan 1983; Pearson and McConnell 1975; Su and Goldberg 1976). In air, the half-life of tetrachloroethylene has been estimated to range from 70 to 251 days (Class and Ballschmiter 1986; Cupitt 1987). The chemical is mobile in soil (Kenaga 1980; Swann et al. 1983) and can contaminate groundwater (Dykson and Hess 1982). It does not appear to be readily transformed in soil (Wakeham et al. 1983; Wilson et al. 1983a) or water (Bouwer and McCarty 1982; Bouwer et al. 1981; Chodola et al. 1989; Jeffers et al. 1989; Roberts et al. 1986). The hydrolysis half-life has been estimated to be from 9 months (Dilling et al. 1975) to 9.9×10^8 years (Jeffers et al. 1989). Because of the great variability in half-life, additional studies regarding the hydrolysis of tetrachloroethylene would be useful. Data are inadequate for predicting the biological degradation of tetrachloroethylene under different soil conditions, e.g., soil characteristics and composition. It is not currently possible to use models to predict the rate of degradation nor the proportions of degradation products that might be produced. It would be very useful to have this capability.

Bioavailability from Environmental Media. No studies have been identified regarding the absorption of tetrachloroethylene following ingestion of contaminated soil and plants grown on contaminated soil near hazardous waste sites and other points sources of pollution. Tetrachloroethylene can be absorbed following inhalation (Hake and Stewart 1977; Monster et al. 1979), oral (Frantz and Watanabe 1983; Pegg et al. 1979; Schumann et al. 1980), or dermal exposure (Jakobson et al. 1982; Stewart and Dodd 1964; Tsuruta 1975). All of these routes of exposure may be of concern to humans because of the potential for tetrachloroethylene to contaminate the air, drinking water, food, and soil. More information on the absorption of tetrachloroethylene following ingestion

of contaminated soil and plants grown on contaminated soil near hazardous waste sites and other sources of pollution would be helpful in determining the bioavailability of the chemical from soil.

Food Chain Bioaccumulation. Data indicate that tetrachloroethylene has a low bioconcentration potential in aquatic organisms and animals (Barrows et al. 1990; Kawasaki 1980; Kenaga 1980; Neely et al. 1974; Veith et al. 1980). No data were located on the bioconcentration potential of this compound in plants. Research on the bioconcentration of tetrachloroethylene in plants would help in assessing the potential for exposure from ingestion of plant foodstuffs. Although biomagnification of tetrachloroethylene in terrestrial and aquatic food chains is not expected to be important because the compound is metabolized in animals, experimental data to confirm the expected behavior would be useful in evaluating the importance of food chain bioaccumulation as a source of human exposure to tetrachloroethylene.

Exposure Levels in Environmental Media. Tetrachloroethylene is widely distributed in the environment and has been detected in air (Brodzinsky and Singh 1982; Hartwell et al. 1987; Ligocki et al. 1985; Singh et al. 1982), water (Dykson and Hess 1982; Kawamura and Kaplan 1983; Ligocki et al. 1985; Staples et al. 1985), soil (Ferrario et al. 1985; Staples et al. 1985), and food (Daft 1989; Entz and Diachenko 1988; Entz and Hollifield 1982; Heikes and Hopper 1986). Ambient air levels in cities in the United States generally range from 0.035 to 1.3 ppb (Hartwell et al. 1987). Surface water concentrations of tetrachloroethylene are generally less than 1 ppb (Ohio River Valley Sanitation Commission 1980), and the median concentration in 79 ground water samples was 0.75 ppb (Westrick et al. 1984). Median concentrations of tetrachloroethylene in 359 sediment samples were <5 ppb (Staples et al. 1985). Continual monitoring data for surface air, water, groundwater, and soil are needed to assess the current potential for exposure to the chemical from these media. Additional data characterizing the concentration of tetrachloroethylene in air, water, and soil surrounding hazardous waste sites and estimating human intake from these media would be helpful in assessing the potential human exposure to this chemical for populations living near hazardous waste sites. Reliable monitoring data for the levels of tetrachloroethylene in contaminated media at hazardous waste sites are needed so that the information obtained on levels of tetrachloroethylene in the environment can be used in combination with the known body burden of tetrachloroethylene to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

Exposure Levels in Humans. Tetrachloroethylene has been detected in human breath (Koppel et al. 1985; Stewart et al. 1977), blood (Altmann et al. 1990; Hams et al. 1993), urine (Koppel et al. 1985), tissues (Gamier et al. 1996; Levine et al. 1981; Lukaszewski 1979), and breast milk (Bagnell and Ellenberger 1977). Most of the monitoring data come from occupational studies of specific worker populations exposed to tetrachloroethylene; however, some studies of exposure in the general population have been done (Aggazzotti et al. 1994a, 1994b; Hartwell et al. 1987; Krotoszynski et al. 1979; Schreiber et al. 1993; Wallace et al. 1985, 1986a). More current information on biological media monitoring of the general population would be helpful in estimating human exposure. Because infants may be more susceptible to tetrachloroethylene, more information on tetrachloroethylene in breast milk would be useful. Data correlating levels in biological samples with media exposure levels and the subsequent development of health effects are especially needed for populations living in the vicinity of hazardous waste sites. This information is necessary for assessing the need to conduct health studies on these populations.

Exposure Registries. No exposure registries for tetrachloroethylene were located. This substance is not currently one of the compounds for which a subregistry has been established in the National Exposure Registry. The substance will be considered in the future when chemical selection is made for subregistries to be established. The information that is amassed in the National Exposure Registry facilitates the epidemiological research needed to assess adverse health outcomes that may be related to exposure to this substance.

5.7.2 On-going Studies

As part of the Third National Health and Nutrition Evaluation Survey (NHANES III), the Environmental Health Laboratory Sciences Division of the National Center for Environmental Health, Centers for Disease Control and Prevention, will be analyzing human blood samples for tetrachloroethylene and other volatile organic compounds. These data will give an indication of the frequency of occurrence and background levels of these compounds in the general population.

The biodegradation of tetrachloroethylene as a method for waste treatment and remediation of polluted sites is the focus of many current research projects (CRIS 1994). Reductive dechlorination of tetrachloroethylene by an anaerobic enrichment culture is being investigated at Cornell University (Principal Investigator, Dr. S.H. Zinder) in order to characterize responsible organisms and the kinetics

of the reactions. Other studies concerned with identifying optimal conditions for both aerobic and anaerobic biotransformation as methods of treatment are in progress (e.g., at Westinghouse, Savannah River Technical Center, Oak Ridge National Laboratory, Occidental Chemical Corporation, U.S. EPA, University of Washington, and University of California).