# 6. POTENTIAL FOR HUMAN EXPOSURE

## 6.1 OVERVIEW

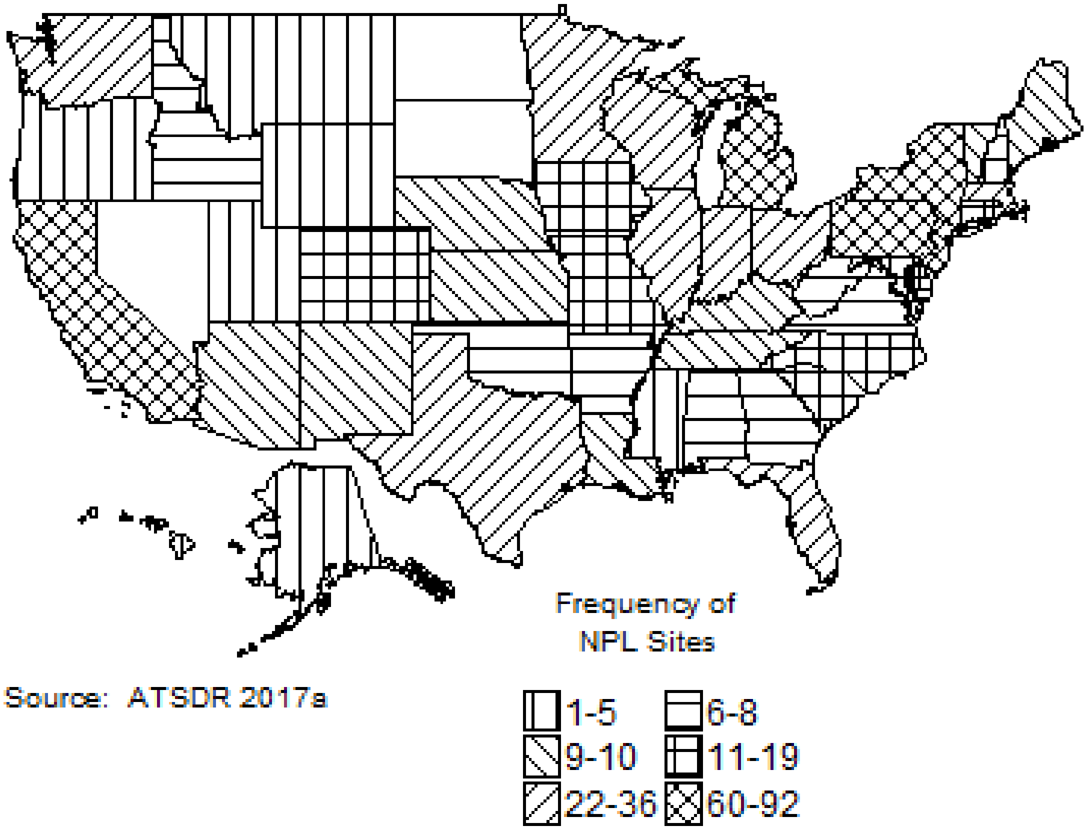
Tetrachloroethylene has been identified in at least 949 of the 1,854 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (ATSDR 2017a). However, the number of sites evaluated for tetrachloroethylene is not known. The frequency of these sites can be seen in Figure 6-1. Of these sites, 943 are located within the United States, 3 are located in the Commonwealth of Puerto Rico (not shown), 1 is located in Guam (not shown), and 1 is located in the Virgin Islands (not shown).

Tetrachloroethylene is a VOC that is widely distributed in the environment. It is released to the environment via industrial emissions and from building and consumer products. Releases are primarily to the atmosphere. However, 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 can last for decades in the groundwater.

Background tetrachloroethylene levels in outdoor air are typically <1 $\mu g/m^3$ (0.15 ppb) for most locations (EPA 2013h, 2018); however, indoor air at source dominant facilities (e.g., dry cleaners) has been shown to have levels >1 $mg/m^3$ (Chiappini et al. 2009; Garetano and Gochfield 2000; Ziener and Braunsdorf 2014). Volatilization from contaminated water (e.g., shower water) as well as the use of household products containing solvents can result in higher indoor than outdoor air concentrations of tetrachloroethylene. Due to its long atmospheric half-life, long-range transport of tetrachloroethylene is possible and it has been detected in remote monitoring locations such as the Antarctic at low levels (Zoccolillo et al. 2009).

Tetrachloroethylene is a common dense nonaqueous phase liquid (DNAPL) that can migrate through the subsurface of water (ITRC 2003). As a result, tetrachloroethylene can also be persistent in the water because it has a higher density than water and relatively low water solubility. Vapor-phase tetrachloroethylene can also seep into the air of homes and commercial buildings from subsurface groundwater and soils through a process called vapor intrusion (see EPA 2012l, 2012n for detailed information regarding soil vapor intrusion). Soil vapor, or the air found between soil particles, can

## Figure 6-1. Frequency of NPL Sites with Tetrachloroethylene Contamination



Source: ATSDR 2017a

become contaminated and migrate up through the soil to the buildings through cracks or perforations in the foundation of the building and in some cases, basement floors or walls. This migration occurs because of pressure differences inside and below the building (NYSDH 2006) and diffusion (EPA 2012m). Because of its pervasiveness and ability to persist under certain conditions, the potential for human exposure may be substantial.

The primary routes of exposure to tetrachloroethylene for most members of the general population are inhalation of the compound in the indoor and outdoor (ambient) air and ingestion of contaminated drinking water. Ingestion from food containing tetrachloroethylene is another potential exposure route for the general population. Persons working in certain occupations such as dry cleaning businesses or metal degreasing operations are potentially exposed to much greater levels of tetrachloroethylene due to the high levels of this substance in indoor air of these facilities.

## 6.2 RELEASES TO THE ENVIRONMENT

The TRI is an annual compilation of information on the release of toxic chemicals by manufacturing and processing facilities. TRI data should be used with caution because only certain types of facilities are required to report (EPA 2005). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the TRI only if they employ 10 or more full-time employees; if their facility is included in Standard Industrial Classification (SIC) Codes 10 (except 1011, 1081, and 1094), 12 (except 1241), 20–39, 4911 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4931 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4939 (limited to facilities that combust coal and/or oil for the purpose of generating electricity for distribution in commerce), 4953 (limited to facilities regulated under RCRA Subtitle C, 42 U.S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited S.C. section 6921 et seq.), 5169, 5171, and 7389 (limited to facilities primarily engaged in solvents recovery services on a contract or fee basis); and if their facility produces, imports, or processes ≥25,000 pounds of any TRI chemical or otherwise uses >10,000 pounds of a TRI chemical in a calendar year (EPA 2005).

### 6.2.1 Air

Estimated releases of 667,902 pounds (~303 metric tons) of tetrachloroethylene to the atmosphere from 216 domestic manufacturing and processing facilities in 2016, accounted for about 75% of the estimated total environmental releases from facilities required to report to the TRI (TRI16 2018). These releases are summarized in Table 6-1.

Likewise, EPA’s National Emission Inventory (NEI) database contains data regarding sources that emit criteria air pollutants and their precursors, and HAPs for the 50 United States, Washington DC, Puerto Rico, and the U.S. Virgin Islands (prior to 1999, criteria pollutant emission estimates were maintained in the National Emission Trends [NET] database and HAP emission estimates were maintained in the National Toxics Inventory [NTI] database). The NEI database derives emission data from multiple sources, including state and local environmental agencies; the TRI database; computer models for on- and off-road emissions; and databases related to EPA's Maximum Achievable Control Technology (MACT) programs to reduce emissions of HAPs. Data downloaded from the 2008 and 2011 NEI indicated that the total emissions of tetrachloroethylene were approximately 5,318 and 11,138 metric tons, respectively, with the biggest source arising from its use as a dry cleaning solvent (EPA 2013b, 2015b). These data are summarized in Table 6-2.

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 byproduct (Weant and McCormick 1984). Tetrachloroethylene emissions to the atmosphere may occur at sites used in disposing the chemical (EPA 2013b, 2015b; TRI16 2018), including incineration facilities for municipal and hazardous waste (Oppelt 1987). Tetrachloroethylene is also speculated to be released to the atmosphere from the ocean where it is produced by some macroalgae (Abrahamsson et al. 1995).

Tetrachloroethylene partitions primarily to the atmosphere when released into the environment (NICNAS 2001). The highest levels of tetrachloroethylene emissions from the dry cleaning industry are from uncontrolled, or fugitive, emissions (OSHA 2005). In addition, due to its volatility, tetrachloroethylene lost from contaminated soil can escape to the atmosphere (LHWMP 2013).

## Table 6-1. Releases to the Environment from Facilities that Produce, Process, or Use Tetrachloroethylene[a]

| | | Reported amounts released in pounds per year[b] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Total release | | |
| State[c] | RF[d] | Air[e] | Water[f] | UI[g] | Land[h] | Other[i] | On-site[j] | Off-site[k] | On- and off-site |
| AL | 3 | 16,268 | 0 | 0 | 0 | 0 | 16,268 | 0 | 16,268 |
| AR | 4 | 14,328 | 0 | 0 | 1 | 38 | 14,328 | 39 | 14,367 |
| CA | 17 | 72,057 | 3 | 0 | 1 | 5,939 | 72,060 | 5,940 | 78,000 |
| CO | 1 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 2 |
| CT | 1 | 35 | 0 | 0 | 0 | 0 | 35 | 0 | 35 |
| DE | 1 | 4 | 0 | 0 | 0 | 0 | 4 | 0 | 4 |
| GA | 3 | 27,493 | 0 | 0 | 8,297 | 4,977 | 27,493 | 13,274 | 40,767 |
| IL | 11 | 17,162 | 3 | 0 | 2 | 0 | 17,165 | 2 | 17,167 |
| IN | 12 | 63,713 | 0 | 0 | 27 | 0 | 63,713 | 27 | 63,740 |
| KS | 10 | 164,797 | 2 | 3 | 62,779 | 91,251 | 164,802 | 154,030 | 318,833 |
| KY | 5 | 5,555 | 0 | 0 | 0 | 0 | 5,555 | 0 | 5,555 |
| LA | 27 | 93,369 | 178 | 0 | 253 | 1 | 93,547 | 253 | 93,800 |
| MA | 4 | 21,027 | 0 | 0 | 0 | 4,869 | 21,027 | 4,869 | 25,896 |
| MI | 4 | 17,440 | 23 | 0 | 1,874 | 0 | 19,333 | 4 | 19,337 |
| MN | 3 | 2,668 | 9 | 0 | 79 | 0 | 2,677 | 79 | 2,756 |
| MO | 6 | 13,570 | 0 | 0 | 0 | 115 | 13,570 | 115 | 13,685 |
| MS | 2 | 525 | 0 | 0 | 60 | 0 | 525 | 60 | 585 |
| MT | 2 | 833 | 0 | 0 | 1 | 0 | 833 | 1 | 834 |
| NC | 1 | 152 | 0 | 0 | 510 | 0 | 152 | 510 | 662 |
| NE | 1 | 1 | 0 | 0 | 14,741 | 0 | 14,742 | 0 | 14,742 |
| NJ | 2 | 155 | 0 | 0 | 0 | 0 | 155 | 0 | 155 |
| NV | 1 | 5,795 | 57 | 0 | 0 | 1 | 5,852 | 1 | 5,853 |
| NY | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OH | 10 | 32,256 | 0 | 0 | 0 | 2,515 | 32,256 | 2,515 | 34,771 |
| OK | 7 | 7,180 | 5 | 0 | 0 | 1,310 | 7,185 | 1,310 | 8,495 |
| OR | 2 | 11,324 | 0 | 0 | 30,425 | 0 | 41,749 | 0 | 41,749 |
| PA | 11 | 14,210 | 0 | 0 | 4 | 0 | 14,210 | 4 | 14,214 |
| RI | 2 | 98 | 0 | 0 | 0 | 0 | 98 | 0 | 98 |
| SC | 2 | 506 | 0 | 14 | 0 | 0 | 506 | 14 | 520 |
| TN | 1 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 7 |
| TX | 41 | 59,782 | 174 | 38 | 118 | 143 | 59,986 | 269 | 60,256 |

## Table 6-1. Releases to the Environment from Facilities that Produce, Process, or Use Tetrachloroethylene[a]

| | | Reported amounts released in pounds per year[b] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Total release | | |
| State[c] | RF[d] | Air[e] | Water[f] | UI[g] | Land[h] | Other[i] | On-site[j] | Off-site[k] | On- and off-site |
| UT | 3 | 187 | 4 | 0 | 10 | 0 | 191 | 10 | 201 |
| WA | 4 | 152 | 0 | 0 | 0 | 0 | 152 | 0 | 152 |
| WI | 6 | 5,251 | 0 | 0 | 0 | 0 | 5,251 | 0 | 5,251 |
| Total | 216 | 667,902 | 457 | 55 | 119,181 | 111,159 | 715,428 | 183,327 | 898,755 |

[a] The TRI data should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list. Data are rounded to nearest whole number.

[b] Data in TRI are maximum amounts released by each facility.

[c] Post office state abbreviations are used.

[d] Number of reporting facilities.

[e] The sum of fugitive and point source releases are included in releases to air by a given facility.

[f] Surface water discharges, waste water treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).

[g] Class I wells, Class II-V wells, and underground injection.

[h] Resource Conservation and Recovery Act (RCRA) subtitle C landfills; other onsite landfills, land treatment, surface impoundments, other land disposal, other landfills.

[i] Storage only, solidification/stabilization (metals only), other off-site management, transfers to waste broker for disposal, unknown

[j] The sum of all releases of the chemical to air, land, water, and underground injection wells.

[k] Total amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

Source: TRI16 2018

## Table 6-2. Emissions of Tetrachloroethylene

| Emission sector | 2008 Emissions (pounds) | 2011 Emissions (pounds) |
|---|---:|---:|
| Bulk gasoline terminals | 3,394.73 | 5,133.80 |
| Commercial cooking | 0 | 0 |
| Dust; construction dust | 56.05 | 57.32 |
| Fuel comb; commercial/institutional, biomass | 1,132.58 | 391.15 |
| Fuel comb; commercial/institutional, coal | 36.20 | 90.51 |
| Fuel comb; commercial/institutional, natural gas | 10,681.70 | 1,163.69 |
| Fuel comb; commercial/institutional, oil | 301.86 | 0.00 |
| Fuel comb; commercial/institutional, other | 599.15 | 703.84 |
| Fuel comb; electric generation, biomass | 2,691.08 | 3,265.24 |
| Fuel comb; electric generation, coal | 41,672.06 | 38,388.57 |
| Fuel comb; electric generation, natural gas | 545.02 | 411.79 |
| Fuel comb; electric generation, oil | 71.07 | 441.67 |
| Fuel comb; electric generation, other | 2,646.36 | 2,783.53 |
| Fuel comb; industrial boilers, ICEs, biomass | 15,337.23 | 17,890.94 |
| Fuel comb; industrial boilers, ICEs, coal | 1,386.21 | 1,231.64 |
| Fuel comb; industrial boilers, ICEs, natural gas | 2,377.53 | 3,121.94 |
| Fuel comb; industrial boilers, ICEs, oil | 16,159.03 | 394.50 |
| Fuel comb; industrial boilers, ICEs, other | 827.79 | 277.74 |
| Fuel comb; residential, natural gas | 0 | 0.00 |
| Fuel comb; residential, oil | 0 | 0.00 |
| Fuel comb; residential, other | 12.26 | 12.28 |
| Gas stations | 49.97 | 382.00 |
| Industrial processes; cement manufacturing | 46.34 | 372.56 |
| Industrial processes; chemical manufacturing | 70,789.19 | 76,094.10 |
| Industrial processes; ferrous metals | 5.60 | 867.08 |
| Industrial processes; mining | 0.54 | 1.36 |
| Industrial processes; NEC | 144,943.85 | 225,610.97 |
| Industrial processes; non-ferrous metals | 87,002.84 | 5,066.34 |
| Industrial processes; oil and gas production | 1,140.31 | 1,140.72 |
| Industrial processes; petroleum refineries | 24,768.85 | 25,371.75 |
| Industrial processes; pulp and paper | 126,152.51 | 103,874.15 |
| Industrial processes; storage and transfer | 80,568.03 | 34,716.74 |
| Miscellaneous non-industrial NEC | 0 | 0 |
| Mobile; non-road equipment, diesel | 1,100.80 | 0 |
| Solvent; consumer and commercial solvent use | 911,059.81 | 3,304,916.12 |
| Solvent; degreasing | 1,236,680.40 | 536,881.74 |
| Solvent; dry cleaning | 7,471,498.64 | 18,871,297.86 |
| Solvent; graphic arts | 4,792.01 | 12,967.57 |
| Solvent; industrial surface coating and solvent use | 820,254.87 | 794,163.91 |

## Table 6-2. Emissions of Tetrachloroethylene

| Emission sector | 2008 Emissions (pounds) | 2011 Emissions (pounds) |
|---|---:|---:|
| Solvent; non-industrial surface coating | 162,519.17 | 48,449.24 |
| Waste disposal | 477,429.76 | 43,0127.85 |

ICE = internal combustion engine; NEC = not elsewhere classified

Sources: EPA 2013b, 2015b.

Vapor-phase tetrachloroethylene can migrate into the air of homes and buildings from below a contaminated site. For example, tetrachloroethylene was in an aquifer beneath a Colorado building because the chemical was stored improperly and leached into the soil to the water below. The vapors from the contaminated groundwater and/or soils were found to migrate through the vadose zone, and then into homes and buildings (ATSDR 2006a).

The concept of vapor intrusion was introduced in the late 1990s. It was previously thought that contaminated water was a threat only when the groundwater was used as drinking water. In 1979, 4,100 gallons of 1,1,1-trichloroethlyene were spilled in the Village of Endicott, New York. Tetrachloroethylene was one of the many chemicals found in the groundwater analysis after the spill; however, the compound was not present because of the spill, but rather from previous spills and releases. In 2000–2001, it was discovered that residents in the Village of Endicott, New York, were exposed to 0.1–24 μg/m$^3$ of tetrachloroethylene in the indoor air (Forand et al. 2012). McDonald and Wertz (2007) proposed that such high concentrations of tetrachloroethylene were primarily due to background sources of tetrachloroethylene rather than vapor intrusion processes.

Spatial locations and temporal changes are important factors when assessing sites contaminated with tetrachloroethylene. Spatial and temporal variability can lead to variations in the vapor intrusion process. In other words, it may be difficult to assess the impact of tetrachloroethylene above ground because factors such as the season of year, time of month, space between homes, etc. may alter the concentrations below ground. In some cases, the presence of contamination below ground does not always lead to contaminated vapors above ground (Folkes et al. 2009). Tetrachloroethylene has been detected in several sites as indicated in the EPA’s Vapor Intrusion Database (EPA 2012l). The spatiotemporal variability of tetrachloroethylene levels in residential indoor air due to vapor intrusion was investigated in a community located in San Antonio, Texas that was built atop a shallow plume of contaminated groundwater (Johnston and Gibson 2013, 2014). It was determined that while the indoor air levels of the 20 residences studied were below risk-based screening levels, tetrachloroethylene concentrations increased with the magnitude of the barometric pressure drop and humidity, while levels decreased as wind speed increased, during the winter months, and in homes without air conditioners.

Pennell et al. (2013) found that there were higher levels of tetrachloroethylene on the first floor of homes, with lower levels of tetrachloroethylene in the basement of homes at a research site in Boston. These higher levels on the first floor were accompanied by sewer gas smells. The authors reported that tetrachloroethylene can be present in sewer gas from bathroom plumbing that, in turn, can contaminate indoor air as well.

### 6.2.2 Water

Estimated releases of 457 pounds (~0.2 metric tons) of tetrachloroethylene to surface water from 216 domestic manufacturing and processing facilities in 2016, accounted for <1% of the estimated total environmental releases from facilities required to report to the TRI (TRI16 2018). These releases are summarized in Table 6-1.

A variety of industries that use tetrachloroethylene (such as metal degreasing and dry cleaning) generate aqueous wastes containing the compound and this subsequently ends up at waste treatment facilities (Weant and McCormick 1984). Aeration processes at waste treatment facilities strip much of the tetrachloroethylene from the water and release it into the atmosphere as a result of the high volatility of this chemical (Lurker et al. 1982). Exchange rates of tetrachloroethylene from water to air were measured by means of the Reynolds number. Tetrachloroethylene had exchange rates of 3.13–82.0 as a function of the VOCs in the water and oxygen in the atmosphere (DeWulf et al. 1998).

Tetrachloroethylene has also been detected in groundwater due to inappropriate disposal and release from dry cleaning facilities or from landfills in Canada and the United States. Tetrachloroethylene has been detected in most drinking water, groundwater, surface water, and rainwater supplies. Tap water may be an important source of exposure to tetrachloroethylene when levels of the compound are >10 ppb in the water supply (CEPA 2001). Three percent of the water supply systems that use well water contain ≥0.5 µg/L (≥0.5 ppb) tetrachloroethylene (WHO 2003). One of the primary causes of contamination was found to be due to solvent degreasing activities. Tetrachloroethylene volatilizes readily into the atmosphere due to the high volatility of the compound; however, it can also persist in the groundwater for decades (CDPHE 2002). Concentrations of tetrachloroethylene in the groundwater are not expected to be at levels that heavily impact aquatic life (NICNAS 2001).

In addition to industrial releases, tetrachloroethylene can be released into drinking water by leaching from liners in pipes, as in the case of contaminated water in New England. The liners were installed to asbestos cement pipes to take away a foul taste in the water (Larson et al. 1983). They were comprised of vinyl plastic and tetrachloroethylene. The manufacturers expected tetrachloroethylene to volatilize from the pipe after they administered the compound; however, it stayed in the coating and was found to progressively leach into the drinking water (Aschengrau et al. 2003). Tetrachloroethylene was present at concentrations ranging from 1.5 to 7,750 μg/L in Cape Cod, Massachusetts, and was reduced to 40 μg/L after bleeding and flushing the pipes (Aschengrau et al. 2012).

### 6.2.3 Soil

Estimated releases of 119,181 pounds (~54 metric tons) of tetrachloroethylene to soils from 216 domestic manufacturing and processing facilities in 2016, accounted for about 13% of the estimated total environmental releases from facilities required to report to the TRI (TRI16 2018). An additional 55 pounds (~0.03 metric tons) were released via underground injection (TRI16 2018). These releases are summarized in Table 6-1.

Many of the processes in which tetrachloroethylene is used as a solvent involve recycling the compound by various methods (EPA 1991). 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 (NICNAS 2001; Schultz and Kjeldsen 1986). Leaking of tetrachloroethylene from underground storage tanks can also result in the contamination of soil. When released to the soil, tetrachloroethylene may be evaporated into the atmosphere or leach into the groundwater (Newcombe 2000). Tetrachloroethylene can enter the subsurface groundwater as a DNAPL, migrate to the surface waters, and intrude into homes and buildings (ITRC 2003).

## 6.3 ENVIRONMENTAL FATE

### 6.3.1 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 6.4.1).

Tetrachloroethylene has been detected in a number of rainwater samples collected in the United States and elsewhere (see Section 6.4.2). However, the relatively low water solubility of tetrachloroethylene suggests that wet deposition occurs very slowly compared to other volatile chlorinated hydrocarbons. For example, concentrations of the more water-soluble 1,1,1-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. 1989). 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. 1989). 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 that 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. 1989). 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 m deep, flowing 1 m/second with a wind velocity of 3 m/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. 1989). Volatilization rates from soil, like water, appear to be related to surface-to-volume ratio (Zytner et al. 1989). 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. 1989). 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 10- and 100-fold slower than from water, depending on soil type, which directly affects the amount of sorption (Park et al. 1988; Zytner et al. 1989).

Sorption of chlorinated solvents is expected to be a function of the organic carbon content in sediments and soils. Experimentally measured soil sorption coefficients based on the organic carbon content ($K_{oc}$) ranged from 646 to 6,026. The values were collected from three Danish contaminated clayey till sites. Each site had differing clay contents ranging from 23.0 to 27.0% clay (Lu et al. 2011). These values are indicative of low soil mobility, although this may partially be explained by the clay content of the soil. Older experimental measured $K_{oc}$ values for tetrachloroethylene ranged from 177 to 534 (Seip et al. 1986). 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).

In addition, mobility of tetrachloroethylene in the soil, as well as aqueous solubility, is also enhanced with the presence of humic substances in the surface water or waste water. Effluent concentrations of tetrachloroethylene were found to be much higher with the addition of humic acid in the feed solution. This change in concentration was dependent on the particular chemical, the carbon content, and the presence of humic acid (Diamadopoulos et al. 1998).

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 that 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).

Similarly, exposure pathways, or models, have been developed that help to explain the transport of chemicals, including tetrachloroethylene, into homes through vapor intrusion. Johnson and Ettinger (1991) developed a heuristic model that utilizes equations and several assumptions to estimate the vapor intrusion rate of contaminants. Abreu and Johnson (2005) developed a three-dimensional model that takes into account the relationships between vapor source, building structure, and indoor air impacts. Similarly, Pennell et al. (2009) established a three-dimensional model that also implements advective and diffusive transport. The model was applied to five different scenarios that took into account unique factors such as the building structure, location, and size.

Remediation efforts have been undertaken to facilitate the removal of sorbed and deposited chemicals in the environment (Pennell et al. 1994). Tetrachloroethylene, however, can be difficult to remediate, and remediation efforts, while aggressive, do not always result in complete restoration. Workshops have been devoted to efforts of understanding remediation efforts in soils contaminated by chlorinated solvents (Stroo et al. 2012).

Soil remediation is usually characterized as either *ex-situ* (out of ground) or *in-situ* (in the ground). *Ex-situ* soil remediation is the more cost-effective technique; it usually involves the moving of the contaminated material to another site for disposal (CDPHE 2006). *In-situ* soil remediation of DNAPLs involves a variety of techniques. One of the more common techniques of *in-situ* soil remediation is soil vapor extraction that includes the formation of wells. The wells are used to bring up vapors trapped in the subsurface soils by applying negative pressure to the vadose zone (CDPHE 2006). Remediation efforts were undertaken in Saga, Japan, where tetrachloroethylene-contaminated sites were cleaned up by soil vapor extraction. Contamination of the site was likely due to tetrachloroethylene being trapped in a surface clay sand layer (vadose zone), gradually diffused into the soil vapor, and dissolved into rainfall and subsequently into groundwater (Chia and Miura 2004).

Mobilization of tetrachloroethylene with mixtures of sodium sulfosuccinate (a surfactant) was shown to be the best method for removing residual tetrachloroethylene from Ottawa sand (Pennell et al. 1994). Contaminants in the soil can also undergo remediation by *in-situ* thermal treatment (ISTT); however, this technique is the most costly and often does not eliminate all of the compound. *In-situ* chemical oxidation (ISCO) involves the reaction of oxidation products (hydrogen peroxide, potassium permanganate, etc.) with the contaminant to produce less harmful byproducts; however, this technique is also costly and there have been issues with concentrations of the compounds rebounding after treatment. *In-situ* bioremediation (ISB) facilitates reductive dechlorination by adding electron donors to the soil (Stroo et al.

2012). Reductive dechlorination in tetrachloroethylene involves the reduction of tetrachloroethylene to ethene by removal of the chlorine atoms (CDPHE 2006). Stroo et al. (2012) lists chemical reduction as a natural process that involves degradation of the contaminant.

A considerable number of monitoring studies have detected tetrachloroethylene in groundwater (see Section 6.4.2), 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).

Groundwater remediation techniques range from traditional to innovative. Traditional methods include the use of a groundwater pump-and-treat method and are usually less cost effective. Innovative methods include *in-situ* remediation (enhanced bioremediation, direct chemical oxidation, air sparging, aquifer flushing, and thermal treatment). The innovative techniques usually are cost effective; however, there are problems when attempting to treat the specific contaminated area with the treatment chemical (CDPHE 2006).

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 BCF of 49 for bluegill sunfish. Somewhat lower BCFs were determined by Saisho et al. (1994) for blue mussel (25.7) and killifish (13.4). Measured BCFs in Norway spruces were 64.4–85.3 (Polder et al. 1998). These measured BCF values indicate that bioconcentration of tetrachloroethylene in aquatic organisms is low.

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 up to 11 ppb (wet weight) in other tissues were found in various species of fish collected off the coast of Great Britain near several organochlorine plants

(Pearson and McConnell 1975). 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 <100-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 6.4.4), 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. Exposure of plants to a contaminant can occur from the roots via the soil or the aboveground plants via the vapors and aerosols in the air. Since plants contribute to human and animal diets, the contaminant levels may contribute significantly to the total daily intake in humans (Polder et al. 1998).

## 6.3.2 Transformation and Degradation

### 6.3.2.1 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 ($1.67\text{x}10^{-13}$ $\text{cm}^3$/molecule-second) and a typical atmospheric hydroxyl (OH) radical concentration of $5\text{x}10^5$ molecules/$\text{cm}^3$ (Atkinson 1985), the half-life is calculated at about 96 days. Class and Ballschmiter (1986) estimated a half-life of approximately 70 days. An atmospheric lifetime of 119–251 days was calculated by Cupitt (1987), assuming removal predominantly by reaction with hydroxyl radicals and using a range of temperatures, rates, and hydroxyl radical 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 first-order kinetics and may be substantially longer.

The reaction of volatile chlorinated hydrocarbons with hydroxyl 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). 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 1996). Therefore, tetrachloroethylene has been added to the list of compounds excluded from the definition of VOCs for purposes of preparing state implementation plans to attain the national ambient air quality standards for ozone.

#### 6.3.2.2 Water

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 $9.9 \times 10^8$ years, which suggests that hydrolysis does not occur under normal environmental conditions. In contrast, estimates of the hydrolysis half-life of tetrachloroethylene using different methodologies 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.

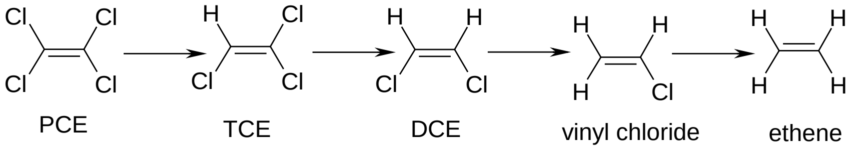
Most tetrachloroethylene present in surface waters can be expected to volatilize into the atmosphere. However, tetrachloroethylene is a DNAPL and as such, is denser than water and only slightly soluble in water. The tetrachloroethylene that is not immediately volatilized may be expected to sink and be 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 and remediation efforts difficult.

Various aerobic 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). Newer studies indicate that aerobic degradation of tetrachloroethylene is possible with the white rot fungus, *Trametes versicolor*. The degradation product, trichloroacetic acid, is formed by cytochrome P-450-mediated oxidation of tetrachloroethylene (Marco-Urrea et al. 2006).

Anaerobic screening studies have noted more rapid biodegradation, with the presence of microbes that are adapted to tetrachloroethylene (Parsons et al. 1984, 1985; Tabak et al. 1981). Biotransformation is the primary factor in the anaerobic degradation of tetrachloroethylene from soil and groundwater pollution.

Anaerobic biodegradation is possible by reductive dechlorination, with the degradation products of tetrachloroethylene being trichloroethylene, cis/trans-dichloroethylene, vinyl chloride, and ethane (see below). Tetrachloroethylene is dehalogenated to trichloroethylene (TCE), trichloroethylene to cis/trans-dichloroethylene (DCE), dichloroethylene to vinyl chloride, and eventually vinyl chloride to ethene. While complete degradation to ethene is possible, traces of vinyl chloride usually remain because of the rate-limiting step from vinyl chloride to ethene.



An anaerobic enrichment culture that degraded 99% of large concentrations of tetrachloroethylene to ethene in the absence of methanogenesis was discovered in 1991 (DiStefano et al. 1991). Tetrachloroethylene was also found to be converted to ethene by a culture containing *Dehalococcoides*. The culture was obtained from a chlorinated ethene anaerobic contaminated aquifer in Bitterfield, Germany. It was found that the microorganisms use tetrachloroethylene and other chlorinated ethenes as electron acceptors with lactate as the electron donor. The reductive dechlorination process also allows for the growth and energy conservation of the microorganisms (Cichocka et al. 2010).

New bacteria are also being discovered from contaminated sites. Tetrachloroethylene is transformed via trichloroethylene to cis-1,2-dichloroethene at high rates with the presence of the aerobic strain MS-1 (Sharma and McCarty 1996). In addition, new and emerging tests, such as isotope fractionation, have proven to be useful in the analysis of the dechlorination of tetrachloroethylene to ethene in contaminated aquifers. With isotope fractionation, a shift in the compound-specific isotope ratios indicates that biodegradation has occurred. The origin or source of the contaminant can also be identified from this shift (Hunkeler et al. 1999).

### 6.3.2.3 Sediment and Soil

Biodegradation of tetrachloroethylene in soil was thought 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. 1983). However, recent studies have indicated that tetrachloroethylene is able to be degraded under both aerobic and anaerobic conditions.

Tetrachloroethylene was aerobically degraded by *Pseudomonas stutzeri* OX1 with the expression of toluene-o-xylene monoxygenase (Ryoo et al. 2000). Anaerobically, tetrachloroethylene is metabolized by microorganisms through a reductive dechlorination process to trichloroethylene, dichloroethylene, and vinyl chloride, with the major intermediate being trichloroethylene (Vogel and McCarty 1985). In one study, anaerobic enrichment cultures, which support methanogenesis, were found to be capable of dechlorinating tetrachloroethylene to ethylene in the presence of an electron donor (Freedman and Gossett 1989). Recent studies have also indicated that the complete anaerobic degradation of tetrachloroethylene can occur with mixed cultures and sediments (Krumholz et al. 1996).

Cabirol et al. (1996) found that a methanogenic and sulfate-reducing mixed culture from the anaerobic sludge of a waste water treatment plant has the potential to dechlorinate tetrachloroethylene through reductive dechlorination. Tetrachloroethylene was found to have completely disappeared within 37 days and as it disappeared, trichloroethylene was formed. Cabirol et al. (1998) also found that tetrachloroethylene was completely degraded with the same cultures in a fixed bed reactor. In addition, anaerobic biodegradation of very high concentrations of tetrachloroethylene (600 μM) occurred in a continuous flow system in a period of <21 months. Very high concentrations of tetrachloroethylene were completely degraded to vinyl chloride in the 21 months, and vinyl chloride was observed to be degraded to ethene over a longer period of time (Isalou et al. 1998).

Tetrachloroethylene was 94% anaerobically degraded using a mixed enriched culture. Culture enrichment was performed on a sample contaminated with tetrachloroethylene and other halogenated aliphatic compounds obtained from ditch sludge mixed with sewage (Chang et al. 1998). Tetrachloroethylene was also completely degraded to the intermediate, 1,2-dichlroethene, in 13 days, and subsequently to ethene after 130 days, with a mixed anaerobic culture AMEC-4P (Kim et al. 2010).

In addition, new isolates that degrade tetrachloroethylene are being discovered, such as the strain *Propionibacterium sp.* HK-1, which was able to degrade tetrachloroethylene by 20% (Chang et al. 2011).

## 6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to tetrachloroethylene depends in part on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of tetrachloroethylene in unpolluted atmospheres and in pristine surface waters are often so low as to be near the limits of current analytical methods. In reviewing data on tetrachloroethylene levels monitored or estimated in the environment, please note that the amount of chemical identified analytically is not necessarily equivalent to the amount that is bioavailable. The analytical methods available for monitoring tetrachloroethylene in a variety of environmental media are detailed in Chapter 7.

### 6.4.1 Air

Outdoor (ambient) air monitoring studies in the United States have shown tetrachloroethylene concentrations of 400–2,100 ng/m$^3$ (0.059–0.31 ppb) in Portland, Oregon, in 1984 (Ligocki et al. 1985), 5.2 μg/m$^3$ (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 in 1980–1981 (Singh et al. 1982). A Total Exposure Assessment Methodology (TEAM) study of three industrialized areas 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 6.3.2.1).

Tetrachloroethylene was detected at levels ranging from 32 to 75 ng/m$^3$ (0.0047–0.011 ppb) at five locations in the Antarctic (Zoccolillo et al. 2009). It was also found that there were elevated levels of tetrachloroethylene and other volatile chlorinated hydrocarbons in the winter in Niigata, Japan between April 1989 and March 1992 (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.

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).

The Air Quality System (AQS) database is EPA's repository of criteria air pollutant and HAPs monitoring data from the United States, Puerto Rico, and the Virgin Islands. Detailed air monitoring data for tetrachloroethylene and other HAPs may be obtained from the AQS website. Table 6-3 summarizes the range of tetrachloroethylene levels at various locations in the United States for 2006 (EPA 2013h). In general, the average concentration of tetrachloroethylene in outdoor air is <1 μg/m$^3$ (0.15 ppb) for the majority of the U.S. locations sampled; however, several 24-hour average values exceeded 1 μg/m$^3$ for this time period, suggesting that levels can be highly variable. McCarthy et al. (2007) analyzed data from the AQS over three trend periods (1990–2005, 1995–2005, and 2000–2005) and reported that tetrachloroethylene levels decreased over time at most sites during these trend periods at a rate of about 6–8% per year. The median concentration in 1990, 1995, and 2000 were 1.2 μg/m$^3$ (0.18 ppb), 0.7 μg/m$^3$ (0.10 ppb) and 0.6 μg/m$^3$ (0.088 ppb), respectively. More recent data regarding the levels of tetrachloroethylene from the AQS is presented in Table 6-4, which illustrates the annual mean percentile distributions of tetrachloroethylene for years 2010–2018 (EPA 2018). As indicated in Table 6-4, tetrachloroethylene levels in ambient air have continued to decline nationally over these years.

Tetrachloroethylene was detected in indoor and outdoor air at 0.15–3.5 and 0.01–1.3 μg/m$^3$, respectively, above a contaminated site in Colorado (ATSDR 2006a).

Measurement of 8-hour TWA exposures in the breathing zones of workers from 196 dry cleaning plants in Australia yielded mean and geometric mean exposure estimates of 10.3 and 4.7 ppm, respectively (NICNAS 2001). About 90% of the exposures were <25 ppm, and only 3% of exposures were >50 ppm.

In addition, in data reported by the Dow Company in the United States, the TWA exposures were 37, 9, and 5 ppm for first-, third-, and fourth-/fifth-generation dry cleaning machines, respectively. It was discovered that the emissions of tetrachloroethylene were less with the introduction of third- and fourth-/fifth-generation machines, which included an integrated carbon absorber and an interlocking system (to reduce venting) (NICNAS 2001).

## Table 6-3. Tetrachloroethylene Concentrations in Ambient Air for 2006

| Concentration (μg/m$^3$) | Concentration (ppb)[a] | Number of samples | State[b] |
|---|---|---|---|
| 0.050–0.64 | 0.0074–0.094 | 21–70 | CA |
| 0.34 | 0.050 | 61 | CO |
| 0.35 | 0.052 | 61 | DC |
| 0.09–0.44 | 0.013–0.065 | 58–59 | DE |
| 0.10–0.69 | 0.015–0.10 | 42–61 | FL |
| 0.10–0.45 | 0.015–0.066 | 19–61 | GA |
| 0.34 | 0.050 | 59 | HI |
| 0.24–0.48 | 0.035–0.071 | 21–26 | IA |
| 0.34–0.76 | 0.050–0.11 | 60–61 | IL |
| 0.17–0.19 | 0.025–0.028 | 41–61 | IN |
| 0.77–0.88 | 0.11–0.13 | 33–61 | KY |
| 0.19–0.22 | 0.028–0.032 | 51–52 | MA |
| 0.24–0.36 | 0.035–0.053 | 56–61 | MD |
| 0.26–1.10 | 0.038–0.16 | 21–50 | MI |
| 0.09–6.65 | 0.013–0.98 | 41–58 | MN |
| 0.17 | 0.025 | 59 | MO |
| 0.14–0.18 | 0.021–0.026 | 59–66 | MS |
| 0.24–0.58 | 0.035–0.086 | 43–58 | NC |
| 0.17–0.23 | 0.025–0.034 | 26–31 | NH |
| 0.12–0.35 | 0.018–0.052 | 53–58 | NJ |
| 0.17–3.32 | 0.025–0.49 | 40–56 | NY |
| 0.20 | 0.029 | 41 | OK |
| 0.34 | 0.050 | 24–61 | OR |
| 0.17–0.39 | 0.025–0.058 | 37–61 | PA |
| 0.09–0.25 | 0.013–0.37 | 40–57 | PR |
| 0.15–0.32 | 0.022–0.047 | 53–61 | RI |
| 0.17 | 0.025 | 60 | SC |
| 0.07–0.08 | 0.010–0.011 | 59–61 | SD |
| 0.06–0.08 | 0.0088–0.011 | 44–45 | TN |
| 0.17–0.37 | 0.025–0.054 | 42–61 | TX |
| 0.17 | 0.025 | 59 | UT |
| 0.20–1.67 | 0.029–0.25 | 57–60 | VA |
| 0.34–0.37 | 0.050–0.054 | 23–54 | VT |
| 0.34 | 0.050 | 61 | WI |
| 0.13–0.39 | 0.019–0.058 | 43–51 | WV |

[a] Data originally reported in units of μg/m$^3$ and converted to ppb to facilitate comparison with other data.
[b] Post office abbreviations used.

Source: EPA 2013h

### Table 6-4. Percentile Distribution of Annual Mean Tetrachloroethylene Concentrations (ppb) Measured in Ambient Air at Locations Across the United States[a]

| Year | Number of U.S. locations | 25th | 50th | 75th | 95th | Maximum |
|---|---|---|---|---|---|---|
| 2010 | 304 | 0.0072 | 0.015 | 0.029 | 0.077 | 0.20 |
| 2011 | 292 | 0.0075 | 0.014 | 0.024 | 0.060 | 0.16 |
| 2012 | 287 | 0.0054 | 0.011 | 0.021 | 0.061 | 0.20 |
| 2013 | 264 | 0.0050 | 0.010 | 0.018 | 0.052 | 0.19 |
| 2014 | 245 | 0.0038 | 0.0085 | 0.018 | 0.043 | 0.29 |
| 2015 | 224 | 0.0046 | 0.011 | 0.021 | 0.055 | 0.59 |
| 2016 | 205 | 0.0038 | 0.011 | 0.022 | 0.065 | 0.28 |
| 2017 | 174 | 0.000 | 0.004 | 0.14 | 0.049 | 0.14 |
| 2018 | 155 | 0.000 | 0.003 | 0.011 | 0.054 | 0.45 |

[a] Data were originally reported in units of parts per billion carbon, but converted to parts per billion volume to facilitate comparison with other data.

Source: EPA 2018

In a study conducted by Roda et al. (2013), tetrachloroethylene was found in the indoor air of Paris homes. Air samples were collected using passive devices. Annual levels ranged from 0.6 to 124.2 μg/m$^3$ (0.09–18.3 ppb) in residential homes that were in close proximity to dry cleaning facilities and do-it-yourself activities (e.g., photographic development, “silverware”), had air vents, and were built prior to 1945.

In another locality in France, the highest measured concentration of tetrachloroethylene (678 μg/m$^3$; 100 ppb) was found in front of a dry cleaning shop in the indoor air of a shopping center. The highest mean concentrations in apartments and establishments directly above the dry cleaning facility ranged from 296 μg/m$^3$ (carbon absorber equipped machine) to 2.9 mg/m$^3$ (carbon absorber unequipped machine). The study was carried out with passive samplers (Chiappini et al. 2009).

In a study conducted in Hudson County, New Jersey, residents above cleaners that used exhaust fans were exposed to concentrations of 1.2 mg/m$^3$ of tetrachloroethylene, while residents above cleaners that did not use exhaust fans were exposed to 2.5 mg/m$^3$. Adherence to all of EPA regulations was also associated with decreased tetrachloroethylene levels above dry cleaning facilities. It was found that the mean 48-hour average concentration in residences above cleaners that adhered to EPA’s regulations was 0.57 mg/m$^3$, while the concentration was 2.1 mg/m$^3$ with cleaners that partially followed EPA’s regulations and 2.7 mg/m$^3$ with cleaners with no documentation of adherence to the rules (Garetano and Gochfield 2000). In an older study, elevated levels of tetrachloroethylene were also 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 a.m. to 7 p.m., and from 0.01 to 5.4 ppm when measured from 7 p.m. to 7 a.m. 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. An EPA final rule has called for the phase out of tetrachloroethylene use in dry cleaners above residential areas (EPA 2006).

Levin and Hodgson (2003) compiled information from 13 studies for existing residences, new residences, and office buildings and compared the central tendency concentrations among each residence or building. The central tendency concentrations were >3 times higher for the office building than for the existing residences. However, even with the prevalence of tetrachloroethylene in office buildings, the authors concluded that the average indoor concentrations of tetrachloroethylene have decreased since 1990.

Johnston and Gibson (2013, 2014) detected tetrachloroethylene in the indoor air of homes of individuals exposed to tetrachloroethylene through soil vapor intrusion. Maximum levels ranged from <0.13 to 1.50 μg/m$^3$ in the homes in San Antonio, Texas. Forand et al. (2012) reported that tetrachloroethylene levels ranged from 0.1 to 24 μg/m$^3$ in indoor air after residents in the Village of Endicott, New York were exposed to tetrachloroethylene through vapor soil intrusion. These levels are much higher than the average U.S. indoor residential air concentrations measured by the EPA. Burk and Zarus (2013) reported selected results from 135 vapor intrusion public health assessments and consultations for 121 sites published on ATSDR's website between 1994 and 2009. Tetrachloroethylene indoor air levels were attributed to vapor intrusion and detected at 39 sites; levels at 5 of these sites were high enough to be considered a public health hazard. In addition to vapor intrusion, tetrachloroethylene can also be present in the indoor air of homes from sewer gas emissions coming up through the bathroom plumbing (Pennell et al. 2013).

Tetrachloroethylene was present in 62.5% of background samples collected in North American residences between 1990 and 2005 (EPA 2011). In a study conducted by Sack et al. (1992), 63 out of 1,159 of household products contained tetrachloroethylene. The percentages of tetrachloroethylene in the household products were 10.8% in automotive products, 2.7% in household cleaners/polishes, 1.3% in paint-related products, 18.7% in fabric and leather treatments, 2.9% in cleaners for electronic equipment, 8.1% in oils, greases and lubricants, 5.3% in adhesive-related products, and 5.6% in miscellaneous products.

Building occupants can also be exposed to tetrachloroethylene in the indoor air through cleaning products and air fresheners. Ventilation, mixing within a room, mixing between rooms, homogenous and heterogeneous transformations, sorptive interactions on surfaces, and active air cleaning are factors that influence the distribution and behavior of tetrachloroethylene in indoor air (Nazaroff and Weschler 2004). Carpet also can also be a source of tetrachloroethylene in indoor air as it sorbs the compound in the fibers of the carpet (Won et al. 2000).

### 6.4.2 Water

Tetrachloroethylene was detected in 130 of 1,179 well samples in the drinking water from domestic wells in the United States (Rowe et al. 2007).

Williams et al. (2002) reported annual levels of tetrachloroethylene measured in 3,422–4,218 California drinking water sources between 1995 and 2001. Approximately 10–13% of the sampled drinking water sources contained detectable levels over this 7-year period. The average annual detected concentration of tetrachloroethylene ranged from 17.0 μg/L (2000) to 28.0 μg/L (1998).

Tetrachloroethylene and several other VOCs have been detected at high levels in drinking water at the Camp Lejeune, Marine Corps Base in North Carolina (ATSDR 1998, 2013). Tetrachloroethylene levels in tap water were shown to range from <1 to 215 μg/L (ppb), and groundwater levels as high as 170,000 μg/L (ppb) were observed in 1985. A recent historical reconstruction study of this site, which applied additional modeling methods, reported a maximum monthly average concentration of 183 ppb (Maslia et al. 2016). The MCL for tetrachloroethylene is 5 μg/L (ppb).

Tetrachloroethylene was monitored in a comprehensive survey conducted by the USGS of VOCs in private and public groundwater wells used for drinking water (USGS 2006). Tetrachloroethylene was identified in approximately 4% of 3,498 aquifer samples at a median concentration of 0.090 μg/L for the samples having positive detections. The percentage of samples exceeding the 5 μg/L MCL was 0.70% (USGS 2006). In an analysis of domestic groundwater wells, the median concentration of tetrachloroethylene was reported as 0.058 μg/L for samples having positive detections.

Tetrachloroethylene was detected in groundwater from 16 out of 30 wells located in Salt Lake Valley, Utah, at a maximum concentration of 7.8 μg/L (USGS 2003). Although the median concentration was <0.1 μg/L, water from four wells in the northwestern part of the valley had concentrations >1 μg/L.

In other countries, drinking water samples from Zagreb, Croatia, contained 0.36–7.80 μg/L (0.36–7.80 ppb) (Skender et al. 1993). Rainwater samples collected in Tokyo between October 1989 and September 1990 had a mean tetrachloroethylene level of 99 ng/L (99 ppt), with higher levels in samples obtained during the winter (Jung et al. 1992). The World Health Organization (WHO) guideline value in drinking water for tetrachloroethylene is 40 μg/L (WHO 2010).

The mean detected concentration of tetrachloroethylene in the drinking water of California was 3–6 times higher than the MCL of 5 μg/L from 1995 to 2000 (Williams et al. 2002). 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 percent contribution of tap water to total tetrachloroethylene exposure has been estimated to range from 2.9 to 10.7% in urban areas depending upon the assumed level of tetrachloroethylene in the water supply and from 4.3 to 14.9% for rural areas (CEPA 2001).

### 6.4.3 Sediment and Soil

Soil gas was assessed for contaminants at three former fuel-dispensing sites at Fort Gordon, Georgia, from October 2010 to September 2011. More than half of the 30 soil-gas samplers installed at one location had tetrachloroethylene mass greater than the minimum detection limit (MDL) of 0.02 μg.

The bottom sediments and interstitial water from Watson creek at Aberdeen Proving Ground, Maryland, were found to contain concentrations of tetrachloroethylene ranging from 310 to 550 μg/L. The concentrations in the bottom sediment were found to be similar to observed concentrations of tetrachloroethylene in wells near the shoreline. In addition, tetrachloroethylene in the sediment was found to be an indicator of groundwater contamination (Vroblesky et al. 1991).

### 6.4.4 Other Environmental Media

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 that 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 8).

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).

In older studies, tetrachloroethylene was detected in a variety of foods ranging from 1 to 230 ng/g (1–230 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).

In other studies, tetrachloroethylene has been detected in lettuce sap, mid-vein, and mesophyll samples grown on contaminated soils (Boekhold et al. 1989). Tetrachloroethylene has also been detected in fatty foods such as butter, cream, vegetable oil, margarine, sausage, and cheese in residences or food stores near dry cleaners (Schreiber et al. 1993).

In Switzerland, the highest concentration of tetrachloroethylene was in the milk and meat products at 3–3490 µg/kg. In Germany, in a dry cleaning shop and in an apartment above a dry cleaning shop, concentrations of tetrachloroethylene were highest in an ice-cream confection at 18,750 µg/kg and butter at 58,000 µg/kg. The total daily intakes for Switzerland and Germany were 160 and 87 µg/day, respectively (de Raat 2003).

Likewise, tetrachloroethylene can be present in breast milk. Pellizzaari et al. (1982) found that tetrachloroethylene was present as frequent as seven times in the eight samples analyzed from the mother’s milk in four urban areas. Bagnell and Ellenberger (1977) also observed tetrachloroethylene in a mother’s milk in a case study that resulted in the baby getting sick with obstructive jaundice and hepatomegaly.

## 6.5 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 the indoor and outdoor (ambient) air and ingestion of contaminated drinking water. Available data generally indicate that dermal exposure is not an important route for most people. General population exposure from inhalation of the indoor and outdoor (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 exposure was measured in the population of children from two inner-city schools in Minneapolis, Minnesota. Concentrations ranged from 0.1 to 1.3 $\mu g/m^3$ in four locations, including outdoors, outdoors at school, indoors at home, and personal VOC samples. It was found that the indoor air at home contained the highest levels of tetrachloroethylene, followed by the personal samples, outdoors, and indoors at school (Adgate et al. 2004).

Tetrachloroethylene in the ambient air was assessed in Tokyo with participants who were not directly exposed to tetrachloroethylene in their workplace. It was found that the mean level of tetrachloroethylene in the breathing air was $1.1\pm0.8$ $\mu g/m^3$ and the daily intake was calculated to be 23 µg/person (Nakahama et al. 1997).

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 that combined PBPK modeling with a single compartment model for a “typical” home (Thompson and Evans 1993) suggested 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.

The Fourth National Report on Human Exposure to Environmental Chemicals (CDC 2015) provides an ongoing assessment of the exposure of the U.S. population to environmental chemicals by the use of biomonitoring (CDC 2015). The geometric means and selected percentiles of whole blood concentrations of tetrachloroethylene organized by age, gender, and ethnicity of the U.S. population are provided in Table 6-5. Lin et al. (2008) studied the relationship between tetrachloroethylene levels detected in the blood and personal air samples of a subsample of the 2003–2004 and 1999–2000 NHANES survey. Blood levels were positively correlated with airborne tetrachloroethylene levels, while the smoking status (smoker versus nonsmoker) did not affect the relationship between personal air levels and blood levels of the subjects.

# Table 6-5. Geometric Mean and Selected Percentiles of Tetrachloroethylene Blood Concentrations (in ng/mL) for the U.S. Population from NHANES

| | Survey | Geometric mean | 50th percentile | 75th percentile | 90th percentile | 95th percentile | Sample size |
|---|---|---|---|---|---|---|---|
| Total | 2001–2002 | *[a] | <LOD | 0.50 | 0.100 | 0.190 | 978 |
| | 2003–2004 | * | <LOD | <LOD | 0.076 | 0.140 | 1,317 |
| | 2005–2006 | * | <LOD | <LOD | 0.070 | 0.126 | 2,940 |
| 12–19 years age | 2005–2006 | * | <LOD | <LOD | 0.049 | 0.79 | 865 |
| 20–59 years age | 2001–2002 | * | <LOD | 0.50 | 0.100 | 0.190 | 978 |
| 20–59 years age | 2003–2004 | * | <LOD | <LOD | 0.076 | 0.140 | 1,317 |
| 20–59 years age | 2005–2006 | * | <LOD | <LOD | 0.074 | 0.130 | 1,458 |
| ≥60 years of age | 2005–2006 | * | <LOD | <LOD | 0.071 | 0.113 | 617 |
| Males | 2001–2002 | * | <LOD | 0.50 | 0.110 | 0.210 | 457 |
| Males | 2003–2004 | * | <LOD | <LOD | 0.082 | 0.230 | 639 |
| Males | 2005–2006 | * | <LOD | <LOD | 0.085 | 0.230 | 1,404 |
| Females | 2001–2002 | * | <LOD | 0.50 | 0.100 | 0.150 | 521 |
| Females | 2003–2004 | * | <LOD | <LOD | 0.069 | 0.120 | 678 |
| Females | 2005–2006 | * | <LOD | <LOD | 0.056 | 0.090 | 1,536 |
| Mexican/American | 2001–2002 | * | <LOD | <LOD | 0.060 | 0.070 | 226 |
| Mexican/American | 2003–2004 | * | <LOD | <LOD | 0.049 | 0.100 | 248 |
| Mexican/American | 2005–2006 | * | <LOD | <LOD | 0.069 | 0.130 | 713 |
| Non-Hispanic blacks | 2001–2002 | * | <LOD | <LOD | 0.070 | 0.110 | 195 |
| Non-Hispanic blacks | 2003–2004 | * | <LOD | <LOD | 0.086 | 0.220 | 284 |
| Non-Hispanic blacks | 2005–2006 | * | <LOD | <LOD | 0.074 | 0.120 | 776 |
| Non-Hispanic whites | 2001–2002 | * | <LOD | 0.50 | 0.110 | 0.210 | 487 |
| Non-Hispanic whites | 2003–2004 | * | <LOD | <LOD | 0.072 | 0.140 | 686 |
| Non-Hispanic whites | 2005–2006 | * | <LOD | <LOD | 0.070 | 0.130 | 1,229 |

[a] The geometric mean was not calculated because the proportion of the results below LOD was too high to provide a valid result.

LOD = limit of detection; NHANES = National Health and Nutrition Examination Survey

Source: CDC 2015

Higher blood levels of tetrachloroethylene have been noted for urban and industrial residential settings when compared to rural settings. Residing near dry cleaning facilities or storing recently dry-cleaned clothes at home can contribute to increased blood tetrachloroethylene levels. In occupationally exposed workers, tetrachloroethylene blood levels have been reported to be many thousand times higher than in the unexposed general population.

Tetrachloroethylene has been measured in the blood and urine in a sample of the general population in Italy (Brugnone 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 rural (74% positive; average 119 ng/L) and urban populations (74% positive; average 90 ng/L). Tetrachloroethylene was also detected in urine samples of dry cleaning workers at concentrations of 1–19.9 µg/L (Rutkiewicz et al. 2011). In Zagreb, Croatia, tetrachloroethylene concentrations ranged from 210 to 7,800 ng/L in the drinking water and from <10 to 239 ng/L in blood (Skender et al. 1994).

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 slight 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 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 initial levels, 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 was thus 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 a TWA of 48.4 ppm, while 1,027 operators in plants with dry-to-dry units were exposed to a TWA of 16.9 ppm (Andrasik and Cloutet 1990). An in-depth series of studies of the dry cleaning industry was completed by NIOSH in 1997. 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 tetrachloroethylene were within the ACGIH-recommended threshold limit value of 25 ppm (ACGIH 2012). The primary exposure of the workers occurred during the loading and unloading of the dry cleaning machines.

A study was conducted on the exposure of workers in six commercial and three industrial dry cleaners. It was found that the operator's mean TWA exposures in the commercial dry cleaning shops and industrial cleaners were 4.1 and 4.6 ppm. Both the presser and the customer service personnel had significantly lower TWA exposures of 0.5 and 0.1 ppm, respectively. The results were again lower than the occupational limit values in the United States, with the outdoor tetrachloroethylene emissions below the limit values (Raisanen et al. 2001).

In a study conducted in Iran, concentrations of tetrachloroethylene uptake went from 6.58 µg/L before exposure to 18.04 µg/L after the end of the shift (post exposure) with an 8-kg dry cleaning machine. Likewise, concentrations increased from 14.17 to 36.77 µg/L with a 12-kg dry cleaning machine and from 21.95 to 63.55 µg/L with an 18-kg dry cleaning machine (Rastkarie et al. 2011).

Individuals are not exposed to the same magnitude of tetrachloroethylene as in the past. In a study conducted in Italy, the mean concentration of tetrachloroethylene in the air was 52.32 mg/m$^3$ with tetrachloroethylene concentrations in the blood end-shift at 0.617 mg/L (pre-shift: 0.304 mg/L) and in the urine at 0.0204 mg/L (pre-shift: 0.012). It was also found that the smaller shops that employed 1–3 people had the greatest exposure to tetrachloroethylene (Macca et al. 2012).

In addition, a biological exposure assessment was done with female workers in an Ohio dry cleaning facility. Four dry cleaning facilities and 18 women participated in the assessment. The dry cleaning machines were 30–60-pound drums and ranged from 9 to 12 years old. Personal breathing zone samples, as well as blood, urine, and post-shift exhaled breath samples, were collected for the women. It was found that post-shift exhaled breath tetrachloroethylene increased during the week from 0.94 ppm on Wednesday to 1.38 ppm on Thursday and to 1.63 ppm on Friday; however, the tetrachloroethylene in exhaled breath and urine decreased after 2 days without renewed exposure to tetrachloroethylene (McKernan et al. 2008).

Various consumer products have been found to contain tetrachloroethylene. These include printing ink, glues, sealants, polishes, lubricants, and silicones (ACGIH 1991). In addition, VOCs may be emitted from cleaners, air fresheners, scented candles, carpets, insulation, paint, etc. Tetrachloroethylene was detected in 64% of samples of indoor background air from 1990 in residences not affected by vapor intrusion (Dawson and McAlary 2009).

Showering or bathing with contaminated water can also result in tetrachloroethylene exposure. Rao and Brown (1993) described 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/L. The PBPK model is described further in Section 3.4.5. 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/minute. 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.

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 1.2–1.9 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.

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.

## 6.6 EXPOSURES OF CHILDREN

This section focuses on exposures from conception to maturity at 18 years in humans. Differences from adults in susceptibility to hazardous substances are discussed in Section 3.7, Children's Susceptibility.

Children are not small adults. A child's exposure may differ from an adult's exposure in many ways. Children drink more fluids, eat more food, breathe more air per kilogram of body weight, and have a larger skin surface in proportion to their body volume than adults. A child's diet often differs from that of adults. The developing human's source of nutrition changes with age: from placental nourishment to breast milk or formula to the diet of older children who eat more of certain types of foods than adults. A child's behavior and lifestyle also influence exposure. Children crawl on the floor, put things in their mouths, sometimes eat inappropriate things (such as dirt or paint chips), and may spend more time outdoors. Children also are generally closer to the ground and have not yet developed the adult capacity to judge and take actions to avoid hazards (NRC 1993).

In addition to breathing air or consuming contaminated water, infants can also be exposed to tetrachloroethylene in breast milk. 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 scenarios for the low concentrations were 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, exposure scenarios were 8 hours at 50 ppm and 16 hours at 0.004 ppm (residential background). Assuming that 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. 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 1-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 that 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.

## 6.7 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, evidence suggests that people living with workers in the dry cleaning industry may be subjected to higher exposures, even if their homes are far removed from the work site (Aggazzotti et al. 1994a); 30 such homes surveyed showed a range of indoor tetrachloroethylene levels of 34–3,000 μg/m$^3$ (5.0–442 ppb), which was significantly higher than that found in control homes (1–16 μg/m$^3$ or 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). Tetrachloroethylene levels in the exhaled air of dry cleaning workers ranged from 3.4 to 16.7 μg/L (3,400–16,700 μg/m$^3$), but was under the detection limits of 0.005 μg/L for a control group of non-occupationally exposed individuals (Ziener and Braunsdorf 2014). The greatest exposure occurred for two subjects involved in machine operating job functions.

Service members and their families stationed at the Camp Lejeune Marine Corps Base, North Carolina were exposed to high levels of tetrachloroethylene and other VOCs from bathing in and consuming contaminated water (ATSDR 2013).

Residents living in apartment buildings in New York City also housing dry cleaners were exposed to higher levels of tetrachloroethylene (indoor air level of 27.5 µg/m$^3$), as compared to residents living in buildings without a dry cleaner (2.3 µg/m$^3$) (Storm et al. 2013). When the residents were categorized by minority status, the mean level of tetrachloroethylene in the indoor air was 82.5 µg/m$^3$ in the minorities living in apartment buildings with dry cleaners, compared to 16.5 µg/m$^3$ in non-minority households living in the buildings with dry cleaners. No differences in indoor air levels were found between minority and non-minority residents living in buildings without dry cleaners. Mean indoor tetrachloroethylene air levels were also higher in low-income family homes in buildings with dry cleaners (105.5 µg/m$^3$) compared to high-income family homes in buildings with dry cleaners (17.8 µg/m$^3$). Likewise, mean blood tetrachloroethylene levels in residents living in apartment buildings with dry cleaners were 0.27 ng/mL in minority children and 0.46 ng/mL in minority adults, while mean blood levels were 0.12 ng/mL in non-minority children and 0.15 ng/mL in non-minority adults. The same trend was observed in low-income children and adults, where mean blood levels were 3 and 4 times higher than the levels of the high-income children and adults. The study shows that residents living in buildings with co-located dry cleaners in minority, low-income areas have higher exposures to tetrachloroethylene than residents living in buildings with co-located dry cleaners in non-minority, high-income areas (Storm et al. 2013).

Similarly, 37.1–62.6% of blood samples were above the detection limits for tetrachloroethylene in a School Health Imitative: Environment, Learning, Disease (SHIELD) study of children attending schools in minority neighborhoods in Minneapolis, Minnesota (Sexton et al. 2005). Exposure was due to multiple media including air, water, soil, dust, food, beverages, and consumer products. Blood levels ranged from 0.02 to 0.82 ng/mL and were generally ≥2 times lower than concentrations in nonsmoking and smoking adults from the NHANES III study.

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 six children living near a factory in the Netherlands had a mean concentration of 24 µg/m$^3$ (3.5 ppb) tetrachloroethylene in their breath, compared with 11 control children with a mean level of 2.8 µg/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 study conducted in New Jersey attempted to identify factors associated with risk of higher inhalation exposure of tetrachloroethylene (Wallace et al. 1986b). The following factors (in order of decreasing importance) were identified: employment (not otherwise specified), wood processing, visiting a dry cleaner, working at a textile plant, using pesticides, and working at or being in a paint store.

## 6.8 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 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.

### 6.8.1 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 2013; Lide 2008). Estimates of the distribution of tetrachloroethylene in the environment based on available constants (e.g., water solubility, log $K_{ow}$, log $K_{oc}$, vapor pressure) (HSDB 2013; Seip et al. 1986) are generally in good agreement with experimentally determined values. Carpet is a source of tetrachloroethylene in the indoor air (Won et al. 2000). Additional information on tetrachloroethylene partitioning between indoor air and building materials is needed, as well as information on the sorption kinetics for those materials.

**Production, Import/Export, Use, Release, and Disposal.** 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 TRI, which contains this information for 2016, became available in 2018. This database is updated yearly and should provide a list of industrial production facilities and emissions.

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 (Dow 2008; HSDB 2013). It is also released to surface water and land in sewage sludge and industrial liquid or solid waste (Schultz and Kjeldsen 1986; Weant and McCormick 1984). Tetrachloroethylene-containing material is considered a hazardous waste and its disposal is subject to regulations (EPA 2007). 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.

**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 (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). Tetrachloroethylene can be biodegraded under the appropriate conditions in soil (Cabirol et al. 1996, 1998; Chang et al. 1998, 2011;

Isalou et al. 1998; Kim et al. 2010; Krumholz et al. 1996) and groundwater (Cichocka et al. 2010; Hunkeler et al. 1999; Sharma and McCarty 1996,). However, the non-aqueous phase is quite difficult to treat and as a result, tetrachloroethylene persists at many hazardous waste sites (Chilton et al. 1990; Doust and Huang 1992). Vapor-phase tetrachloroethylene can migrate up from contaminated water or soil to above ground inside a home or building through vapor intrusion (ATSDR 2006a; Forand et al. 2012; Johnston and Gibson 2013, 2014; NYYSDH 2006). More studies are needed to investigate the environmental fate of subsurface tetrachloroethylene, especially with regard to vapor intrusion. The hydrolysis half-life has been estimated to be from 9 months (Dilling et al. 1975) to $9.9 \times 10^8$ years (Jeffers et al. 1989). Because of the great variability in half-life, additional studies regarding the hydrolysis of tetrachloroethylene would be useful.

**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 point 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, animals, and plants (Barrows et al. 1990; Kawasaki 1980; Kenaga 1980; Neely et al. 1974; Polder et al. 1998; Saisho et al. 1994; Veith et al. 1980). 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.** 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.

Tetrachloroethylene is widely distributed in the environment and has been detected in air (Adgate et al. 2004; Aggozzotti et al. 1994a; Roda et al. 2013), water (Dykson and Hess 1982; Lee et al. 2002; Rao and Brown et al. 1993; Ligocki et al. 1985; Rowe et al. 2007; Williams et al. 2002), soil (Vroblesky et al. 1991), and food (Daft 1989; Entz and Diachenko 1988; Entz and Hollifield 1982; Grob et al. 1990; Heikes and Hopper 1986). Tetrachloroethylene was found to be present in lettuce, and is prevalent in other fruits and vegetables (Boekhold et al. 1989; de Raat 2003). Additional data on the occurrence of tetrachloroethylene in foods would be important in understanding how the compound contaminates the food.

Ambient air levels in cities in the United States generally range from 0.035 to 1.3 ppb (Hartwell et al. 1987). 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.

**Exposure Levels in Humans.** Tetrachloroethylene has been detected in human breath (Aggazzotti et al. 1994b; Koppel et al. 1985; Stewart et al. 1977), blood (Altmann et al. 1990; Brugnone et al. 1994; Hattis et al. 1993; Skender et al. 1994), urine (Koppel et al. 1985; Rutkiewicz et al. 2011), tissues (Garnier 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 (McKernan et al. 2008; Raisanen et al. 2002); however, some studies of exposure in the general population have been done (CDC 2015; Chiappini et al. 2009; Garetano and Gochfeld 2000; Roda et al. 2013; Zocollio et al. 2009). 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. There are data that suggest that levels of tetrachloroethylene among minorities who live in buildings with a dry cleaner are higher than non-minority levels (Storm et al. 2013); however, there is a need for more studies that focus on minority populations and their exposure to tetrachloroethylene.

This information is necessary for assessing the need to conduct health studies on these populations.

**Exposures of Children.** Limited data are available regarding the exposures of children to tetrachloroethylene. Tetrachloroethylene was present at unspecified levels in breast milk samples (Bagnell and Ellenberger 1977; Pellizzari et al. 1982). 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. Using an exposure scenario similar to that described by Bagnell and Ellenberger (1977), other investigators (Byczkowski and Fisher 1994) estimated that a 1-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. Additional information regarding the levels of tetrachloroethylene in these and other matrices, such as tissue, neonatal blood, cord blood, and meconium fluid, would be helpful in assessing the exposure of children to this substance.

Child health data needs relating to susceptibility are discussed in Section 3.12.2, Identification of Data Needs: Children's Susceptibility.

**Exposure Registries.** No exposure registries for tetrachloroethylene were located. This substance is not currently one of the compounds for which a sub-registry has been established in the National Exposure Registry. The substance will be considered in the future when chemical selection is made for sub-registries 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.

### 6.8.2 Ongoing Studies

Ongoing studies identified in the National Institutes of Health (NIH) Research Portfolio Online Reporting Tools (RePORTER) pertaining to tetrachloroethylene are shown in Table 6-6.

## Table 6-6. Ongoing Studies on Tetrachloroethylene

| Principal investigator | Study topic | Institution | Sponsor |
|---|---|---|---|
| Loeffler, F. | Bioremediation strategies for the reductive dechlorination of chlorinated solvents such as tetrachloroethylene at hazardous waste sites | University of Tennessee, Knoxville | National Institute of Environmental Health Sciences |

Source: RePORTER 2018