

6. POTENTIAL FOR HUMAN EXPOSURE

6.1 OVERVIEW

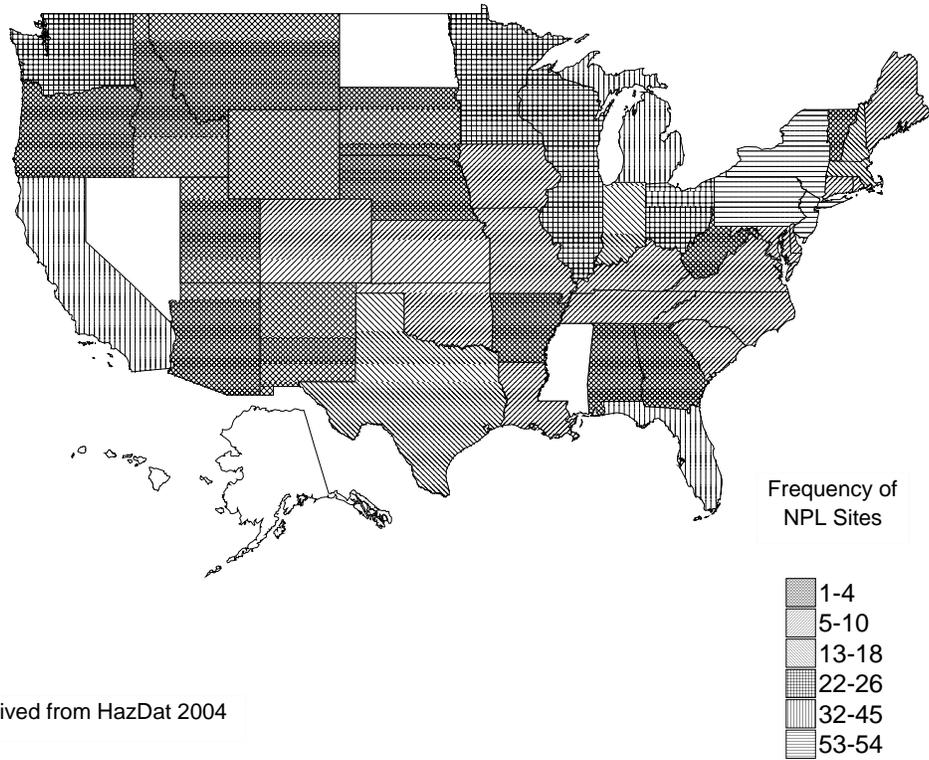
Vinyl chloride has been identified in at least 616 of the 1,647 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (HazDat 2004). However, the number of sites evaluated for vinyl chloride is not known. The frequency of these sites can be seen in Figure 6-1. Of these sites, all are located within the continental United States with the exception of one site located in the Virgin Islands and one site in the Commonwealth of Puerto Rico (not shown).

Vinyl chloride is used almost exclusively in the United States by the plastics industry for the production of polyvinyl chloride (PVC) and several copolymers. Anthropogenic sources are responsible for all of the vinyl chloride found in the environment. Most of the vinyl chloride released to the environment eventually escapes to the atmosphere. Lesser amounts are released to groundwater. Vinyl chloride has been detected in the ambient air in the vicinity of vinyl chloride and PVC manufacturing plants and hazardous waste sites. The compound has also leached into groundwater from spills, landfills, and industrial sources; it can also enter groundwater after being produced by the bacterial degradation of trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane (Smith and Dragun 1984).

Effluents and emissions from vinyl chloride and PVC manufacturers are responsible for most of the vinyl chloride released to the environment. When released to the atmosphere, vinyl chloride is expected to be removed by reaction with photochemically generated hydroxyl radicals (half-life=1–2 days). Reaction products include hydrochloric acid, formaldehyde, formyl chloride, acetylene, chloroacetaldehyde, chloroacetylchloranil, and chloroethylene epoxide. In photochemical smog, the half-life of vinyl chloride is reduced to a few hours. When released to water, volatilization is expected to be the primary environmental fate process. In waters containing photosensitizers, such as humic materials, sensitized photodegradation may also be important. Sensitized photodegradation may occur when a molecule other than the compound of interest absorbs light, promoting it to an excited state; a transfer of energy occurs between the excited state of the photosensitizer and the compound of interest, which involves no direct absorption of photons by that particular compound. When released to soil, vinyl chloride either volatilizes rapidly from soil surfaces or leaches readily through soil, ultimately entering groundwater.

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Figure 6-1. Frequency of NPL Sites with Vinyl Chloride Contamination



Derived from HazDat 2004

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Segments of the general population living in the vicinity of emission sources are exposed to vinyl chloride by inhalation of contaminated air. Average daily intake of vinyl chloride by inhalation for these people ranges from trace amounts to 2,100 µg/day. The average daily intake of vinyl chloride by inhalation is expected to be very low for the remainder of the population. The majority of the general population is not expected to be exposed to vinyl chloride through ingestion of drinking water. The average daily intake of vinyl chloride through the diet is essentially zero. Workers, particularly in plastic industries, are exposed to vinyl chloride mainly by inhalation, with some absorption through the skin possible. The National Occupational Exposure Survey (NOES), conducted by NIOSH from 1981 to 1983, estimated that 81,314 workers employed at 3,711 plant sites were potentially exposed to vinyl chloride (NOES 1990).

6.2 RELEASES TO THE ENVIRONMENT**6.2.1 Air**

The major source of vinyl chloride releases to the environment is believed to be emissions and effluents from plastic industries, primarily vinyl chloride and PVC manufacturers. Worldwide emissions of vinyl chloride into the atmosphere during 1982 totaled approximately 400 million pounds (Hartmans et al. 1985). Another emission source is tobacco smoke, which has been found to contain 5.6–28 ng vinyl chloride per cigarette (Hoffman et al. 1976). According to TRI data for 2002 (TRI02 2004), an estimated total of 670,992 pounds of vinyl chloride, amounting to 83% of the total environmental releases, was discharged to the air from the manufacturing and processing facilities in the United States in 2001 (Table 6-1). The TRI data should be used with caution because only certain types of facilities are required to report. This is not an exhaustive list. Vinyl chloride was detected in the air at 63 of the 1,647 current or former EPA NPL hazardous waste sites (HazDat 2004).

6.2.2 Water

Vinyl chloride released in waste water from the plastics industries is expected to volatilize fairly rapidly (on the order of hours to days) into the atmosphere. Anaerobic reductive dehalogenation of trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane also releases vinyl chloride into groundwater at hazardous waste sites (Smith and Dragun 1984) or other locations where the proper conditions are found in the subterranean strata. Vinyl chloride leaches into groundwater from spills,

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Table 6-1. Releases to the Environment from Facilities that Produce, Process, or Use Vinyl Chloride^a

State ^c	RF ^d	Reported amounts released in pounds per year ^b							
		Air ^e	Water ^f	UI ^g	Land ^h	Total release			
						On-site ⁱ	Off-site ^j	On- and off-site	
AL	1	2,823	No data		0	0	2,823	0	2,823
AR	2	6,587	No data		0	0	6,587	0	6,587
CA	1	9,539	0		0	0	9,539	0	9,539
DE	2	139,656	1		0	5	139,657	5	139,662
IL	2	64,382	14		0	6	64,396	6	64,402
KS	1	13	No data		12	0	25	0	25
KY	6	49,507	4		0	1	49,511	1	49,512
LA	12	77,481	192	139,450	42		217,123	42	217,165
MI	2	535	0		0	0	535	0	535
MO	1	91	0		0	0	91	0	91
MS	1	28,069	No data		0	0	28,069	0	28,069
NC	1	16	No data		0	0	16	0	16
NJ	3	30,520	39		0	39	30,559	39	30,598
OH	3	255	5		0	255	260	255	515
OK	1	2,500	0		0	0	2,500	0	2,500
PA	1	97,100	0		0	0	97,100	0	97,100
TX	12	161,918	288		0	1	162,206	1	162,207
Total	52	670,992	543	139,462	349		810,997	349	811,346

Source: TRI02 2004 (Data are from 2002)

^aThe 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.

^bData in TRI are maximum amounts released by each facility.

^cPost office state abbreviations are used.

^dNumber of reporting facilities.

^eThe sum of fugitive and point source releases are included in releases to air by a given facility.

^fSurface water discharges, wastewater treatment-(metals only), and publicly owned treatment works (POTWs) (metal and metal compounds).

^gClass I wells, Class II-V wells, and underground injection.

^hResource Conservation and Recovery Act (RCRA) subtitle C landfills; other on-site landfills, land treatment, surface impoundments, other land disposal, other landfills.

ⁱThe sum of all releases of the chemical to air, land, water, and underground injection wells.

^jTotal amount of chemical transferred off-site, including to POTWs.

RF = reporting facilities; UI = underground injection

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landfills, and industrial sources (TRI02 2004). According to data collected from the analysis of leachates and monitoring wells at sites where groundwater was contaminated by municipal solid waste landfill leachate, vinyl chloride was present in both the leachates and the groundwater samples (Sabel and Clark 1984). Vinyl chloride has been found in groundwater at other landfills also (Agency for Toxic Substances and Disease Registry 1995a, 1995b). Vinyl chloride was detected in groundwater at 325 of the 1,647 current or former EPA NPL hazardous waste sites, and in surface water at 109 of the 1,647 current or former EPA NPL hazardous waste sites (HazDat 2004).

According to TRI data for 2002 (TRI02 2004), an estimated total of 543 pounds of vinyl chloride, constituting <1% of the total environmental releases, was discharged to the water from the manufacturing and processing facilities in the United States (Table 6-1). The TRI data should be used with caution because only certain types of facilities are required to report. This is not an exhaustive list.

6.2.3 Soil

Vinyl chloride can either enter the soil from leachates at hazardous waste sites or enter the ground via underground injection. Release through either of these mechanisms is, however, only a small fraction of the total environmental discharge (TRI02 2004). According to TRI data for 2002 (TRI02 2004), an estimated total of 349 pounds of vinyl chloride, amounting to <1% of the total environmental releases, was discharged to the soil from manufacturing and processing facilities in the United States in 2002 (Table 6-1). The TRI also reported that 139,462 pounds of vinyl chloride, amounting to about 17% of the total released was injected underground (TRI02 2004). The TRI data should be used with caution because only certain types of facilities are required to report. This is not an exhaustive list. Vinyl chloride was detected in soil at 158 of the 1,647 current or former EPA NPL hazardous waste sites, and in sediment at 47 of the 1,647 current or former EPA NPL hazardous waste sites (HazDat 2004).

6.3 ENVIRONMENTAL FATE

6.3.1 Transport and Partitioning

Based on a vapor pressure of 2,660 mmHg at 25 °C, essentially all vinyl chloride in the atmosphere is expected to exist solely as a gas (Eisenreich et al. 1981; Verschuereen 1983). Consequently, removal from the atmosphere by dry deposition is not expected to be an important fate process.

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The primary transport process for vinyl chloride from natural water systems is volatilization into the atmosphere. The Henry's law constant of vinyl chloride has been measured as $0.0278 \text{ atm}\cdot\text{m}^3/\text{mol}$ at $24.8 \text{ }^\circ\text{C}$ (Gossett 1987), which suggests that vinyl chloride should partition rapidly to the atmosphere. The half-life for vinyl chloride volatilization from a typical pond, river, and lake has been estimated to be 43.3, 8.7, and 34.7 hours, respectively. These values are based on an experimentally determined reaeration rate ratio of approximately 2 and assumed oxygen reaeration rates of 0.008, 0.04, and 0.01 per hour for a typical pond, river, and lake, respectively (EPA 1982a). Predicted half-lives should be considered rough estimates since the presence of various salts in natural water systems may affect the volatility of vinyl chloride significantly (EPA 1979d). Many salts have the ability to form complexes with vinyl chloride and can increase its water solubility; therefore, the presence of salts in natural waters may significantly influence the amount of vinyl chloride remaining in the water (EPA 1979d). The half-life of vinyl chloride in bodies of water is also affected by depth and turbidity.

The relatively high vapor pressure of vinyl chloride indicates that the compound volatilizes quite rapidly from dry soil surfaces (Verschueren 1983). The effective half-life (due to volatilization and degradation) of vinyl chloride incorporated 10 cm deep in dry soil is predicted to be 12 hours (Jury et al. 1984). Vinyl chloride is soluble in water and thus can leach through the soil and enter groundwater before evaporation can occur (Cowfer and Magistro 1983).

Experimental data regarding adsorption of vinyl chloride to soil were not located. Based on the regression equations given by Lyman et al. (1982), Sabljic (1984), and Kenaga and Goring (1980), the soil organic carbon adsorption coefficient (K_{oc}) for vinyl chloride was estimated to range from 14 to 131. These K_{oc} values suggest a very low sorption tendency, meaning that this compound would be highly mobile in soil. Thus, vinyl chloride has the potential to leach into groundwater.

Vinyl chloride is soluble in most common organic solvents (Cowfer and Magistro 1983). In situations where organic solvents exist in relatively high concentrations (e.g., landfills, hazardous waste sites), cosolvation of vinyl chloride could have the effect of reducing its volatility, thus causing it to have even greater mobility than indicated by estimated K_{oc} values.

Vinyl chloride's small octanol/water partition coefficient ($\log K_{ow}=1.23$) indicates that the potential for bioconcentration in aquatic organisms is low (EPA 1982a). Using a $\log K_{ow}$ of 1.23 and a regression derived equation (Meylan et al. 1999), the bioconcentration factor (BCF) for vinyl chloride is estimated as 3. Freitag et al. (1985) measured BCFs in algae, fish, and activated sludge. The BCFs for algae, fish,

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and activated sludge were 40, <10, and 1,100, respectively. The very low value for fish, in comparison to the algae and activated sludge, may suggest a detoxification process in more highly developed organisms such as fish. Lu et al. (1977) examined the bioaccumulation of ¹⁴C-vinyl chloride in a closed model aquatic ecosystem over a 3-day period. The high volatility of vinyl chloride minimized any potential bioaccumulation. Relatively low tissue concentrations found in fish suggested that vinyl chloride is not biomagnified in aquatic food chains to any substantial degree.

6.3.2 Transformation and Degradation

6.3.2.1 Air

Reaction of gaseous vinyl chloride with photochemically generated hydroxyl radicals is predicted to be the primary degradation mechanism for this compound in the atmosphere (Cox et al. 1974; Howard 1976; Perry et al. 1977). The rate constant for this reaction has been measured as 6.96×10^{-12} cm³/molec-second (Kwok and Atkinson 1994). This rate constant corresponds to an atmospheric half-life of about 18 hours assuming a hydroxyl radical concentration of 1.5×10^6 molecules/cm³. Products of this reaction are hydrochloric acid, formaldehyde, formyl chloride, carbon monoxide, carbon dioxide, chloroacetaldehyde, acetylene, chloroethylene epoxide, chloroacetylchloranil, and water (Müller and Korte 1977; Woldbaek and Klaboe 1978). Under conditions of photochemical smog, the half-life of vinyl chloride would be reduced to a few hours (Carassiti et al. 1977). Reaction with ozone, nitrate radicals and direct photolysis are less important degradation mechanisms of vinyl chloride in the atmosphere (EPA 1976a, 1985c; Zhang et al. 1983). Vinyl chloride in the gas phase does not absorb light of wavelengths above 220 nm (EPA 1976a). Since atmospheric ozone blocks almost all sunlight with wavelengths <295 nm, direct photolysis is likely to occur very slowly, if at all, in the atmosphere (EPA 1976a).

6.3.2.2 Water

The primary removal process for vinyl chloride from surface waters is volatilization into the atmosphere. Vinyl chloride in water does not absorb ultraviolet radiation above 218 nm; therefore, direct photolysis in the aquatic environment is expected to occur very slowly, if at all (EPA 1976a). In sunlit surface waters containing photosensitizers, such as humic materials, photodegradation may be more rapid. If so, in some waters, sensitized photodegradation may be an important removal mechanism (EPA 1976a).

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The hydrolytic half-life of vinyl chloride has been estimated to be <10 years at 25 °C (EPA 1976a). Since the volatilization rate of vinyl chloride is much more rapid than the predicted rate of hydrolysis, hydrolysis is not a significant aquatic fate (EPA 1976a, 1979d). Vinyl chloride is not oxidized chemically by reaction with photochemically generated molecular oxygen in natural water systems (EPA 1976a). Experiments carried out at 20 mg/L vinyl chloride in water saturated with molecular oxygen at elevated temperatures showed that, after 12 hours at 85 °C, no degradation of vinyl chloride was observed. At temperatures and oxygen concentrations in natural waters, therefore, vinyl chloride is not expected to degrade by molecular oxygen at a significant rate (EPA 1976a).

EPA (1977) observed no change in the biochemical oxygen demand in raw sewage seed (used as a microbial inoculum) and raw sewage seed plus vinyl chloride at 20 °C over a 25-day period. The study authors interpreted this to mean that no biodegradation of vinyl chloride occurred. However, more recent data has shown that vinyl chloride can undergo microbial degradation under aerobic conditions. *Rhodococcus* sp. strains SM-1 and Wrink, which were isolated from a trichloroethylene-degrading bacterial mixture, and *Rhodococcus rhodochrous* ATCC 21197 were shown to degrade >99.9% of vinyl chloride within 7 days (Malachowsky et al. 1994). No significant differences in the amount of vinyl chloride degraded were found among the three organisms. The majority (66–83%) of the labeled carbon was metabolized to carbon dioxide (CO₂).

Vinyl chloride (1 ppm) was rapidly degraded under aerobic conditions in a laboratory study that used soil-water microcosms from aquifer material without the addition of other nutrients, such as nitrogen and phosphorus (Davis and Carpenter 1990). About 25% of the vinyl chloride was degraded after 1 week and more than 99% was degraded after 108 days. Sixty-five percent of labeled vinyl chloride was recovered as ¹⁴CO₂ after 108 days, demonstrating the extent of the mineralization.

Rhodococcus sp. Strain SM-1, a member of the order *Actinomycetales*, obtained from a trichloroethylene-degrading consortium was found to mineralize vinyl chloride to CO₂ by using propane as an energy source during growth experiments or cell suspension experiments (Phelps et al. 1991). Vinyl chloride concentrations decreased by more than 90%; growth cultures and cell suspensions incorporated about 10% of the transformed vinyl chloride into biomass (Phelps et al. 1991). *Mycobacterium vaccae* JOB5 degraded 100% of vinyl chloride in a 2-hour incubation (Wackett et al. 1989).

Degradation of vinyl chloride generally occurs slowly in anaerobic groundwater and sediment; however, under methanogenic or Fe(III) reducing conditions anaerobic degradation occurs more rapidly. Vinyl

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chloride was mineralized approximately 34% in 84 hours in anaerobic aquifer microcosms supplemented with Fe(III) and held under Fe(III) reducing conditions (Bradley and Chapelle 1996).

6.3.2.3 Sediment and Soil

Most vinyl chloride present on soil surfaces will volatilize to the atmosphere. Vinyl chloride is also mobile in soil and susceptible to leaching (Lyman et al. 1982). The presence of other organic solvents, such as those found at hazardous waste sites, may affect the mobility of the substance in the soil (Cowfer and Magistro 1983). Photodegradation on the surface of soils is expected since sensitized photodegradation in water occurs.

Several laboratory studies have indicated that both aerobic and anaerobic biodegradation of vinyl chloride can occur in soils and aquifer materials via a number of mechanisms (Barrio-Lage et al. 1990; Castro et al. 1992a, 1992b; Davis and Carpenter 1990), although these degradation processes were generally slow. More recently, Nelson et al. (1993) investigated methanotrophic degradation of vinyl chloride using a laboratory-scale, methanotrophic, attached-film, expanded-bed bioreactor. They found that this technique is an efficient way to degrade vinyl chloride, with the removal efficiency >90%. Under methanotrophic conditions, vinyl chloride was mineralized between 5 and 44% over 37 days using creek bed sediment microcosms obtained from a naval station near Jacksonville, Florida (Bradley and Chapelle 1997). Slightly higher mineralization rates were observed under Fe(III) reducing conditions.

6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT**6.4.1 Air**

Air in rural/remote and urban/suburban areas of the United States typically contains very low or no detectable amounts of vinyl chloride (EPA 1982f; Grimsrud and Rasmussen 1975a, 1975b; Harkov et al. 1984; Pratt et al. 2000; Stephens et al. 1986; Wallace et al. 1984). The mean concentration of vinyl chloride from 3,650 samples monitored in the state of Minnesota over an 8-year study period (1991–1998) was 0.01 $\mu\text{g}/\text{m}^3$, with a maximum observed value of 1.77 $\mu\text{g}/\text{m}^3$ (Pratt et al. 2000). Sampling was performed at 25 different sites across the state with sampling sites chosen to measure concentrations of pollutants near specific point sources, or to collect baseline data near the Minneapolis-St. Paul area.

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Limited monitoring data indicate that in areas near vinyl chloride and PVC manufacturing facilities, the concentration of vinyl chloride in air typically ranges from trace levels to $105 \mu\text{g}/\text{m}^3$ (0.041 ppm) (EPA 1979a, 1982f; Gordon and Meeks 1977) but may exceed $2,600 \mu\text{g}/\text{m}^3$ (1 ppm) (Fishbein 1979). Elevated levels of vinyl chloride may also be found in the vicinity of hazardous waste sites and municipal landfills. Concentrations ranging from below detection limits to $5\text{--}8 \mu\text{g}/\text{m}^3$ (0.002–0.003 ppm) have been measured in the air above some landfills (Baker and Mackay 1985; Stephens et al. 1986). Homes near one hazardous waste site in southern California were found to contain levels as high as $1,040 \mu\text{g}/\text{m}^3$ (0.4 ppm) (Stephens et al. 1986) and homes near another site contained between 1 and 9 ppb (Miller and Beizer 1985). Gaseous emissions from 20 Class II (nontoxic) landfills in southern California were analyzed for vinyl chloride (Wood and Porter 1987). Vinyl chloride was found in emissions from 85% of the landfills tested, and concentrations $>2,600 \mu\text{g}/\text{m}^3$ (1 ppm) were detected in more than half of the landfill emissions. The concentrations of vinyl chloride measured in this study ranged from 0.624 to $114.4 \text{ mg}/\text{m}^3$ (0.24–44 ppm). Based on their observations, the study authors concluded that the presence of vinyl chloride at these landfills was due to either illegal disposal or *in situ* generation by the degradation of chlorinated solvents by bacteria and other microbes (Wood and Porter 1987). Ambient air monitoring data downwind from the Eastview Road Landfill located in Guelph, Ontario indicated the presence of vinyl chloride at low levels. Concentrations ranging from 0.0023 to $0.042 \mu\text{g}/\text{m}^3$ were observed downwind from this facility during sampling conducted in May and June 1993 (Chadder 1994).

6.4.2 Water

Vinyl chloride has been detected at varying concentrations in surface water, groundwater, and drinking water throughout the United States. Concentrations of vinyl chloride in drinking water wells and surface water in New York State were found to be $50 \mu\text{g}/\text{L}$ (0.05 ppm) and $10 \mu\text{g}/\text{L}$ (0.01 ppm), respectively (Burmester 1982). Monitoring studies in nine states have identified concentrations as high as $380 \mu\text{g}/\text{L}$ (0.38 ppm) in groundwater (Dyksen and Hess 1982). Vinyl chloride levels ranged from below the detection limit ($0.64 \mu\text{g}/\text{L}$) to $55.6 \mu\text{g}/\text{L}$ ($3.35 \mu\text{g}/\text{L}$ mean value) in river water sampled near vinyl chloride and PVC manufacturing facilities in Osaka, Japan (Yamamoto et al. 2001).

Levels of vinyl chloride in groundwater in the United States were determined during the 1982 EPA Groundwater Supply Survey (Westrick et al. 1984). Water supplies from 945 sites throughout the United States were studied. Vinyl chloride was positively identified in only 0.74% of the 945 groundwater supplies (detection limit 0.001 ppm). It was reported that 0.5% of 186 random sample sites and 3.8% of 158 nonrandom sample sites contained detectable levels of vinyl chloride. The maximum concentrations

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at the random and nonrandom sites were 1.1 µg/L (0.0011 ppm) and 8.4 µg/L (0.0084 ppm), respectively (Westrick et al. 1984). Approximately half of the samples were taken from a random list of water systems, which were subdivided into two sets of systems—those serving fewer than 10,000 people and those serving more than 10,000 people. The nonrandom samples were taken from systems selected by the states, using groundwater sources that were likely to include volatile organic compounds in drinking water (Westrick et al. 1984). Other studies have reported the occurrence of vinyl chloride in groundwater samples collected throughout the United States at levels at or below 380 µg/L (0.38 ppm) (Cotruvo 1985; EPA 1982f; Goodenkauf and Atkinson 1986; Stuart 1983). In a study of three landfills located in Orange County, Florida, vinyl chloride was detected in water samples obtained at four out of nine wells with average concentrations ranging from 2.0 to 26.5 µg/L (Hallbourg et al. 1992). In a survey of 30 industrial sites located in Taiwan, vinyl chloride was detected in six groundwater wells at concentrations of 100,000 (1993 sampling period) and 22,000 µg/L (1994 sampling period) (Kuo et al. 2000).

6.4.3 Sediment and Soil

Monitoring data for vinyl chloride in soil were not located in the available literature.

6.4.4 Other Environmental Media

In the past, vinyl chloride had been detected in various foods and bottled drinking water as a result of migration from PVC food wrappings and containers (Benfenati et al. 1991; Gilbert et al. 1980). Vinyl chloride has been found in vinegar at levels up to 98,000 µg/L (98 ppm), in edible oils at 300–1,800 µg/L (0.3–1.8 ppm), and in alcoholic beverages at 0.0–8,400 µg/L (0.0–8.4 ppm) when these foods were packaged and stored in PVC containers (Williams 1976; Williams and Miles 1975). At present, the Food and Drug Administration (FDA) regulates the use of PVC polymers in food packaging materials and the amount of residual monomer in polymers and as a result, significant reduction in the levels of vinyl chloride in food samples has been achieved since the early 1970s (WHO 1999). In 1986, FDA determined that thick-walled PVC food packaging (i.e., bottles and blister packages) was safe provided that the polymer contained <10 ppb vinyl chloride (McNeal et al. 2003). To determine whether the residual vinyl chloride levels in PVC containing food packages in current use are <10 ppb, a survey and analysis of PVC containing food packages was recently conducted (McNeal et al. 2003). The results showed that vinyl chloride levels found in the packages ranged from none detected (<1 ppb) to about 275 ppb. The package containing 275 ppb residual vinyl chloride was a not a food contact material

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(McNeal et al. 2003). Dietary exposure to vinyl chloride from PVC packages used for food has been calculated by several agencies, and based upon estimated average intakes in the United Kingdom and the United States, an exposure of $<0.0004 \mu\text{g}/\text{kg}/\text{day}$ was estimated for the late 1970s and early 1980s (WHO 1999).

In a modeling study using liquid chromatography to simulate migration conditions of vinyl chloride from PVC in actual food packaging and storage, it was shown that at the very low concentrations ($<1 \text{ ppm}$) of residual vinyl chloride monomer in PVC packaging material, "essentially zero" migration of the vinyl chloride monomer into foods occurs (Kontominas et al. 1985). Vinyl chloride levels were determined in Italian drinking water bottled in PVC; levels ranged from 13 to 83 parts per trillion (ppt) (mean, 48 ppt) (Benfenati et al. 1991). It was also determined that there was a progressive migration of vinyl chloride from the bottle to the water, which occurred at a rate of $1 \text{ ng}/\text{L}/\text{day}$ (Benfenati et al. 1991). Vinyl chloride was also detected in bottled water from Saudi Arabia packaged in PVC bottles at levels of $\leq 0.6 \text{ ppb}$ (Fayad et al. 1997).

Vinyl chloride has been detected in municipal drinking water supplies. A study by EPA (1982f) estimated that 12 of 11,202 public water supplies that used surface water as their primary source had levels of vinyl chloride between $1.0 \mu\text{g}/\text{L}$ (0.001 ppm) and $5.0 \mu\text{g}/\text{L}$ (0.005 ppm); none had levels above $5 \mu\text{g}/\text{L}$ (0.005 ppm). Another study found that drinking water that ran through PVC pipes contained vinyl chloride at $1.4 \mu\text{g}/\text{L}$ (0.0014 ppm), whereas water that ran through a PVC system 9 years older contained $0.03\text{--}0.06 \mu\text{g}/\text{L}$ (0.03–0.06 ppb) (Dressman and McFarren 1978). The amount of vinyl chloride migrating from rigid PVC water pipes into drinking water was directly proportional to the residual level of vinyl chloride in the pipe itself. Current data on levels of vinyl chloride in drinking water and on the potential for leaching of vinyl chloride from PVC pipes were not located. Under certain test conditions, vinyl chloride in drinking water reacts with chlorine and is converted to chloroacetaldehyde and chloroacetic acid (Ando and Sayato 1984). Information concerning the effect of this reaction on drinking water supplies that are treated with chlorine and the extent of this reaction was not stated.

During an EPA study, detectable levels of vinyl chloride were found in indoor air samples taken from two of seven new 1975 model cars. Levels of vinyl chloride in indoor air in the two cars ranged from 400 to $1,200 \mu\text{g}/\text{L}$ (0.4–1.2 ppm). Ventilation of the car interiors led to the dissipation of vinyl chloride. The cars involved in the study had a high ratio of plastic to interior volume and were expected to provide worst-case concentrations for vinyl chloride in interior car air (EPA 1976b). Because of the limited

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nature of these data and the fact that this study is somewhat dated, no conclusions can be drawn regarding levels of vinyl chloride monomer in interior air of cars currently being produced.

Vinyl chloride has been detected in tobacco smoke. Cigarette smoke and smoke from small cigars has been found to contain 5.6–27 ng vinyl chloride per cigarette (Hoffman et al. 1976). The study authors suggested that the inorganic chloride concentrations in the tobacco determine the amount of vinyl chloride formed upon combustion of tobacco and released into the smoke (Hoffman et al. 1976).

6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

Inhalation of ambient or workplace air containing vinyl chloride is the most likely route of exposure for the general population. Typical values for the average daily intake of vinyl chloride by inhalation in urban/suburban and rural/remote areas not near emission sources are very small, since only trace levels of vinyl chloride are usually found in ambient air. Assuming that the average adult intake of air is 20 m³/day, the average daily intake of vinyl chloride by people living in the vicinity of emission sources has been estimated to range from trace amounts to 2,100 µg (EPA 1979a, 1982f; Gordon and Meeks 1977). The majority of drinking water supplies in the United States do not contain detectable levels of vinyl chloride (EPA 1982f; Westrik et al. 1984). Based on this conclusion, it is estimated that the average daily intake of vinyl chloride by ingestion of drinking water for most people in the United States is essentially zero (at or below 0.028 µg/kg/day [EPA 1982f]). Estimates provided by EPA (1985b) indicate that 0.9% of the U.S. population is exposed to levels of vinyl chloride in drinking water ≥ 1 µg/L, and 0.3% of the population is exposed to levels >5 µg/L.

NOES conducted by NIOSH from 1981 to 1983 estimated that 81,314 workers employed at 3,711 plant sites were potentially exposed to vinyl chloride in the United States (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. Exposure is believed to occur primarily through inhalation with some possible absorption through the skin (Hefner et al. 1975a). Workers that are involved in welding applications that use PVC pipes or other PVC materials may be exposed to higher levels of vinyl chloride from subsequent fumes. Airborne vinyl chloride levels of less than the detection limit of 0.05 ppm (0.13 mg/m³) to 0.1 ppm (0.26 mg/m³) were observed during the thermal welding of PVC pipes (Williamson and Kavanaugh 1987). Workers involved in the production of vinyl chloride or the manufacture of PVC materials have the potential to be occupationally exposed to high levels of vinyl chloride. Table 6-2 summarizes the level of vinyl chloride observed in

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Table 6-2. Vinyl Chloride Levels in Five Polyvinyl Chloride Manufacturing Facilities^a

Sample site	Number of samples	Mean (mg/m ³)	Median (mg/m ³)	Range (mg/m ³)
Outside reaction tank	4	296.30	86.25	6.19–1009.32
Reaction tank farm	18	13.60	9.97	0.18–110.59
Vinyl chloride recovery	9	9.25	5.46	0.85–33.39
Vinyl chloride shipping	3	5.98	7.38	0.85–9.71
Vinyl chloride storage tanks	6	4.97	3.03	0.60–14.25
Stripper	12	3.86	1.68	<LOD–18.62
Waste water treatment	7	3.37	3.32	0.83–6.73
Drier	11	2.62	1.55	<LOD–7.17
Control room (inside)	6	2.15	1.48	0.57–5.13
Control room (inside)	7	1.71	0.91	0.18–4.07
Polyvinyl chloride warehouse	17	1.66	1.79	<LOD–5.96
Factory perimeter	3	1.66	0.85	<LOD–3.34
Additive preparation	6	1.61	0.78	0.57–4.07
Administrative office	4	0.65	0.67	<LOD–1.27
Plastic pallet making area	1	<LOD	<LOD	<LOD

^aDu et al. 1996LOD = limit of detection (0.1259 mg/m³)

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five PVC manufacturing facilities located in Taiwan, and Table 6-3 provides the 8-hour time-weighted average (TWA) exposure to workers performing various job tasks (Du et al. 1996). Tank suppliers, cleaners, and PVC relievers were observed to have the highest TWA exposure since they more often came into direct contact with vinyl chloride in these job functions. In the United States, vinyl chloride is an Occupational Safety and Health Administration (OSHA) regulated substance. Current OSHA regulations impose a permissible exposure limit (PEL) of 1.0 ppm (2.6 mg/m³) averaged over an 8-hour period or a short-term exposure of no more than 5 ppm over a 15-minute period (Cowfer and Gorenssek 1997). Where concentrations cannot be lowered below the PEL of 1.0 ppm, employers must create an area with controlled access and a respirator program conforming to OSHA standards.

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. 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 spend more time outdoors. Children also are closer to the ground, and they do not use the judgment of adults to avoid hazards (NRC 1993).

Children are likely to be exposed to vinyl chloride via the same pathways that affect non-occupationally exposed adults; namely inhalation of ambient air and ingestion of food items or drinking water that may contain low levels of vinyl chloride. Children's plastic products such as bath toys, squeeze toys, and dolls are often made from PVC. Chewing or sucking on these toys has the potential to release any unpolymerized vinyl chloride from the object; however, no quantitative data exists regarding this potential exposure route and it is unlikely that there are significant levels of vinyl chloride in PVC-based toys. Vinyl chloride has not been detected in samples of human maternal adipose tissue, maternal blood, cord blood, or breast milk. No body burden studies that quantitatively or qualitatively identified vinyl chloride in children were located.

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Table 6-3. Time-weighted Average Exposure to Workers in Polyvinyl Chloride Manufacturing Facilities^a

Job description	Number of samples	Mean (mg/m ³)	Median (mg/m ³)	Range (mg/m ³)
Tank supplier	9	659.67	23.70	5.70–3,677.8
Polyvinyl chloride reliever	10	153.07	47.92	1.04–825.69
Tank cleaner	14	95.57	69.15	0.36–341.88
Vinyl chloride unloading	2	12.56	12.56	10.23–14.97
Safety/health specialist	4	12.04	1.74	1.19–22.87
Foreman	4	9.04	6.89	1.84–20.59
Stripper operator	3	4.51	3.37	2.33–7.82
Vinyl chloride recovery	5	4.38	4.48	0.88–5.93
Control room operator	8	4.01	3.47	1.04–10.02
Field supervisor	6	3.42	3.47	1.19–7.95
General office personnel	4	3.34	2.56	<LOD–8.18
Maintenance	3	2.69	1.76	0.85–5.49
Dryer operator	6	1.84	1.48	<LOD–4.25
Bagger and trucker	5	0.93	1.09	<LOD–1.58
Gatekeeper	2	0.93	0.93	<LOD–1.86

^aDu et al. 1996LOD = limit of detection (0.1259 mg/m³)

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6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Individuals located near or downwind of production facilities, hazardous waste disposal sites, and landfills may be exposed to atmospheric levels of vinyl chloride higher than ambient background levels. Concentrations around 5–8 $\mu\text{g}/\text{m}^3$ (0.002–0.003 ppm) have been measured in the air above some landfills (Baker and Mackay 1985; Stephens et al. 1986). Homes near one hazardous waste site in southern California were found to contain levels as high as 1,040 $\mu\text{g}/\text{m}^3$ of vinyl chloride (0.4 ppm) (Stephens et al. 1986) and homes near another site contained levels between 2.6 and 23.4 $\mu\text{g}/\text{m}^3$ (Miller and Beizer 1985). These concentrations are several times greater than ambient air levels that are generally $<1 \mu\text{g}/\text{m}^3$ (Pratt et al. 2000). For specific levels associated with health effects, see Section 3.4. Individuals living near hazardous waste sites and landfills may also be exposed to vinyl chloride in their drinking water. Workers involved in the production or use of vinyl chloride are likely to be exposed to levels greater than the levels that the general public is exposed to (see Section 6.5).

Cigarette smoke and smoke from small cigars have been found to contain vinyl chloride at levels of 5.6–27 ng per cigarette (Hoffman et al. 1976). Therefore, people who smoke heavily may be potentially exposed to higher levels of vinyl chloride than nonsmokers.

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 adverse health effects of vinyl chloride is available. Where adequate information is not available, ATSDR, in conjunction with NTP, is required to ensure the initiation of a program of research designed to determine the adverse health effects (and techniques for developing methods to determine such health effects) of vinyl chloride.

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.

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6.8.1 Identification of Data Needs

Physical and Chemical Properties. The physical and chemical properties of vinyl chloride are sufficiently well characterized to permit estimation of its environmental fate (Amoore and Hautala 1983; Cowfer and Magistro 1983; EPA 1985b; Fire 1986; HSDB 2004; IARC 1979; Lewis 1996; Lyman et al. 1982).

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 Toxics Release Inventory (TRI02 2004), which contains this information for 2002, became available in July of 2004. This database will be updated yearly and should provide a list of industrial production facilities and emissions.

Vinyl chloride is released primarily to the atmosphere via emissions from vinyl chloride and PVC manufacturing facilities (Hartmans et al. 1985; SRI 1990a, 1990b, 1993, 1994; TRI02 2004). The risk of exposure to vinyl chloride is highest for workers in the plastics industry and populations living near industrial areas or hazardous waste sites. Current production, use, and manufacturing methods are well described in the literature (Cowfer and Magistro 1985; HSDB 1996; IARC 1979; SRI 1990a, 1990b, 1993, 1994; TRI02 2004; USITC 1994). More current information on releases and disposal methods might assist in estimating potential exposures to vinyl chloride, particularly for populations living near hazardous waste sites.

Environmental Fate. Vinyl chloride primarily partitions to the air where it is degraded relatively quickly by photochemically produced hydroxyl radicals (Kwok and Atkinson 1994). It is removed from surface water and soils mainly by volatilization and photodegradation (EPA 1976a). Biodegradation and hydrolysis also occur (Barrio-Lage et al. 1990; Castro et al. 1992a, 1992b; Davis and Carpenter 1990; EPA 1976a), but these reactions are generally slow as compared to the volatilization rate. More information regarding the transformation and degradation in soil and water would be helpful in defining the potential pathways for human exposure.

Bioavailability from Environmental Media. Vinyl chloride can be absorbed following inhalation (Bolt et al. 1977; Krajewski et al. 1980; Withey 1976), oral (Feron et al. 1981; Watanabe et al. 1976a; Withey 1976), and to a much lesser extent, dermal exposure (Hefner et al. 1975a). These routes of

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exposure may be of concern to humans because of the potential of vinyl chloride to contaminate air (Baker and MacKay 1985; EPA 1979a; Fishbein 1979; Gordon and Meeks 1977; Stephens et al. 1986; Wood and Porter 1987), water (Burmester 1982; Cotruvo 1985; Dyksen and Hess 1982; Goodenkauf and Atkinson 1986; Stuart 1983; Westrick et al. 1984), and food (Gilbert et al. 1980; Williams 1976; Williams and Miles 1975). Information regarding the bioavailability from ingestion and dermal contact of contaminated soils would be helpful, particularly for populations living near hazardous waste sites, although vinyl chloride is not believed to be absorbed through skin.

Food Chain Bioaccumulation. Vinyl chloride can bioconcentrate to a limited extent in aquatic organisms (EPA 1982a; Freitag et al. 1985). Biomagnification of vinyl chloride in terrestrial and aquatic food chains does not appear to be important because of its high volatility and the fact that it is readily metabolized by higher-trophic-level organisms (Freitag et al. 1985; Lu et al. 1977). No data were located regarding biomagnification in terrestrial foodchains.

Exposure Levels in Environmental Media. Reliable monitoring data for the levels of vinyl chloride in contaminated media at hazardous waste sites are needed so that the information obtained on levels of vinyl chloride in the environment can be used in combination with the known body burden of vinyl chloride to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites. Vinyl chloride has been detected in air (Baker and Mackay 1985; EPA 1979a; Fishbein 1979; Gordon and Meeks 1977; Stephens et al. 1986; Wood and Porter 1987), water (Burmester 1982; Cotruvo 1985; Dyksen and Hess 1982; Goodenkauf and Atkinson 1986; Stuart 1983; Westrick et al. 1984), sediment (Wang et al. 1985), and food (Gilbert et al. 1980; Williams 1976; Williams and Miles 1975). Intake data for the general population from the various media are available (EPA 1979a, 1985b; Gordon and Meeks 1977; Westrick et al. 1984). Data on levels of vinyl chloride in soils are needed. Site-specific data on concentrations of vinyl chloride in air, soil, and water would be helpful in estimating the risk of exposure for populations living in the vicinity of hazardous waste sites. Also, current data on the extent of release (if any) of vinyl chloride from PVC pipes and from car interiors are needed to estimate the risk of exposure of the general population.

Exposure Levels in Humans. Vinyl chloride has been detected in exhaled breath of humans (Baretta et al. 1969; Conkle et al. 1975), but no other body burden studies are available. More information on exposure levels for populations living in the vicinity of hazardous waste sites would be helpful. This information is necessary for assessing the need to conduct health studies on these

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populations. It is noted that it is difficult to directly analyze for vinyl chloride in humans, which may limit the practicality of conducting these tests.

Exposures of Children. No data exist regarding the levels of vinyl chloride in children. Children are exposed to vinyl chloride by the same pathways that affect adults; inhalation of ambient air and the ingestion of foods or drinking water. It would be useful to determine if there exists any free unpolymerized vinyl chloride that can be extracted from PVC children's toys. 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 vinyl chloride were located. This substance is not currently one of the compounds for which a subregistry has been established in the National Exposure Registry. The substance will be considered in the future when chemical selection is made for subregistries to be established. The information that is amassed in the National Exposure Registry facilitates the epidemiological research needed to assess adverse health outcomes that may be related to exposure to this substance.

6.8.2 Ongoing Studies

The Federal Research in Progress (FEDRIP 2004) database provides additional information obtainable from a few ongoing studies that may fill in some of the data needs identified in Section 6.8.1.

John Furgeson (University of Washington) is investigating the *in-situ* bioremediation of chlorinated aliphatics (including vinyl chloride) at hazardous waste sites by anaerobic reductive transformation pathways. Josse Fabien and Zhou Rongnong of the University of Marquette (Milwaukee, Wisconsin) are attempting to characterize and design polymer-coated chemical sensors for the direct, rapid, *in-situ* monitoring of vinyl chloride and other hazardous constituents in water. Envirogen Incorporated (R.J. Steffan, Principal Investigator) is attempting to develop specialized bio-catalysts that will aid in the remediation of aquifers contaminated with chlorinated volatile organic compounds, including vinyl chloride. It is hypothesized that bioaugmentation of contaminated aquifers with microorganisms capable of greater sediment penetration, continuous enzyme expression, and prolonged activity will significantly improve *in situ* bioremediation efforts. Stuart Strand (University of Washington) is studying the ability of several plant strains to take up and transform various chlorinated hydrocarbons, including vinyl chloride, in order to aid in remediation strategies. Karla Thrall (Oregon Health and Science University) is studying

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the potential for human exposure to vinyl chloride and other VOC near Superfund sites. Exposure assessment studies will be conducted with volunteers using a novel real-time breath analysis system to determine the uptake of any of the nine potential contaminants of study from tap water by each of three routes: inhalation, ingestion, and dermal contact.