6. POTENTIAL FOR HUMAN EXPOSURE

6.1 OVERVIEW

Styrene has been identified in at least 251 of the 1,699 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (HazDat 2007). However, the number of sites evaluated for styrene is not known. The frequency of these sites can be seen in Figure 6-1. Of these sites, 30 are located within the United States and one is located in the Commonwealth of Puerto Rico (not shown).

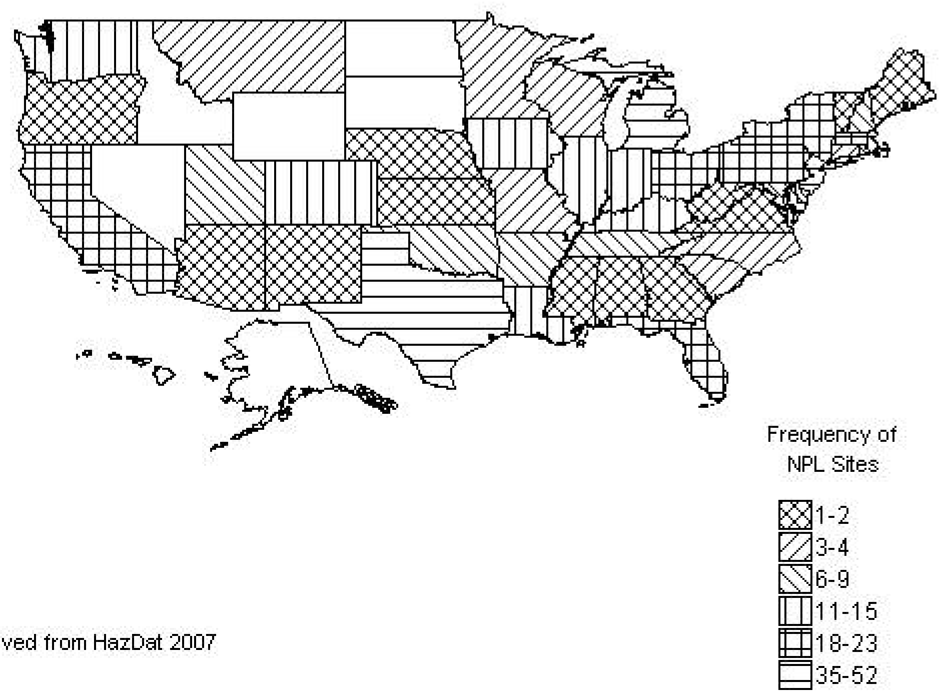
Styrene is a widely used industrial chemical with reported atmospheric emissions of >51 million pounds annually in the United States (TRI06 2008). Styrene photodegrades in the atmosphere, with a half-life ranging between 7 and 16 hours (which are the degradation half-lives catalyzed by reactions with hydroxyl radical and ozone, respectively). Styrene is moderately mobile in soil and volatilizes from water to the atmosphere. Styrene will undergo biodegradation in most top soils and aquatic environments, but degradation will be much slower in environments that are anaerobic. Bioconcentration does not appear to be significant.

The principal route of styrene exposure for the general population is probably by inhalation of contaminated indoor air. Mean indoor air levels of styrene have been reported in the range of 0.1–50 $\mu g/m^3$, and can be attributed to emissions from building materials, consumer products, and tobacco smoke. It should be pointed out that the workplace or home office may have substantially higher levels of airborne styrene, due to emissions from laser printers and photocopiers. General workplace styrene concentrations ranged from 89 to $1.5x10^6$ $\mu g/m^3$ ($20–3.4x10^5$ ppmv). The most significant exposure route in these settings is also likely by inhalation. The industries with the highest potential exposure are probably the reinforced plastics factories, boatbuilding facilities, and polystyrene factories. Exposure may also be high in areas near major spills. Exposure to styrene from hazardous waste sites is potentially important, but the magnitude of the problem is unknown. The potential for outdoor exposure to styrene is lower than indoor exposure, with reported mean air levels ranging from 0.28 to 20 $\mu g/m^3$ (0.064–4.6 ppmv).

6.2 RELEASES TO THE ENVIRONMENT

The Toxics Release Inventory (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

Figure 6-1. Frequency of NPL Sites with Styrene Contamination



Derived from HazDat 2007

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 47.3 million pounds (21,500 metric tons) of styrene to the atmosphere from 1,558 domestic manufacturing and processing facilities in 2006, accounted for 93% of the estimated total environmental releases from facilities required to report to the TRI (TRI06 2008). These releases are summarized in Table 6-1.

Styrene may be emitted to the atmosphere from industrial production and usage processes, motor vehicle operation, combustion processes, building materials, and consumer products. Estimated atmospheric industrial styrene emissions reported to EPA for the 2005 TRI totaled 47.3 million pounds, with >38 million pounds released from point sources and >10 million pounds released as fugitive emissions (TRI06 2008). Styrene ranked 16th among air emissions for reported chemicals and chemical group compounds in the United States in 2005. Since EPA regulations that require reporting of toxic chemical emissions apply only to selected facilities producing and/or using substantial quantities of the chemical (EPA 1988a), the total air emissions of styrene are probably greater than those reported. Typical sources of industrial styrene emissions are those facilities producing styrene, polystyrene, other plastics, synthetic rubber, and resins (EPA 1975, 1987d; Graedel 1978; IARC 1979; NIOSH 1983). The number of facilities reporting styrene emissions to the TRI are listed in Table 6-1, along with number of reporting facilities in each state and Puerto Rico, and the primary routes of styrene release from those facilities.

Styrene has been identified as a component of motor vehicle emissions from both gasoline- and diesel-powered engines (Hampton et al. 1982, 1983). Styrene emission rates ranging from 6.2 to 7.0 mg/km

Table 6-1. Releases to the Environment from Facilities that Produce, Process, or Use Styrene[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	37	1,493,262	501	0	4,259	0	1,493,763	4,259	1,498,021
AR	27	656,082	0	0	32,770	1,455	656,082	34,225	690,307
AZ	23	555,904	1,458	0	63,937	0	557,362	63,937	621,299
CA	104	2,185,575	115	0	7,042	2,316	2,186,674	8,374	2,195,048
CO	10	100,590	0	0	4,500	0	100,590	4,500	105,090
CT	7	38,287	1	0	0	0	38,288	0	38,288
DE	6	40,812	0	0	0	230	40,812	230	41,042
FL	119	4,259,337	1	0	4,862	61,840	4,259,700	66,340	4,326,040
GA	59	3,347,294	7	0	956	1,560	3,347,301	2,516	3,349,817
IA	21	712,311	No data	0	4,044	253	712,311	4,297	716,608
ID	3	166,603	No data	0	0	0	166,603	0	166,603
IL	50	1,124,354	11	0	113,965	58	1,205,331	33,057	1,238,388
IN	90	5,470,677	160	0	48,127	48,461	5,470,837	96,588	5,567,424
KS	24	705,880	0	0	467	0	705,880	467	706,347
KY	29	290,945	71	0	18,263	800	291,016	19,063	310,079
LA	44	704,823	129	0	496,584	0	1,187,861	13,675	1,201,536
MA	14	50,678	0	0	15,179	369	50,678	15,548	66,226
MD	10	419,548	0	0	0	0	419,548	0	419,548
ME	7	65,572	No data	0	0	1,747	65,572	1,747	67,319
MI	43	1,656,863	49	0	9,627	2,638	1,656,928	12,249	1,669,177
MN	30	1,128,972	0	0	1	1,410	1,128,972	1,411	1,130,383
MO	31	820,328	0	0	0	1,841	820,328	1,841	822,169
MS	13	536,877	10	0	310,794	0	536,887	310,794	847,681
MT	3	1	No data	0	0	0	1	0	1
NC	66	1,617,112	0	0	13,718	27,822	1,620,882	37,770	1,658,652
ND	4	281,137	5	0	0	0	281,142	0	281,142
NE	9	144,188	0	0	3,103	2	144,438	2,855	147,293
NH	5	49,891	No data	0	0	0	49,891	0	49,891
NJ	23	167,841	69	0	0	0	167,910	0	167,910
NM	2	21,387	No data	0	6	0	21,387	6	21,393
NV	7	47,800	0	0	1,959	0	47,800	1,959	49,759
NY	18	99,248	360	0	83	113	99,608	196	99,804
OH	123	1,583,501	17	0	388,345	4,834	1,583,518	393,179	1,976,697
OK	25	574,291	0	0	110	0	574,291	110	574,401
OR	21	901,084	0	0	3,617	0	901,084	3,617	904,701
PA	60	1,154,378	25	0	89,876	8,555	1,154,403	98,431	1,252,834

Table 6-1. Releases to the Environment from Facilities that Produce, Process, or Use Styrene[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
PR	5	43,422	0	0	32,400	99,360	43,422	131,760	175,182
RI	4	61,640	No data	0	0	0	61,640	0	61,640
SC	47	1,499,535	0	115	531,750	306	1,499,535	532,171	2,031,706
SD	3	47,512	No data	0	0	0	47,512	0	47,512
TN	47	4,495,679	255	0	89,127	119	4,495,934	89,246	4,585,179
TX	166	4,271,673	754	425,575	97,903	237,905	4,698,326	335,484	5,033,810
UT	8	45,615	No data	0	8	2	45,615	10	45,625
VA	22	483,346	No data	0	776	0	483,346	776	484,122
VT	1	12,441	No data	0	0	0	12,441	0	12,441
WA	25	1,275,024	40	0	0	2,285	1,275,064	2,285	1,277,349
WI	48	1,480,404	No data	0	30,095	16,686	1,480,404	46,781	1,527,186
WV	14	393,651	5	0	20,828	1,000	393,736	21,748	415,484
WY	1	14,559	No data	0	0	0	14,559	0	14,559
Total	1,558	47,297,934	4,043	425,690	2,439,081	523,967	48,297,213	2,393,502	50,690,715

[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 on-site 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: TRI06 2008 (Data are from 2006)

distance for gasoline-powered vehicles and 1.4–2.1 mg/km for diesel trucks have been reported (Hampton et al. 1983). Styrene may also be emitted into the air by other combustion processes. Styrene has been identified in the stack emissions from waste incineration (Junk and Ford 1980), and Kleindienst et al. (1986) reported the presence of styrene in wood smoke emissions, but no quantitative data were reported.

Emissions of styrene from building materials (carpets, floor tiles, insulation), office copiers, and consumer products (disinfectants, plastics, paint, cigarettes) may contribute significantly to indoor air pollution (Crump 1995). A styrene emission rate from glued carpet of 98 ng/minute/m^2 was calculated by Wallace et al. (1987b), and Girman et al. (1986) identified styrene as a major emittant from adhesives used in the constructing and finishing of buildings. Hodgson et al. (1993) determined an average styrene emission rate from new carpets of 410 ng/minute/m^2 over a 24-hour time period, but this was reduced to 30 ng/minute/m^2 when emissions were measured over 168 hours. Carpet cushioning material showed higher styrene emission rates of 2,300 ng/minute/m^2 when measured over 6 hours, but this material also showed significantly lower emission rates of 83 ng/minute/m^2 when measured over a longer span of 96 hours (Schaeffer et al. 1996). Polystyrene products such as packaging materials, toys, housewares, and appliances that may contain small amounts of the monomer also contribute to air levels. The workplace or home office may have substantial levels of airborne styrene due to emissions from laser printers and photocopiers. In the case of laser printers, styrene concentrations measured in test chambers during printer operation were reported to be as high as 380 μg/m^3 (87 ppmv) (Kagi et al. 2007). For photocopiers, emission rates from four different copiers averaged 3,300 μg/hour, but one copier had an emission rate of 12,000 μg/hour (Leovic et al. 1996). General workplace styrene concentrations ranged from 89 to 1.5×10^6 μg/m^3 (20–3.4×10^5 ppmv). Styrene has also been detected in sidestream smoke emitted from cigarettes but concentrations were not reported (IARC 1979).

6.2.2 Water

Estimated releases of 4,043 pounds (~1.83 metric tons) of styrene to surface water from 1,558 domestic manufacturing and processing facilities in 2006, accounted for about 0.01% of the estimated total environmental releases from facilities required to report to the TRI (TRI06 2008). These releases are summarized in Table 6-1.

The principal sources of styrene releases to water are industrial effluents. Styrene has been detected in effluents from chemical, textile, latex, and coal gasification plants (EPA 1976; Pellizzari et al. 1979). Styrene was also identified in one of 63 industrial effluents at a concentration of <10 μg/L (EPA 1979b).

Styrene occurred at concentrations up to 83 μg/L in coal gasification effluents (Pellizzari et al. 1979), and King and Sherbin (1986) reported styrene concentrations up to 970 μg/L in chemical plant effluents. The daily styrene loading from a single chemical plant into the St. Clair River (just south of Lake Huron on the Michigan/Ontario border) was estimated at 133 kg (King and Sherbin 1986). Styrene was detected (but not quantified) in the leachate from an industrial landfill in a study of 58 municipal and industrial landfill leachates (Brown and Donnelly 1988). Styrene has also been detected at trace concentrations in the River Elbe at two different sampling locations, with concentrations ranging from 6.1 to 46 ng/L (Gotz et al. 1998).

6.2.3 Soil

Estimated releases of 2.44 million pounds (~1,110 metric tons) of styrene to soils from 1,558 domestic manufacturing and processing facilities in 2006, accounted for about 5% of the estimated total environmental releases from facilities required to report to the TRI (TRI06 2008). An additional 0.426 million pounds (~193 metric tons), constituting about 0.8% of the total environmental emissions, were released via underground injection (TRI06 2008). These releases are summarized in Table 6-1.

Soil and sediments may become contaminated with styrene by chemical spills, landfill disposal of styrene-containing wastes, or discharge of styrene-contaminated water. A small amount of styrene is produced naturally through the activities of microorganisms, and some plants also produce styrene that may be released to soil. The amounts released to soil through these processes, however, are not expected to be significant in comparison to human activities that generate and release styrene to soil.

6.3 ENVIRONMENTAL FATE

6.3.1 Transport and Partitioning

Should styrene be released to the environment, its vapor pressure indicates that it will partition to the atmosphere. In the atmosphere, styrene exists as a vapor. Styrene is an oily liquid that is slightly volatile; its vapor pressure has been determined to be approximately 5 mm Hg at 20 °C (Verschueren 2001). A small fraction of the styrene released to the atmosphere may dissolve into condensed water vapor such as clouds and raindrops. A Henry's law constant (H) is a measure of the tendency of a chemical to partition between its gas phase and water. A value for H has not been experimentally measured for styrene, but it may be estimated by dividing the vapor pressure of styrene by its solubility in water at the same temperature (EPA 1982a). In this case, the value of H is approximately 2.61×10^{-3} atm-m^3/mole at 25 °C.

Analogous air-water partition coefficients were measured at 37 °C, yielding a value of approximately 5.4×10^{-1} atm-m^3/mole (Sato and Nakajima 1979). The magnitude of these values suggests that only a small fraction of vapor-phase styrene would dissolve into atmospheric water droplets. Physical processes such as precipitation and dry deposition would not be significant mechanisms for removing styrene from the atmosphere because of its high photochemical reactivity (EPA 1984b).

Should styrene be released to lakes, rivers, streams, or other waterways, the magnitude of the estimated Henry's law constant (2.61×10^{-3} atm-m^3/mole, assuming a water solubility of 300 mg/L at 20 °C [Verschueren 2001]) and its water solubility suggest that a large fraction of the chemical dissolved in the water will volatilize into the atmosphere (depending on temperature gradients, relative humidity, air currents, and the extent of mixing of the solution). From a modeling perspective, it should be pointed out that the dependence of this process depends on an accurate determination of the chemical's water solubility. In this case, while styrene is only sparingly soluble in water, the reported values are not precise, and range from 160 mg/L at 23 °C to 310 mg/L at 20 °C to 400 mg/L at 40 °C (Banerjee et al. 1980; Valvani et al. 1981; Verschueren 2001). Therefore, estimated rates of volatilization have some uncertainty associated with them. Volatilization of styrene, however, has been measured in surface lake and distilled water samples such that different loadings of styrene were examined. When 2–10 mg of styrene was added to 1 L of lake water, 50% was lost to the atmosphere in 1–3 hours. For the distilled water, volatilization occurred more slowly, with 50% loss occurring within 6–7 hours (Fu and Alexander 1992). The volatilization half-life of styrene in moving water that is 1 meter deep (assuming a solubility of 300 mg/L) may be on the order of 6 hours, based on the empirical relationship reported by Dilling (1977) for the volatilization of chlorinated hydrocarbons from water. The half-life of styrene in the Rhine River was estimated from field measurements at about 14 hours, but it was not known if the loss was due to volatilization, biodegradation, or photodegradation (Zoeteman et al. 1980). Volatilization from ponds and lakes is estimated to be slower, with half-life estimates ranging from 3 to 13 days (EPA 1984b).

Styrene released to soils or sediments will also likely volatilize to the atmosphere, but the rate of this process depends on the characteristics of the soil or sediment. The extent of adsorption of sparingly water-soluble compounds such as styrene is often correlated with the organic carbon content of the adsorbent (i.e., the soil or sediment; Hassett et al. 1983). When adsorption is expressed as a function of organic-carbon content, an organic carbon/water partition coefficient (K_{oc}) is generated, and may be used to rank the relative mobility of the chemical in soil. A K_{oc} value for styrene has not been experimentally measured, but may be estimated from its solubility in water, using the empirical regression of Hassett et al. (1983). Assuming that the solubility of styrene is 300 mg/L, a calculated K_{oc} value for styrene is 260.

The magnitude of this estimated K_{oc} suggests that styrene is "moderately mobile" in soil (Roy and Griffin 1985). In surface soils, where the amount of organic carbon will be highest, the movement of styrene will therefore be retarded by adsorption. In deeper subsurface environments where the amount of organic carbon may be lower, adsorption may not be as significant. The transport of styrene in aquifers by the movement of groundwater contaminant plumes has been observed (Colombani et al. 2009; Roberts et al. 1980). Based on field measurements, the rate of movement of styrene in an aquifer was about 80 times slower than that of the groundwater (Roberts et al. 1980). The slower rate of movement was attributed to adsorption. No information was located to corroborate the estimated K_{oc} value, and apparently, there are no studies in which the adsorption-desorption characteristics of styrene by soils and sediments have been measured.

The octanol/water partition coefficient (K_{ow}) reflects the partitioning of a chemical between octanol and water and is believed to be a good indication of the tendency for a chemical to accumulate in the fatty structures in plants and animal tissues (Kenaga and Goring 1980). The K_{ow} of styrene has been measured to be 1,445 (Banerjee et al. 1980), 891 (log K_{ow}=2.95) (Hansch et al. 1995), and 891 (Valvani et al. 1981), suggesting that styrene will partition to fat tissues. This is shown to be the case by the work of Engstrom et al. (1978a) and EPA (1986d).

Even though styrene does tend to partition into fat, it does not tend to bioaccumulate to high levels, mainly because of its metabolism and excretion. A bioconcentration factor (BCF) relates the concentration of a chemical in an organism to the concentration of the chemical in the medium in which it is exposed. Based on the empirical regression of Kenaga (1980), the BCF for styrene is about 25. An experimentally-measured BCF for goldfish was 13.5 (Ogata et al. 1984). These low BCFs suggest that bioconcentration is not a significant fate of styrene released into the environment (EPA 1984b). No other measured BCFs were located to corroborate these reported values.

6.3.2 Transformation and Degradation

6.3.2.1 Air

The major fate of atmospheric styrene is determined by the rate of photooxidation. Styrene may be transformed by direct photolysis, but the half-life of this process may be on the order of 50 years (EPA 1984b). Kopczynski et al. (1972) found that styrene was not degraded by direct photolysis after 6 hours of exposure.

Styrene is more quickly photooxidized by ozone and hydroxyl radicals. The rate constant for the reaction of styrene with ozone at ambient temperatures (about 25 °C) has been measured and is approximately $0.17–2.16\text{x}10^{-19}$ cm^3/molecule-second (Atkinson et al. 1982; EPA 1979a). Assuming that the mean concentration of ozone in the troposphere is $10\text{x}10^{12}$ molecules/cm^3 (EPA 1980), the half-life of styrene would be approximately 13 hours. The rate constant for the reaction of styrene with hydroxyl radicals has been measured as $5.3\text{x}10^{-11}$ cm^3/molecule-second (Bignozzi et al. 1981). Assuming that the concentration of tropospheric hydroxyl radicals varies from $3\text{x}10^5$ to $1\text{x}10^7$ molecules/cm^3 (Mac Leod et al. 1984), it follows that the atmospheric half-life of styrene would be between 0.5 and 17 hours. More recent studies provide a similar rate constant of $5.9\text{x}10^{-11}$ cm^3/molecule-second (Bunce and Dryfhout 1992) and $5.8\text{x}10^{-12}$ cm^3/molecule-second (EPA 1993a), with a corresponding half-life of ~2.2 hours. Consequently, it is not expected that styrene will persist in the atmosphere, due to the combined and rapid effects of ozone- and hydroxyl radical-initiated atmospheric degradation processes. Transformation products resulting from such degradation processes include primarily oxygen-containing hydrocarbons such as phenol, phenylacetaldehyde, and phenoxy radical (Sloane and Brudzynski 1979) or other compounds (Atkinson and Arey 2003), as well as other aromatic hydrocarbons such as the benzyl radical and other unsaturated hydrocarbons (Sloane and Brudzynski 1979).

6.3.2.2 Water

Little is known about abiotic transformations of styrene in water. The reaction of styrene with peroxy radicals appears to be too slow to be significant (EPA 1984b), and no relevant information regarding photochemical reactions in water was located. There is no information that styrene will hydrolyze in water, nor would its chemical structure suggest such potential.

While little is known about the abiotic degradation potential of styrene in water, it has been shown to be biologically degraded in several types of aquatic systems including sewage treatment facilities, biofilm reactors, groundwater, and lakes. In sewage samples, styrene showed a range of biodegradability. In one study where styrene was added at a concentration of 1 mg/L, 20% of the added styrene was completely degraded (i.e., mineralized to CO_2) within 3 days, with >60% degraded within 30 days (Fu and Alexander 1992). In another sewage fate study, however, styrene was only slightly biodegraded; in five different evaluations, conducted for either 17 or 36 days, styrene degradation ranged from 6 to 23% (Pahren and Bloodgood 1961). Bridie et al. (1979) found that 42% of the styrene initially present degraded in 5 days when unadapted sewage was used as the source of microorganisms; when an adapted sewage was used, 80% degradation was observed. Very low concentrations of styrene (<10 μg/L) were completely degraded within 20 minutes in an aerobic biofilm reactor after acclimation, but the chemical was degraded much more slowly (~8% after 2 days) under methanogenic biofilm column conditions (Bouwer and McCarty 1984). When studied in groundwater, styrene biodegradation ranged between 4 and 12% per week (when added at 600–800 μg/L; Wilson et al. 1983) and a more recent study showed similar rates of degradation, with over 40% mineralization after 30 days (Fu and Alexander 1992). Styrene had a similar degradation potential in lake water, with ~35% degradation after 30 days (Fu and Alexander 1992).

6.3.2.3 Sediment and Soil

Styrene is rapidly degraded in most soils when incubated under aerobic conditions, but it persists when soil conditions are anaerobic (e.g., waterlogged). Styrene was rapidly degraded when added to either a low organic-matter content landfill soil or a high organic-matter content loamy soil. When added at 2 g/kg, >87% of the styrene was degraded in the landfill soil, and >95% was degraded in the loamy soil (measured over a period of 16 weeks; Sielicki et al. 1978). When styrene was added to the soils at higher concentrations (5 g/kg), degradation was slower and less was degraded, with ~60% degraded in both soils after a 16-week incubation. Fu and Alexander (1992) showed that styrene was biodegraded in loamy soil (when added at 2 mg/kg soil), with >50% degradation occurring over a 30-day incubation period, and the same soil in a later study showed similar amounts of degradation (40% degradation in 50 days; Fu et al. 1994). In contrast to the findings in aerobic soils, this research group showed that styrene persisted when soil conditions were waterlogged and anaerobic (Fu and Alexander 1996). Other researchers, however, have been able to demonstrate degradation of styrene under anaerobic conditions by consortia of microbial cultures (Grbic-Galic et al. 1990). The relevance of these consortia studies to actual environmental samples is unknown.

Several bacterial and fungal species have been isolated from soils that are capable of using styrene as a sole-carbon source (Braun-Lüllemann et al. 1997; Burback and Perry 1993; Hartmans 1995; Sielicki et al. 1978; Warhurst and Fewson 1994), and these organisms degrade styrene by either side chain oxidation or aromatic ring attack. Initial biodegradation products included styrene oxide, 1-phenylethanol, 2-phenylethanol, and then phenylacetaldehyde, acetophenone, and phenylethanediol, and then phenylacetic acid, with degradation proceeding towards normal metabolic intermediates such as acetaldehyde and pyruvate (Warhurst and Fewson 1994).

6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to styrene depends in part on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of styrene 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 styrene levels monitored or estimated in the environment, it should also be noted that the amount of chemical identified analytically is not necessarily equivalent to the amount that is bioavailable. The analytical methods available for monitoring styrene in a variety of environmental media are detailed in Chapter 7.

6.4.1 Air

Styrene is a common contaminant of ambient urban air. Concentrations of styrene greater than rural air concentrations have been identified in urban and industrial source areas, near hazardous waste sites, in motor vehicle tunnels, in indoor air, and in workplace environments. A summary of monitoring data for these locations is presented in Table 6-2. The data suggest that indoor air concentrations of styrene can be considerably higher than outdoor concentrations. Cigarette smoke has also been implicated as a significant source of styrene in indoor air (EPA 1987e; Vainiotalo et al. 2008; Wallace et al. 1986a), as has the operation of photocopying machinery (Stefaniak et al. 2000; Leovic et al. 1996, 1998) and laser printers (Kagi et al. 2007).

Monitoring studies in Minnesota detected styrene in over 1,400 air samples collected from a total of 2,507 samples (there were 1,004 samples where styrene was below the detection limits) over an 8-year period. The average concentration detected was 0.1 $\mu g/m^3$ (0.02 ppmv); the median concentration detected was 0.08 $\mu g/m^3$ (0.02 ppmv); and the maximum detected amount was 1.49 $\mu g/m^3$ (0.343 ppmv) (Pratt et al. 2000). Styrene monitoring in ambient air conducted in Chiba City, Japan over an 8-week period showed slightly higher mean concentrations, ranging from 0.11 to 0.36 $\mu g/m^3$ (0.025–0.083 ppmv) (Uchiyama and Hasegawa 2000).

6.4.2 Water

Styrene is not frequently found in U.S. water supplies. Styrene was not detected in any of the >1,000 samples of drinking water analyzed during three federal surveys (EPA 1985a), but had been reported occasionally in drinking water supplies in several states (Coleman et al. 1984; EPA 1975, 1976; Kleopfer and Fairless 1972; Kool et al. 1982; Sanjivamurthy 1978) well water (EPA 1985b; Krill and

Table 6-2. Styrene Concentrations in Representative Air Samples

	Concentration (μg/m^3)		
Location	Maximum	Mean	References
Indoor			
Indoors, unspecified	6,500	0.4–8.9 0.3–50	EPA 1987e, 1988c; Fishbein 1992; Sakaguchi and Akabayashi 2003; Shields and Weschler 1992; Wallace et al. 1986a
New homes	14.3	0.9–2.6	Hodgson et al. 2000
Remodeled buildings	167	0.1–10.1	Rothweiler et al. 1992; Zabiegala 1999
Workplaces	$4.5\text{x}10^6$	$<1–1.5\text{x}10^6$	Bartolucci et al. 1986; Cocheo et al. 1983; Correa et al. 2004; Fishbein 1992; Kagi et al. 2007; NIOSH 1983
Photocopy centers	12,000[a]; 220[b]	7,000[a]; 89[b]	Stefaniak et al. 2000; Leovic et al. 1996, 1998
Restaurants	3.3	1.6	Vainiotalo et al. 2008
Outdoor			
Rural/suburban	53	0.28–0.34[c]; 0.43	EPA 1988c; Graedel 1978; Islam and Stancheva 1999; Kinney et al. 2002
Urban	2,500	0.29–3.8; 20	EPA 1987e, 1988c; Fishbein 1992; Grosjean and Fung 1984; Grosjean et al. 1998; Harkov et al. 1985; Wallace et al. 1986b
Industrial source areas	25	1.3[c]–2.1	EPA 1978, 1983, 1988c
Municipal waste sites	6,100	No data	Assmuth and Kalevi 1992; Eitzer 1995
Hazardous waste sites	65	1.1–6.4	Harkov et al. 1985; La Regina and Bozzelli 1986
Tunnels	46	1.1–6.6[d]	Hampton et al. 1983; Zielinska et al. 1996

[a] Value provided is the emission rate, as μg/hour; the emission rate was measured during operation of copier in test chambers.
[b] Value provided is the emission rate, as μg/hour; the emission rate was measured during the idle phase of copier operation in test chambers.
[c] Median value
[d] Range of values, no mean given.

Sonzogni 1986), river water (EPA 1976; Sheldon and Hites 1978), and Lake Erie (Konasewich et al. 1978). Quantitative data were not available in these reports. A more recent survey provided by the EPA National Contaminant Occurrence Database (EPA 2006) noted that styrene was detected rarely in groundwater, where it was detected only 295 times out of over 174,000 analyses (<0.2% of the samples); detected concentrations ranged from <10 to 40 μg/L. Styrene concentrations in raw and treated waters ranged from 0.1 to ≥1.0 μg/L in an evaluation of organic compounds in Canadian water supplies at nine municipalities along the Great Lakes (Otson 1987). Styrene was rarely detected in aquifer materials in a large evaluation of U.S. groundwater and wells conducted by the U.S. Geological Survey (USGS). For >3,400 test evaluations of aquifer materials, there was a very low frequency of detections, with the median concentration being 0.015 μg/L. It was detected less frequently and also at low concentrations in domestic wells (0.014 μg/L), and at slightly higher concentrations in public wells (median=0.13 μg/L) (USGS 2006).

Other bodies of water—those potentially highly contaminated and those that are used for direct ingestion—likewise do not usually contain styrene. Styrene is not commonly detected in groundwater even near superfund sites, and was not found in a drinking water evaluation of public water sources in Torino, Italy (Canter and Sabatini 1994; Zelano et al. 1998). In a study of wells near a superfund site in Florida, styrene was detected at a very low concentration (the maximum detected concentration was 6.3 μg/L) near the site, but it was not detected in any treated water effluents (Canter and Sabatini 1994). Squillace et al. (1999) surveyed a vast number of drinking water wells in the United States over a 10-year period. Styrene was detected in <1% of the 2,900 surveyed urban and suburban wells between 1985 and 1995, and the concentrations detected were >2 orders of magnitude lower than the health advisory level. Styrene was only detected in rural wells, not in urban ones. Finally, Zelano et al. (1998) did not report the detection of any styrene in an evaluation of 21 public drinking water fountains in Torino, Italy.

6.4.3 Sediment and Soil

Limited data were located regarding estimation of styrene in sediments and soils (see Section 6.2.3). Water and sediment samples from the Lower Tennessee River were evaluated for styrene, and low concentrations (4.2 ppb) were found (Goodley and Gordon 1976).

6.4.4 Other Environmental Media

Styrene is a natural component of many foods; however, most styrene associated with food is the result of packaging of the food material in polystyrene containers. Styrene has been found as a natural component of roasted filberts, dried legumes, fried chicken, cooked pork, roasted beef, mussels, clams, eggs, nectarines, and Beaufort cheese (Dumont and Adda 1978; Kinlin et al. 1972; Lovegren et al. 1979; Takeoko et al. 1988; Tang et al. 1983, 2000), but detected concentrations were often very low (Tang et al. 2000), except for turkey sausage, where detected levels were 100 ppb, and in some cheeses, where concentrations detected were up to 5,000 ppb (Tang et al. 2000). In contrast, styrene is a natural component of cinnamon, with concentrations up to 40,000 ppb (Tang et al. 2000). Data on styrene levels from an FDA monitoring study (1996–2000) of volatile organic compounds in food items are presented in Table 6-3 (Fleming-Jones and Smith 2003).

Styrene may enter packaged foods by migration from polystyrene food containers and packaging materials, with concentrations ranging from <100 to >3,000 ppm, but common levels being much lower (5–30 ppb) (EPA 1985a; Tang et al. 2000). Concentrations of styrene measured in yogurt packaged in polystyrene containers ranged from 5.5 to 150 ppb (Withey 1976). Mean levels of styrene in foods packaged in plastic in the United Kingdom ranged from <1 to 180 ppb (Gilbert and Startin 1983). Similar concentrations of styrene were detected in other dairy products packaged in polystyrene containers (IARC 1979). The rate of styrene migration into food is mainly a function of the diffusion coefficient of the monomer in the polymer and of the lipophilicity of the food (Till et al. 1987). For example, 4–6% of the free monomer in polystyrene packaging migrated into corn oil or sunflower oil within 10 days, while only 0.3–0.6% migrated into milk, beef, or water. Similarly, migration of styrene from foam cups into liquids such as water, tea, or coffee was about 8 ng/cm^2, while migration into 8% ethanol (as might be encountered in wine or other alcoholic drinks) was 36 ng/cm^2 (Varner and Breder 1981). However, Withey and Collins (1978) found no clear relationship between the styrene monomer content of packaging material (which varied widely) and the amount leached into food after comparable residence times. Levels of styrene ranged from 0.50 to 46.40 ppb in bottled water stored in 200–250 mL polystyrene containers (Al-Mudhaf et al. 2009). Concentrations in the water increased with time, indicating that the source was migration from the container walls. These authors did not detect styrene in bottled water stored in polyethylene terephthalate (PET) containers.

Styrene has been identified as a component of cigarette smoke (EPA 1984b; Vainiotalo et al. 2008) and has been detected in concentrations of 18 μg/cigarette in the smoke of cigarettes made in the United

Table 6-3. Styrene Levels in Food Items

Food	Number of detections	Minimum (ppb)	Maximum (ppb)
American cheese	4	2	11
Cheddar cheese	3	4	70
Mixed cuts	14	21	104
Ground beef	6	4	13
Pork bacon	7	6	85
Cream cheese	2	2	3
Frankfurters, beef	8	4	77
Chocolate cake with icing	12	7	57
Tuna canned in oil	1	2	2
Fruit flavored cereal	3	2	10
Eggs, scrambled	6	5	10
Peanut butter	13	16	38
Avocado, raw	8	3	550
Popcorn, popped in oil	3	2	2
Blueberry muffin	10	8	141
Strawberries, raw	9	12	350
Orange, raw	2	2	3
Coleslaw with dressing	1	2	2
Sweet roll/Danish	13	13	91
Potato chops	6	2	16
Popsicle	3	4	11
Quarter pound hamburger, cooked	6	4	27
Margarine	10	9	20
Sandwich cookies	14	15	165
Butter	12	11	28
Chocolate chip cookies	12	15	111
Sour cream	3	5	30
Apple pie, fresh/frozen	9	10	40
Chicken nuggets	12	10	66
Graham crackers	6	4	21
French fries	12	8	68
Cheeseburger, quarter pound	5	5	22
Cheese pizza	6	3	23
Bologna	7	2	78
Cheese and pepperoni pizza	7	8	20
Olive/safflower oil	11	3	54
Sugar cookies	14	24	142
Cake doughnuts with icing	10	6	45

Source: Fleming-Jones and Smith (2003).

States (IARC 1979). Indoor air concentrations of styrene may be significantly higher in homes of smokers than nonsmokers (EPA 1987e).

6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

Exposure to styrene may occur by inhalation, ingestion, or dermal absorption. The most likely mode of exposure of the general population to styrene is by inhalation of indoor air (EPA 1985a). Based on the EPA (1989e) estimate that the average person spends 20.4 hours/day indoors (inhaling about 17 m^3 of air during that time based on an air inhalation rate of 20 m^3/day) and the range of mean indoor air concentrations presented in Table 6-2, typical indoor exposure levels to styrene may range from 1.7 to 850 μg/day. Additional exposures may occur from inhalation of outdoor air and ingestion of food that was stored in polystyrene containers. Vitrac and Leblanc (2007) estimated a median styrene intake ranging from 1 to 35 μg/day per person for household exposures resulting from migration of this substance from food packaging. Based on estimated food consumption rates, Tang et al. (2000) reported an estimated annual general population exposure to styrene ranging from 0.8 to 4.5 mg/person from food. Outdoor air concentrations are likely to be lower in rural than urban areas and are likely to be small compared to indoor air concentrations. Exposure from municipal drinking water is probably insignificant. However, groundwater at hazardous waste sites where styrene has been detected may provide significant exposure to styrene if used as a local water supply.

The exposure of the population to styrene varies significantly from the typical to the worst-case scenario. The daily general population exposure to styrene via food has been estimated at 0.2–1.2 μg/person and the exposure via inhalation has been estimated at 18–54 μg/person, with a total estimated exposure ranging from 18.2 to 55.2 μg/day. This is equivalent to 6.7–20.2 mg/year. Therefore, the primary route of exposure for the general population is via inhalation (Tang et al. 2000). Worst-case exposure estimates, on the other hand, are 0–0.5 μg/day from drinking water, 30 μg/day from food, and 65,000 μg/day from air (EPA 1985a). These estimates are based on the highest levels estimated or monitored and, therefore, reflect the highest potential exposure rather than typical exposure for the general population.

Exposure of the general population to styrene is confirmed by human monitoring data. Styrene has been identified in adipose tissue at concentrations of 8–350 ng/g (EPA 1986d), in blood at a mean concentration of 0.4 μg/L (Antoine et al. 1986), and in exhaled breath at mean concentrations of 0.7–1.6 μg/m^3 (EPA 1987e).

A large number of workers are potentially exposed to styrene. NIOSH estimates that approximately 300,000 workers at 22,000 facilities may be exposed to styrene (NIOSH 1990); about 30,000 of these on a full-time basis (NIOSH 1983) and about 86,000 are females. The highest potential exposure occurs in the reinforced-plastics industry, where workers may be exposed to high air concentrations and also have dermal exposure to liquid styrene or resins (Dalton et al. 2007; Fustinoni et al. 2008; Lemasters et al. 1985; NIOSH 1983; Rihs et al. 2008; Sato et al. 2009; Triebig et al. 2008; Van Rooij et al. 2008). Hemminki and Vianio (1984) estimated that heavily exposed workers in this industry in Finland might be exposed to up to 3 g of styrene per day. Van Rooij et al. (2008) estimated that styrene levels ranged from 30 to 222 mg/m^3 in the breathing zone of European open-mold process workers in 2003. Table 6-4 lists levels of styrene measured in the blood, urine, and surrounding air of reinforced plastic workers. Urinary levels of styrene metabolites are also included. Significant occupational exposures may also occur in other industrial settings, including styrene polymerization, rubber manufacturing, and styrene-polyester resin facilities (Engstrom et al. 1978b; NIOSH 1983; Rappaport and Fraser 1977) as well as in photocopy centers or facilities (Leovic et al. 1996, 1998; Stefaniak et al. 2000). Fustinoni et al. (2008) found that concentrations of styrene and its metabolites measured in the urine of 13 varnish workers were comparable to those measured in fiberglass reinforced plastic workers.

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 can be exposed to styrene at home by inhalation of contaminated air and by food consumption. Inhalation-based exposures may occur in both urban and rural home environments, both of which may be contaminated by vehicular and industrial emissions. In addition, exposure to tobacco smoke may provide

Table 6-4. Concentrations of Styrene in the Surrounding Air, Blood, and Urine of Reinforced Plastics Workers, Including Urinary Concentrations of the Styrene Metabolites, MA and PGA

	Styrene			MA	PGA	
Occupation	Air (ppm)	Blood (µg/L)	Urine (µg/L)	Urine (mg/g creatinine)	Urine (mg/g creatinine)	Reference
Boat building (n=248)						Triebig et al. 2008
Mean	<10–40[a]	53.9–108	–	40.7–742	10.6–228	
Boat building (n=67)						Sato et al. 2009
Mean	51.7	–	47.0	300	120	
Minimum	0.3	–	5.2	0.00	0.00	
Maximum	133.5	–	189.2	1.81	0.48	
Boat building (n=88)						Rihs et al. 2008
Mean	55.1–82.0	203.1–264.2	–	–	83.8–190.0	
Minimum	0.2	55.8	–	–	24.3	
Maximum	690.7	662.0	–	–	591.3	
Unspecified reinforced plastics (n=8)						Fustinoni et al. 2008
Mean	4.20	–	1.9–7.5	32.29–148.13	50.05–77.97	
Minimum	0.53	–	1.1	13.04	17.26	
Maximum	21.57	–	29.7	515.12	248.99	
Boat building (n=30)						Dalton et al. 2007
Mean	0.6–22[a]	–	–	–[b]	–[b]	

[a] Levels were calculated based on urinary levels of MA+PGA.
[b] Mean concentrations ranging from 10 to 463 mg/g creatinine were reported for the sum of MA+PGA in urine.

– = not reported; MA = mandelic acid; PGA = phenylglyoxylic acid another route of styrene exposure, especially in homes where one or both parents, any siblings, or other relatives smoke. Children may be also be exposed to higher levels of styrene indoors at home during painting of indoor rooms, especially during winter months (such as over winter school vacations) when the child stays indoors more and during which time, windows may not be opened.

From a food-based exposure perspective, infants may be exposed to styrene from consuming food items such as those listed in Table 6-3. In addition, it is possible that exposure may also result from consumption of infant formula or from nursing practices. In the 5-year FDA study on volatile organic compounds in foods (Fleming-Jones and Smith 2003), soy- and milk-based infant formula was included in the study; however, the results for styrene were not reported. Baby foods and infant formula are often stored in polystyrene containers and the migration of low levels of non polymerized styrene into food items from polystyrene containers has been demonstrated (EPA 1985a; Tang et al. 2000). In a study on chemicals in mother's milk, styrene was identified, but not quantified, in 8 out of 12 samples of mother's milk samples collected from mothers living in four U.S. urban areas (Pellizzari et al. 1982). Duffy and Gibney (2007) estimated the styrene exposure of Irish children between the ages of 5 and 12 years as a result of the migration of styrene from food packaging. The calculated mean styrene intake was 0.122 μg/kg body weight-day when using 90th percentile migration values and 0.169 μg/kg when using maximum migration values. The authors note that these values are well below the provisional maximum tolerable daily intake of 40 μg/kg body weight-day established by the Joint FAO/WHO Expert Committee on Food Additives. Although children are exposed to styrene from the oral routes mentioned above, it has been estimated that >90% of human exposure to styrene arises due to inhalation routes (Fleming-Jones and Smith 2003; Tang et al. 2000).

Aside from food-related intake, children's exposure to styrene may differ from exposures to adults, especially during school, home, or play activities that may expose the children to styrene sources. For example, for elementary aged children (grades 2, 3, 4, and 5) attending inner city schools in Minneapolis, it was found that the lowest exposure to styrene occurred either outdoors or in school, and the highest exposure occurred at home. The latter can be substantially influenced (increased) if smoking occurs in the home. Exposures to styrene while outside, in either winter or spring, were very low (winter: 0.0 μg/m^3; spring: 0.1 μg/m^3), whereas exposures were much higher at school (winter: 31.3 μg/m^3; spring: 39.7 μg/m^3), but were almost three times higher at home (winter: 91.9 μg/m^3; spring: 91.9 μg/m^3) (Adgate et al. 2004). These exposures led to blood level concentrations of styrene that were generally twice as high as the general population (Sexton et al. 2005).

6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

People working in various styrene industries are likely to have the highest exposures to styrene. Lower levels may be encountered near industrial facilities or hazardous waste sites emitting styrene to outdoor air. High indoor styrene concentrations in the home may be due to emissions from building materials, consumer products, tobacco smoke, photocopiers and laser printers. Smokers and those eating a high proportion of foods packaged in polystyrene may also have above average exposure to styrene, with the amounts estimated by smoking (100 μg from 20 cigarettes) more than doubling the normal estimated exposure to styrene (Tang et al. 2000). In addition, workers with long-term employment at photocopy centers may also be exposed to high concentrations of styrene.

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 styrene 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 styrene.

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 solubility of an organic compound in water is indicative of how that chemical will partition between water, soil, and organisms (Banerjee et al. 1980; Hassett et al. 1983; Valvani et al. 1981). Clarification of the exact solubility of styrene in water would be helpful because a range of values is currently reported (Table 4-2). The Henry's law constant and K_{oc} value for styrene need to be verified experimentally to provide more accurate predictions of air-water and soil-water partitioning.

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 2005, became available in May of 2007. This database is updated yearly and should provide a list of industrial production facilities and emissions.

Substantial quantities of styrene are currently produced and used in the United States (Heylin 1989; HSDB 2009; SRI 1989; USITC 1988). Production and import quantities, producers, and uses are well documented, with 4.7×10^{12} g produced in 2000 (HSDB 2009), representing a slight increase in U.S. production since 1997 (3.12×10^{12} g). The United States has imported less styrene over the last several decades, with amounts decreasing more than an order of magnitude, from 1.4×10^{10} g imported in 1978 to 5.7×10^{8} g being imported in 2001 (HSDB 2009). Interestingly, styrene exports increased from 3.6×10^{10} g in 1978 (representing 1% of total U.S. production) to $>1.2 \times 10^{12}$ g exported in 2001 (representing >26% of total U.S. production) (HSDB 2009).

Quantities of styrene disposed of by various disposal methods, other than those reported to the TRI, are not known. Styrene releases into water are regulated by EPA, but styrene is not listed as a hazardous waste constituent and, therefore, land disposal restrictions do not apply to this compound. Additional information on disposal methods used for styrene and styrene-containing products and the quantities disposed of by each method would help to better characterize the potential for human exposure to this compound from disposal at waste sites or other locations.

Environmental Fate. Styrene will partition among the environmental media, with a tendency to volatilize from water to air and to adsorb to soils (EPA 1984b; Roberts et al. 1980; Sato and Nakajima 1979). However, data on styrene volatilization from water and confirmation of the estimated K_{oc} value by adsorption/desorption data would be useful to estimate more accurately the tendency of styrene to partition to air and soil. Confirmation of the K_{oc} would also provide a more reliable basis for estimating the mobility of styrene in the various types of soil.

Although the reaction mechanisms of styrene transformations in the atmosphere are fairly well understood (Atkinson et al. 1982; Bignozzi et al. 1981; EPA 1979a; Sloane and Brudzynski 1979), more information regarding the environmental fates of the transformation products would allow a more accurate prediction of the atmospheric fate of this compound. Biodegradation data are available for styrene under both aerobic and anaerobic conditions (Bridie et al. 1979; Grbic-Galic et al. 1990).

Bioavailability from Environmental Media. Styrene is known to be absorbed following inhalation, oral, and dermal contact (Dutkiewicz and Tyras 1968; Engstrom et al. 1978a, 1978b; Ramsey and Andersen 1984; Ramsey and Young 1978; Withey 1976; Withey and Collins 1979). Absorption rates via inhalation are known (Withey and Collins 1978). Additional data are needed to evaluate absorption rates following oral and dermal exposure. It is believed that absorption of styrene from the gut is believed to be generally rapid and therefore, contact with styrene contaminated food, soil, or water will probably also result in significant absorption. However, this may depend on the medium in which it is contained.

Food Chain Bioaccumulation. Bioconcentration of styrene in aquatic organisms is not likely to be significant, based on both a measured BCF for a single goldfish species (BCF=13.5; Ogata et al. 1984) and an estimated BCF (EPA 1984b; Kenaga 1980; Ogata et al. 1984). No data on biomagnification of styrene in the food chain were located. Since significant bioaccumulation is unlikely, this lack of data may not be a major limitation. No data needs are identified at this time.

Exposure Levels in Environmental Media. Reliable monitoring data for the levels of styrene in contaminated media at hazardous waste sites are needed so that the information obtained on levels of styrene in the environment can be used in combination with the known body burden of styrene to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

Monitoring data for styrene in environmental compartments are extensive, and historical and recent data are available for air (EPA 1987e, 1988c; Uchiyama and Hasegawa 2000), groundwater (Canter and Sabatini 1994; Squillace et al. 1999), and rivers (Gotz et al. 1998; Rathbun 2000). Additional data on styrene levels in water and soil, especially in the vicinity of hazardous waste sites, would be useful in assessing the potential for human exposure. Estimates of human intake from food, air, water, and soil have been made (EPA 1985a; Tang et al. 2000) and will undoubtedly be revised as additional data become available.

Exposure Levels in Humans. Styrene has been detected in human blood, breath, milk, and adipose tissue of the general population (Antoine et al. 1986; EPA 1986d, 1987e; Pellizzari et al. 1982) and metabolites of styrene have been detected in urine of workers exposed to styrene (Elia et al. 1980; Sollenberg et al. 1988). However, data generated by biological monitoring of populations in the vicinity of waste sites with the most sensitive methods (Section 7.1) would be useful in assessing the magnitude of human exposures from this source.

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

Exposures of Children. Additional studies on the exposure of children to styrene would improve understanding of any mechanisms and pathways for styrene exposure and subsequent effects on this subpopulation. The exposure study report by Adgate et al. (2004) and the corresponding blood level study by Sexton et al. (2005) provide a good understanding for styrene exposures and uptake in one metropolitan area in the Midwestern United States, but additional reports investigating exposures and uptake, for example, in other climates, would be beneficial.

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 styrene 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

No current ongoing studies located in the Federal Research in Progress (FEDRIP) database were related to the potential for human exposure. The Computer Retrieval of Information on Scientific Projects (CRISP 2007) National Institutes of Health database identified one study. Scott Ensign of Utah State University proposed to investigate microbial pathways of short-chain hydrocarbon metabolism and the properties of the enzymes, cofactors, and regulatory elements associated with these pathways. The work will be sponsored by the National Institutes of Health/National Institute of General Medical Sciences and will investigate the central roles of carboxylation and novel cofactors/enzymes in bacterial hydrocarbon/epoxide/ketone metabolism of these chemicals, including styrene, by pursuing the biochemical, structural, and genetic characterization of these processes (CRISP 2007).

As part of the Third National Health and Nutrition Evaluation Survey (NHANES III), the Environmental Health Laboratory Sciences Division of the National Center for Environmental Health, Centers for

Disease Control and Prevention, will be analyzing human blood samples for styrene and other volatile organic compounds. These data will give an indication of the frequency of occurrence and background levels of these compounds in the general population.