

6. POTENTIAL FOR HUMAN EXPOSURE

6.1 OVERVIEW

Naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene have been identified in at least 654, 36, and 412, respectively, of the 1,662 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (HazDat 2005). However, the number of sites evaluated for naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene is not known. The frequency of these sites can be seen in Figures 6-1, 6-2, and 6-3, respectively. Of these sites, 654, 36, and 410, respectively, are located within the United States and 0, 0, and 2, respectively, are located in the Virgin Islands (not shown).

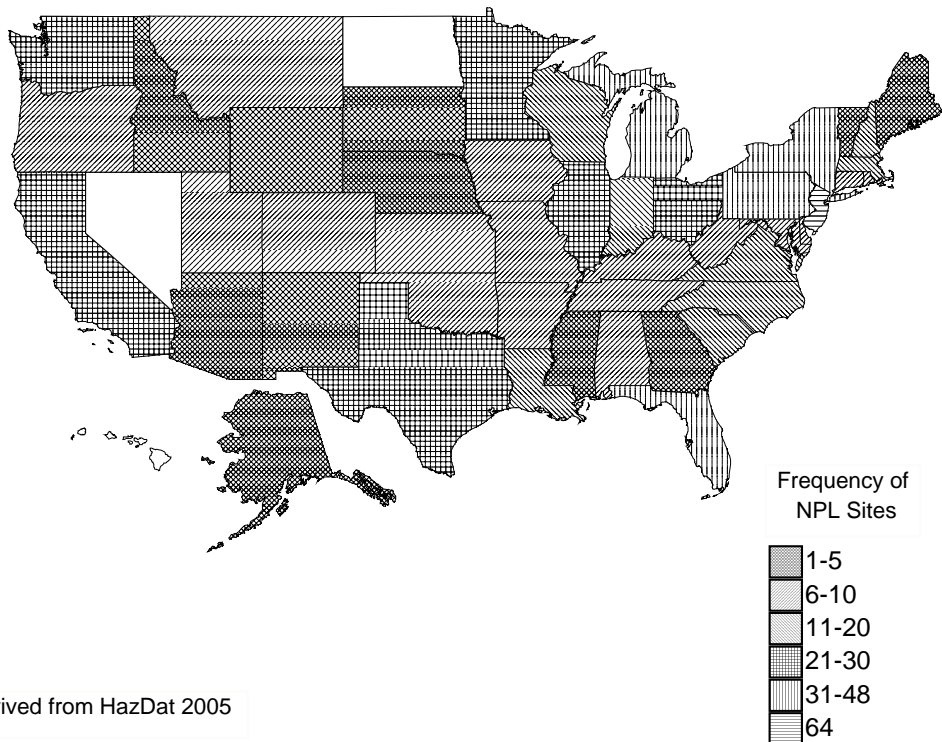
Most of the naphthalene entering the environment is discharged to the air. The largest releases result from the combustion of wood and fossil fuels and the off-gassing of naphthalene-containing moth repellents. Smaller amounts of naphthalene are introduced to water as the result of discharges from coal-tar production and distillation processes. The coal-tar industry is also a major source of the small amounts of naphthalene that are directly discharged to land. A large amount of naphthalene (often considerably more than 1,000 mg/kg) is present in soils contaminated with wastes from manufactured-gas plants.

Naphthalene in the atmosphere is subject to a number of degradation processes, including reaction with photochemically produced hydroxyl radicals. Naphthalene has a short half-life in most natural waters and soils because of its tendency to volatilize and biodegrade. As a consequence of these processes, there is little tendency for naphthalene to build up in the environment over time.

The concentration of naphthalene in air tends to be low in rural areas, but is elevated in urban areas. The highest atmospheric concentrations have been found in the immediate vicinity of specific industrial sources and hazardous waste sites. Naphthalene is also a common indoor contaminant in households using naphthalene-containing moth repellents or where tobacco is smoked. Sidestream smoke from one cigarette contained 46, 30, and 32 μg of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene, respectively. Levels in water, sediments, and soil tend to be low, except in the immediate vicinity of point sources of release, such as chemical waste sites.

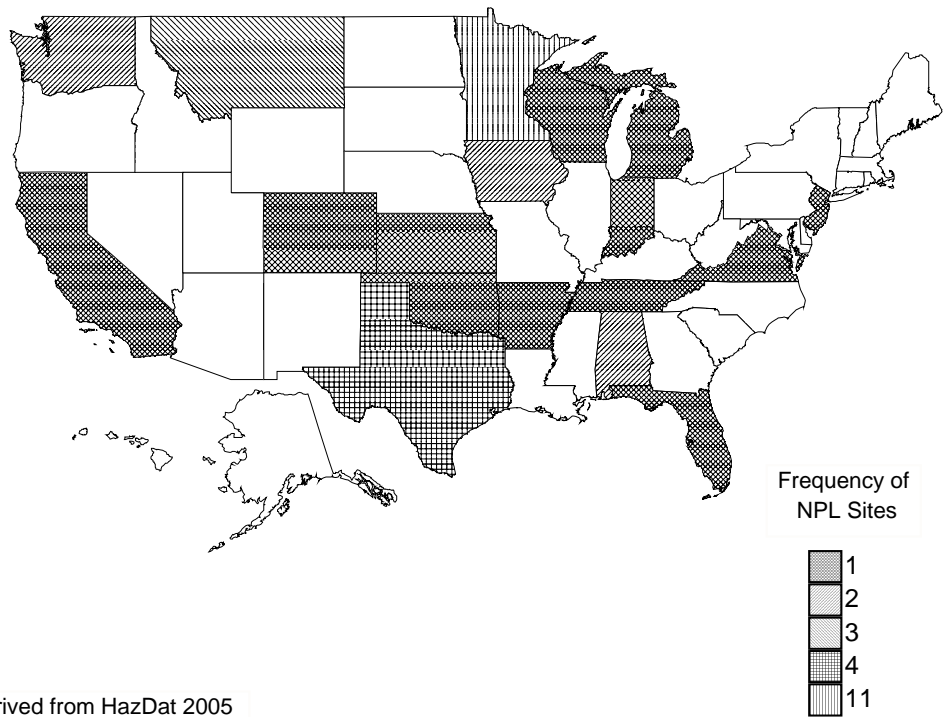
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Figure 6-1. Frequency of NPL Sites with Naphthalene Contamination



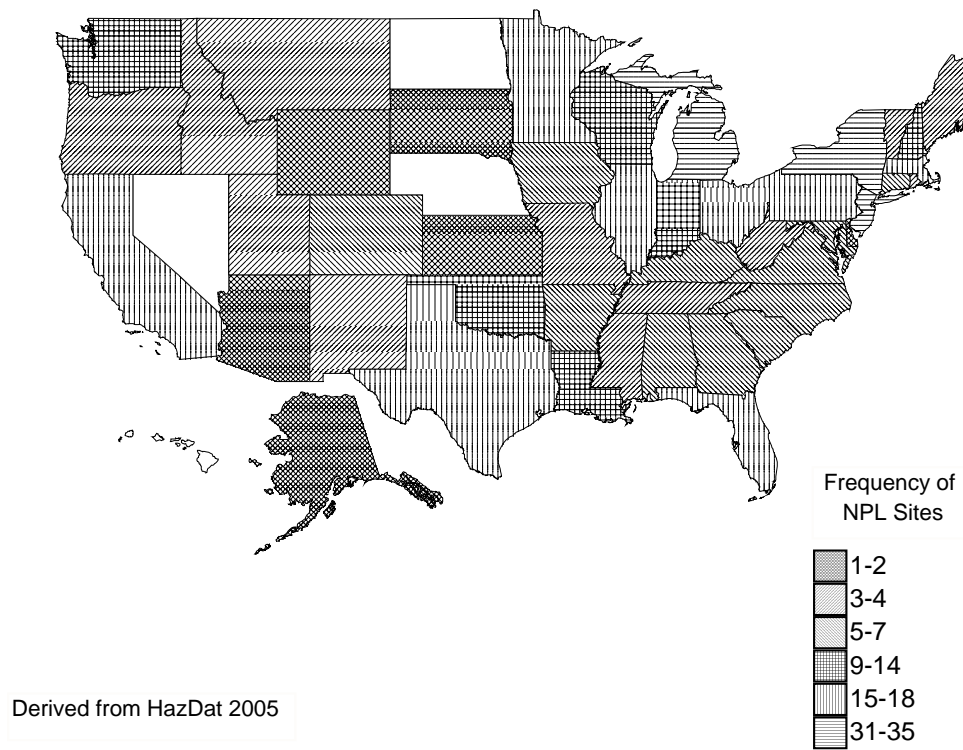
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Figure 6-2. Frequency of NPL Sites with 1-Methylnaphthalene Contamination



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Figure 6-3. Frequency of NPL Sites with 2-Methylnaphthalene Contamination



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The most likely pathway by which the general public is exposed to naphthalene is by inhalation due to the release of this substance from combustion fuels, moth repellents, and cigarette smoke. The estimated average per capita daily intake from ambient air is 19 μg . Exposure by other routes is not likely.

High naphthalene exposure levels could occur near industrial sources or chemical waste sites, but the extent of such exposure to individuals can only be evaluated on a site-by-site basis. High naphthalene exposure levels could also occur in certain work environments in industries that produce and use naphthalene such as wood preserving, tanning, coal distillation, and ink and dye production.

Based on limited data, potential human exposure to 1-methylnaphthalene or 2-methylnaphthalene is expected to be mainly by inhalation from ambient air. Exposure to these chemicals from tobacco smoke is likely.

1-Methylnaphthalene and 2-methylnaphthalene have also been detected in the environment, particularly in air. These are released from many of the same natural and industrial sources as naphthalene (combustion of wood and fossil fuels, tobacco smoke, coal distillation), but in smaller quantities.

Naphthalene has been identified in at least 654 of the 1,662 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (HazDat 2005). 1-Methylnaphthalene has been identified in at least 36 of these sites, and 2-methylnaphthalene has been identified in at least 412 of these sites. However, the number of sites evaluated for these chemicals is not known. The frequency of the sites at which naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene have been identified within the United States can be seen in Figures 6-1 through 6-3.

6.2 RELEASES TO THE ENVIRONMENT

The TRI data should be used with caution because only certain types of facilities are required to report (EPA 1997). This is not an exhaustive list. Manufacturing and processing facilities are required to report information to the Toxics Release Inventory only if they employ 10 or more full-time employees; if their facility is classified under Standard Industrial Classification (SIC) codes 20–39; and if their facility produces, imports, or processes $\geq 25,000$ pounds of any TRI chemical or otherwise uses $>10,000$ pounds of a TRI chemical in a calendar year (EPA 1997).

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Most of the naphthalene entering environmental media is from combustion, mainly residential wood heating, or from the use of naphthalene in moth repellents. About 10% of environmental releases are attributable to coal production and distillation, while naphthalene production losses contribute <1% of environmental releases (EPA 1982d). Methyl naphthalenes are released from similar sources, including fuel combustion and industrial discharges (GDCH 1992). Smoking tobacco also releases small amounts of naphthalene and methyl naphthalenes into the environment.

6.2.1 Air

Estimated releases of 2.07 million pounds (940.2 metric tons) of naphthalene to the atmosphere from 781 domestic manufacturing and processing facilities in 2002, accounted for about 72% of the estimated total environmental releases from facilities required to report to the TRI (TRI02 2004). These releases are summarized in Table 6-1.

Nearly all naphthalene entering the environment is released directly to the air (92.2%). The largest source of emission (more than 50%) is through inadvertent releases due to residential combustion of wood and fossil fuels (EPA 1982d). Naphthalene emissions from unvented kerosene space heaters have been reported (Traynor et al. 1990).

The second greatest contribution comes from the use of naphthalene as a moth repellent (EPA 1982d). Because it volatilizes appreciably at room temperature, virtually all of the naphthalene contained in moth repellent is emitted to the atmosphere. Thus, in 1989, about 12 million pounds of naphthalene were released to air from moth repellent use (see Section 5.3).

Naphthalene may also enter the atmosphere during coal-tar production and distillation processes, through volatilization processes (aeration) in publicly owned treatment works (POTWs), from the use of naphthalene in the manufacture of phthalic anhydride, during the production of naphthalene, and from tobacco smoke. Methyl naphthalenes may be released to air in stack emissions and from fuel combustion, forest fires, and tobacco smoke (GDCH 1992; HSDB 2004; IARC 1993). 1-Methyl naphthalene and 2-methyl naphthalene were reported in jet exhaust at average concentrations of 421 and 430 $\mu\text{g}/\text{m}^3$, respectively, and in the gas phase of diesel motor exhaust at 1.57 $\mu\text{g}/\text{m}^3$ each (GDCH 1992). The smoke of an American unfiltered cigarette contains 2.8 μg of naphthalene, 1.2 μg of 1-methyl naphthalene, and

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

State ^c	RF ^d	Air ^e	Reported amounts released in pounds per year ^b							
			Water ^f	UI ^g	Land ^h	Other ⁱ	Total release			
							On-site ^j	Off-site ^k	On- and off-site	
AK	1	52	0		0	12	0	52	12	64
AL	22	108,624	58		0	221,582	5	295,685	34,585	330,270
AR	8	6,113	7		0	42	250	6,120	292	6,412
AZ	1	14	No data		0	0	0	14	0	14
CA	44	13,482	89		0	17,729	439	28,581	3,158	31,739
CO	7	2,106	0		0	0	0	2,106	0	2,106
CT	4	17,579	0		0	0	0	17,579	0	17,579
DE	2	721	0		0	0	0	721	0	721
FL	15	515,776	5		0	0	0	515,781	0	515,781
GA	13	18,576	0		0	9	0	18,576	9	18,585
GU	1	288	No data		0	0	0	288	0	288
HI	2	623	20		0	50	0	643	50	693
IA	11	13,873	0		0	11	0	13,873	11	13,884
IL	42	161,983	88		0	24,504	2,509	162,071	27,013	189,084
IN	35	166,075	526	26,140	29,037		17	221,609	186	221,795
KS	11	6,607	16		0	2	31,587	6,626	31,587	38,213
KY	20	23,003	840		0	323	0	24,103	63	24,166
LA	51	89,494	1,072		3	4,722	0	92,701	2,590	95,291
MA	7	4,948	0		0	5	262	4,948	267	5,215
MD	11	13,018	0		0	0	0	13,018	0	13,018
ME	3	6,208	No data		0	0	17	6,208	17	6,225
MI	26	104,586	0		0	463	2,040	104,836	2,253	107,089
MN	4	5,369	0		0	6	70	5,371	74	5,445
MO	20	59,389	6		0	8	84	59,400	87	59,487
MS	8	46,209	277		0	0	0	46,487	0	46,487
MT	4	1,192	8		0	17	0	1,216	1	1,217
NC	11	5,273	21		0	2,405	32	6,981	750	7,731
ND	4	1,934	2		0	0	893	1,936	893	2,829
NE	1	1,465	No data		0	9,853	0	1,465	9,853	11,318
NJ	21	17,753	629		0	712	5	18,382	717	19,099
NM	11	10,637	5		5	0	1,199	10,647	1,199	11,846
NV	1	8,075	No data		0	0	0	8,075	0	8,075
NY	19	6,141	0		0	0	500	6,141	500	6,641
OH	47	51,153	37		0	12,718	667	51,198	13,376	64,574
OK	10	28,605	299		0	6,801	48	35,327	426	35,753
OR	3	16,276	0		0	0	3	16,276	3	16,279

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

State ^c	RF ^d	Air ^e	Reported amounts released in pounds per year ^b						
			Water ^f	UI ^g	Land ^h	Other ⁱ	Total release		On- and off-site
							On-site ^j	Off-site ^k	
PA	55	95,520	643	0	9,646	4,065	96,174	13,700	109,874
PR	12	1,745	0	0	0	0	1,745	0	1,745
SC	11	37,030	22,000	0	0	0	59,030	0	59,030
SD	3	52	No data	0	1	0	52	1	53
TN	6	4,706	No data	0	260	0	4,706	260	4,966
TX	127	282,582	738	204,570	11,548	9,282	470,932	37,788	508,720
UT	8	3,999	5	0	250	0	4,003	250	4,253
VA	11	1,357	8	0	2	0	1,365	2	1,367
VI	3	1,667	0	0	25	0	1,667	25	1,692
VT	1	4	No data	0	0	600	4	600	604
WA	15	4,840	0	0	1,087	0	5,537	390	5,927
WI	9	15,802	39	0	1,929	9	15,840	1,938	17,778
WV	10	85,154	63	0	10,983	110,190	85,221	121,169	206,390
WY	9	676	No data	0	1	250	677	250	927
Total	781	2,068,353	27,502	230,718	366,742	165,023	2,551,993	306,345	2,858,337

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.

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

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

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

RF = reporting facilities; UI = underground injection

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1.0 µg of 2-methylnaphthalene. Smoke from an equivalently filtered "little cigar" contains 1.2 µg of naphthalene, 0.9 µg of 1-methylnaphthalene, and 0.7 µg of 2-methylnaphthalene (Schmeltz et al. 1976).

As shown in Table 6-1, an estimated total of 2.1 million pounds of naphthalene, amounting to about 72% of the total environmental release under the TRI program, was discharged to the air from manufacturing and processing facilities in the United States in 2002 (TRI02 2004). The TRI data should be used with caution since only certain types of facilities are required to report. TRI is not an exhaustive list.

6.2.2 Water

Estimated releases of 27.5 thousand pounds (21.5 metric tons) of naphthalene to surface water from 781 domestic manufacturing and processing facilities in 2002, accounted for about 1% of the estimated total environmental releases from facilities required to report to the TRI (TRI02 2004). These releases are summarized in Table 6-1.

About 5% of all naphthalene entering the environment is released to water (EPA 1982d). Most of that amount is attributable to coal-tar production and distillation processes. Some naphthalene (about 60%) from these sources is discharged directly to surface waters; the remainder is distributed to POTWs. The effluent and oil-spills from the wood-preserving industry is the only other source of consequence that releases naphthalene into the nation's waterways,

Naphthalene was detected in 1.6% of effluent samples reported on the STORET database from 1980 to 1982 (Staples et al. 1985). Analysis of STORET data for 1978–1981 indicated that the range of detectable naphthalene concentrations in effluents was <1–36,000 µg/L (EPA 1982d).

The detection of naphthalene and methylnaphthalenes in groundwater in the vicinity of industrial facilities and landfills (see Section 6.4.2) (Brown and Donnelly 1988; Rosenfeld and Plumb 1991) indicates that these chemicals are released to water from these sources. Methylnaphthalenes have been detected in effluents from industrial sources (GDCH 1992; HSDB 2004). 1-Methylnaphthalene and 2-methylnaphthalene were reported in process sewage and production water samples from coal gasification plants at concentrations ranging from 78 to 278 µg/L and from 66 to 960 µg/L, respectively (GDCH 1992).

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As shown in Table 6-1, an estimated total of 27,502 pounds of naphthalene, amounting to about 1.0% of the total environmental release, was discharged to surface water from manufacturing and processing facilities in the United States in 2002 (TRI02 2004). An additional 230,718 pounds (8.0% of the total) was discharged by underground injection. The TRI data should be used with caution since only certain types of facilities are required to report.

6.2.3 Soil

Estimated releases of 366 million pounds reported under the TRI program (166.7 metric tons) of naphthalene to soils from 781 domestic manufacturing and processing facilities in 2002, accounted for about 12.8% of the estimated total environmental releases from facilities required to report to the TRI (TRI02 2004). An additional 0.231 million pounds (104.8 metric tons), constituting about 8.0% of the total TRI environmental emissions, were released via underground injection from facilities required to report to the TRI (TRI02 2004). These releases are summarized in Table 6-1.

It is estimated that only about 2.7% of the environmental releases of naphthalene are discharged to land (EPA 1982d). Sources include coal-tar production and minor contributions from naphthalene production, POTW sludge disposal, and the use of organic chemicals that include naphthalene.

The residuals produced in gas production by coal carbonization, carbureted water gas production, or oil gas production at manufactured gas plants (MGPs) included PAHs (naphthalene, anthracene, phenanthrene and benzo[1]pyrene). These residuals were deposited on site in tar wells, sewers, nearby pits, or streams resulting in widespread soil and groundwater contamination (Luthy et al. 1994).

As shown in Table 6-1, an estimated 366,742 pounds of naphthalene, amounting to about 8.1% of the total environmental release, was discharged to land from manufacturing and processing facilities producing and using naphthalene in the United States in 2002 (TRI02 2004). The TRI data should be used with caution since only certain types of facilities are required to report.

No information was located on releases of 1-methylnaphthalene or 2-methylnaphthalene to soil.

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6.3 ENVIRONMENTAL FATE**6.3.1 Transport and Partitioning**

Naphthalene released to the atmosphere may be transported to surface water and/or soil by wet or dry deposition. Since most airborne naphthalene is in the vapor phase, deposition is expected to be very slow (about 0.04–0.06 cm/sec). It has been estimated that about 2–3% of naphthalene emitted to air is transported to other environmental media, mostly by dry deposition (EPA 1982d).

Naphthalene in surface water may volatilize to the atmosphere. With a vapor pressure of 0.087 mm Hg at 25 °C, solubility in water of 31.7 mg/L at 20 °C, and a Henry's law constant of 4.6×10^{-4} (EPA 1982e), it is likely that volatilization will be an important route of naphthalene loss from water. The rate of volatilization also depends upon several environmental conditions, including temperature, wind velocity, and mixing rates of the air and water columns (EPA 1982d). The half-life of naphthalene in the Rhine River was 2.3 days, based on monitoring data (Zoeteman et al. 1980). In an experiment using a mesocosm, that simulated Narragansett Bay, the half-life in water was 12 days during winter, with loss primarily due to volatilization (Wakeham et al. 1983).

Log octanol/water partition coefficients (K_{ow}) for naphthalene range from 3.29 to 3.37 and log organic carbon coefficients (K_{oc}) range from 2.97 to 3.27 (Bahnick and Doucette 1988; EPA 1982e; Howard 1989; Klecka et al. 1990; Thomann and Mueller 1987). These values include both experimentally determined and calculated values. The reported experimentally determined log K_{oc} is 3.11 (Bahnick and Doucette 1988). Based on the magnitude of these values, it is expected that only a small fraction (<10%) of naphthalene in typical surface water would be associated with particulate matter (Thomann and Mueller 1987). Thus, naphthalene discharged to surface waters would remain largely in solution, with smaller quantities being associated with suspended solids and benthic sediments.

Naphthalene is easily volatilized from aerated soils (Park et al. 1990) and is adsorbed to a moderate extent (10%) (Karickhoff 1981; Schwarzenbach and Westall 1981). The extent of sorption depends on the organic carbon content of the soil, with rapid movement expected through sandy soils (Howard 1989). The estimated soil adsorption coefficient for naphthalene in a soil with <0.6% organic carbon is 1.8 (Klecka et al. 1990). Because it adsorbs to aquifer material (Ehrlich et al. 1982), naphthalene's passage through groundwater will be somewhat retarded. Nevertheless, naphthalene frequently appears in effluent drainage from disposal sites (Rittman et al. 1980; Roberts et al. 1980; Schwarzenbach et al. 1983). However, sorption of naphthalene to aquifer materials with low organic carbon content (<0.03%)

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may be enhanced by the presence of nonionic low-polarity organics, such as tetrachloroethene, commonly found at hazardous waste sites (Brusseau 1991a).

Bioconcentration factors (BCFs) for naphthalene have been measured and calculated from the K_{ow} , K_{oc} , or water solubility. The values reported for log BCF range from 1.6 to 3 (Banerjee and Baughman 1991; Bysshe 1982; Geyer et al. 1982; Kenaga 1980; Southworth et al. 1978; Veith et al. 1979), indicating moderate bioconcentration in aquatic organisms. Naphthalene is reported to be rapidly eliminated from invertebrates when the organisms are placed in pollutant-free water (Eastmond et al. 1984; Tarshis 1981), and naphthalene is readily metabolized in fish (Howard 1989). Based on the magnitude of the K_{ow} , bioaccumulation in the food chain is not expected to occur (Thomann 1989). However, naphthalene exposure of cows and chickens could lead to the presence of naphthalene in milk and eggs (Eisele 1985).

Limited data were located on transport and partitioning of methylnaphthalenes in the environment. The respective vapor pressures (0.054 and 0.068 mmHg), water solubilities (25.8 and 24.6 mg/L), and Henry's law constants (3.60×10^{-4} and 4.99×10^{-4} atm·m³/mol) for 1-methylnaphthalene and 2-methylnaphthalene are of similar magnitude to these properties for naphthalene (HSDB 2004; Yaws et al. 1991). Thus, it is likely that loss of methylnaphthalenes from ambient water occurs by volatilization. In a mesocosm experiment, that simulated Narragansett Bay, the half-life of 2-methylnaphthalene in water was 13 days in winter, with loss primarily due to volatilization (Wakeham et al. 1983). Based on the magnitude of log K_{ow} for 1-methylnaphthalene and 2-methylnaphthalene (3.87 and 3.86, respectively) (HSDB 2004) and the experimental log K_{oc} for 2-methylnaphthalene (3.93) (Bahnick and Doucette 1988), these chemicals may partition similarly to naphthalene in environmental media and are expected to be slightly mobile to immobile in soils (HSDB 2004). Log BCFs calculated for 2-methylnaphthalene range from 2 to 2.8 (Kenaga 1980) and measured log BCFs for 1-methylnaphthalene and 2-methylnaphthalene in oysters ranged from 2.7 to 4.1 (GDCH 1992). Methylnaphthalenes are also metabolized and excreted rapidly by fish and shellfish when they are removed from polluted waters (Breger et al. 1981; GDCH 1992).

6.3.2 Transformation and Degradation

6.3.2.1 Air

The most important atmospheric removal process for naphthalene is reaction with photochemically produced hydroxyl radicals (Howard 1989). The rate for this reaction is 2.17×10^{-11} cm³/molecule·sec (Atkinson et al. 1987) and the atmospheric half-life for naphthalene based on this reaction is <1 day. The

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major products of this reaction are 1- and 2-naphthol and 1- and 2-nitronaphthalene (Atkinson et al. 1987). Naphthalene also reacts with N_2O_5 , nitrate radicals, and ozone in the atmosphere (Atkinson et al. 1984, 1987) and photolysis is expected to occur, although no experimental data were located (Howard 1989).

Methylnaphthalenes also react with hydroxyl radicals. The reported rate constants are 5.30×10^{-11} and $5.23 \times 10^{-11} \text{ cm}^3/\text{molecule-sec}$ for 1-methylnaphthalene and 2-methylnaphthalene, respectively. Based on an atmospheric hydroxyl radical concentration of $1 \times 10^6/\text{cm}^3$, the corresponding atmospheric half-lives are 3.6 and 3.7 hours (GDCH 1992). Reactions of 1-methylnaphthalene and 2-methylnaphthalene with N_2O_5 radicals have half-lives of 24 and 19 days, respectively (GDCH 1992). These chemicals also react with atmospheric ozone.

6.3.2.2 Water

Naphthalene and methylnaphthalenes are degraded in water by photolysis and biological processes. The half-life for photolysis of naphthalene in surface water is estimated to be about 71 hours, but the half-life in deeper water (5 m) is estimated at 550 days (Zepp and Schlotzhauer 1979). The half-lives for photolysis of 1-methylnaphthalene and 2-methylnaphthalene were estimated at 22 and 54 hours, respectively (GDCH 1992).

Biodegradation of naphthalene is sufficiently rapid for it to be a dominant fate process in aquatic systems (Tabak et al. 1981). Data on biodegradation of naphthalene in biodegradability tests and natural systems suggest that biodegradation occurs after a relatively short period of acclimation (rapidly, half-life about 7 days] in oil-polluted water) and the biodegradation rate increases with the naphthalene concentration. The biodegradation occurs slowly (half-lives up to 1,700 days) in unpolluted water (Herbes 1981; Herbes and Schwall 1978; Herbes et al. 1980; Howard 1989; Kappeler and Wuhrmann 1978). Reported biodegradation half-lives range from 3 to 1,700 days in various water systems (Howard 1989). In a static-flask-screening test, naphthalene showed rapid acclimation and 100% loss from the test medium in 7 days (Tabak et al. 1981). In an experiment with Narragansett Bay seawater, the half-life of naphthalene in late summer was reported at 0.8 days, mainly due to biodegradation (Wakeham et al. 1983). The half-life of 2-methylnaphthalene was 0.7 days in the same experiment.

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Methylnaphthalenes are biodegraded under aerobic conditions after adaptation. The highest degradation rates were reported in water constantly polluted with petroleum (GDCH 1992).

6.3.2.3 Sediment and Soil

Naphthalene biodegradation rates are about 8–20 times higher in sediment than in the water column above the sediment (Herbes and Schwall 1978). Half-lives reported in sediment include 4.9 hours and >88 days in oil-contaminated and uncontaminated sediment, respectively (Herbes and Schwall 1978), 9 days in sediment near a coal-coking discharge (Herbes 1981), 3, 5, and >2,000 hours in sediments with high, medium, and low PAH levels, respectively (Herbes et al. 1980), and ranging from 2.4 weeks in sediments exposed to petroleum hydrocarbons to 4.4 weeks in sediments from a pristine environment (Howard 1989). Methylnaphthalenes biodegrade more slowly. Reported half-lives in sediments were 46 weeks for 1-methylnaphthalene and ranged from 14 to 50 weeks for 2-methylnaphthalene (GDCH 1992).

In soils, biodegradation potential is important to biological remediation of soil. Studies on biodegradation of PAHs suggest that adsorption to the organic matter significantly reduces the bioavailability for microorganisms, and thus the biodegradability, of PAHs, including naphthalene (Heitzer et al. 1992; Weissenfels et al. 1992). There is considerable variability in reported naphthalene soil half-lives. The estimated half-life of naphthalene reported for a solid waste site was 3.6 months (Howard 1989). In less contaminated soils, more rapid biodegradation is expected to occur (Howard 1989). In soils with 0.2–0.6% organic carbon and 92–94% sand, the half-lives were 11–18 days (Klecka et al. 1990). In another study, sandy loams with 0.5–1% organic carbon had naphthalene half-lives of 2–3 days (Park et al. 1990). Biodegradation is accomplished through the action of aerobic microorganisms and declines precipitously when soil conditions become anaerobic (Klecka et al. 1990). Studies indicate that naphthalene biodegrades to carbon dioxide in aerobic soils, with salicylate as an intermediate product (Heitzer et al. 1992).

Abiotic degradation of naphthalene seldom occurs in soils. In one study only about 10% of the naphthalene added to two soil samples treated with mercuric chloride to kill microorganisms was degraded over a 105- or 196-day period (Park et al. 1990).

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In contaminated subsurface soils often found at former MGP sites, naphthalene is present as a component coal tar, a dense nonaqueous-phase liquid (DNAPL). It may exist in the subsurface in the form of trapped pools of organic liquid or as immobilized macroporous ganglia. Slow dissolution of naphthalene and other PAHs from DNAPLs into the aqueous phase causes them to be unavailable to the microorganism, thus resulting in the dissolution of the PAHs being the rate-limiting step in their biodegradation (Thomas et al. 1986). Using phenanthrene as a test substance, Birman and Alexander (1996) showed that the viscosity of the NAPL may reflect a slower diffusion of the aromatic substrate in the more viscous NAPLs and its subsequent slower mass transfer to water. Ghoshal and Luthy (1996) demonstrated that a very large fraction of naphthalene can be biodegraded from an accessible coal-tar-NAPL (free flowing) by microorganisms in bioslurry systems. Metabolically active microflora were detected beneath the water table at a former MGP sites from 2.6 to 30.8 m below the ground surface. The subsurface micorflora appeared to be acclimated to the presence of PAHs and were found to mineralize naphthalene (8–55%) in sediment-water microcosms under aerobic conditions. Naphthalene biodegradation half-lives ranged from 18 to 480 days (Durrant et al. 1994).

Naphthalene remaining in soil for extended periods of time was shown to become less available to bacteria and earthworms (Kelsey and Alexander 1997).

The behavior of 1-methylnaphthalene in sandy loam was very similar to that of naphthalene. 1-Methylnaphthalene was easily volatilized from aerated soil, and the biodegradation half-life averaged between 1.7 and 2.2 days (Park et al. 1990). No data were identified on the biodegradation of 2-methylnaphthalene in soil.

6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene depends in part on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene 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 naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene 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

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bioavailable. The analytical methods available for monitoring naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene in a variety of environmental media are detailed in Chapter 7.

6.4.1 Air

Naphthalene has been reported in ambient air at several locations in the United States. The average reported concentration for 67 samples was $5.19 \mu\text{g}/\text{m}^3$, with most (60) of the samples and the highest concentrations at source-dominated locations (EPA 1988g). A median naphthalene level in urban air in 11 U.S. cities of $0.94 \mu\text{g}/\text{m}^3$ has been reported (Howard 1989). An average naphthalene concentration of $170 \mu\text{g}/\text{m}^3$ in outdoor air was reported in a residential area of Columbus, Ohio (Chuang et al. 1991), and naphthalene was measured in ambient air in Torrance, California at a concentration of $3.3 \mu\text{g}/\text{m}^3$ (Propper 1988). Average naphthalene concentrations ranging from 10 to $888 \text{ ng}/\text{m}^3$ were measured in several sites in Phoenix and Tucson, Arizona from 1994 to 1996 (Zielinska et al. 1998). A mean naphthalene concentration of $0.129 \text{ ng}/\text{m}^3$ was detected in ambient air at the Mississippi Sandhill Crane National Wildlife Refuge, Jackson County from May to September 1991 (White and Hardy 1994).

Average naphthalene concentrations detected in ambient air at five hazardous waste sites and one landfill in New Jersey ranged from 0.42 to $4.6 \mu\text{g}/\text{m}^3$ (LaRegina et al. 1986).

Naphthalene concentrations in indoor air may be higher than outdoors, with reported average indoor concentrations in various areas of homes ranging from 0.860 to $1,600 \mu\text{g}/\text{m}^3$ (Chuang et al. 1991; Hung et al. 1992; Wilson et al. 1989). However, based on a careful analysis of Chuang et al. (1991), the reported upper range value may be in error. A more representative upper limit concentration for indoor air may be $32 \mu\text{g}/\text{m}^3$, recorded in buildings in heavily trafficked urban areas of Taiwan (Hung et al. 1992).

Concentrations of naphthalene detected in indoor and outdoor air measured in 24 low-income homes in North Carolina ranged from 0.33 to 9.7 and from 0.57 to $1.82 \mu\text{g}/\text{m}^3$ respectively (Chuang et al. 1999). In homes with smokers, indoor and outdoor air concentrations were measured to be 2.2 and $0.3 \mu\text{g}/\text{m}^3$, respectively. Comparable values in homes without smokers were 1.0 and $0.1 \mu\text{g}/\text{m}^3$, respectively (EPA 1991e; IARC 1993). The average reported concentration of naphthalene inside automobiles in commuter traffic is about $4.5 \mu\text{g}/\text{m}^3$ (Lofgren et al. 1991).

Naphthalene has also been detected in air in industrial facilities. Reported naphthalene vapor levels ranged from 11 to $1,100 \mu\text{g}/\text{m}^3$ in a coke plant and from 0.72 to $310 \mu\text{g}/\text{m}^3$ in an aluminum reduction plant

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(Bjorseth et al. 1978a, 1978b). Reported particulate levels for the same facilities ranged from nondetected to $4.4 \mu\text{g}/\text{m}^3$, and from 0.9 to $4 \mu\text{g}/\text{m}^3$, respectively.

Naphthalene has been detected in the emissions from motor vehicles. Mean concentrations of 104.3, 31.9, and $54.1 \mu\text{g}/\text{m}^3$ of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene, respectively, were measured in the air samples collected from the Caldecott Tunnel located in San Francisco (Zielinska and Fung 1994). Mean concentrations of 1,709, 131, and $162.5 \text{ mg}/\text{m}^3$ of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene, respectively, were measured in the air samples collected from the Van Nuys Tunnel in Los Angeles (Fraser et al. 1998a). Mean concentration ranges of 0–589.2, 0–188.6, and 0–333.3 $\mu\text{g}/\text{m}^3$ of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene, respectively, were measured in the air samples collected from the Fort McHenry Tunnel in Baltimore. Mean concentration ranges of 16.2–68.9, 9.4–20.0, and 21.9–35.7 $\mu\text{g}/\text{m}^3$ of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene, respectively, were measured in the air samples collected from the Tuscarora Tunnel on the Pennsylvania Turnpike (Zielinska et al. 1996). Average concentrations of 137–1714, 92–1,458, and 154–2,129 ng/m^3 of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene, respectively, were detected during various flight related and ground-support activities of C-130H aircraft at an Air National Guard base (Childers et al. 2000).

Shauer et al. (2002) compared the tailpipe emissions of catalyst- and noncatalyst-converter-equipped motor vehicles. Approximately $1,000 \mu\text{g}/\text{km}^{-1}$ of naphthalene and 2-methylnaphthalene and $500 \mu\text{g}/\text{km}^{-1}$ of 1-methylnaphthalene were detected in the catalyst-equipped vehicles. Approximately $50,000 \mu\text{g}/\text{km}^{-1}$ of naphthalene and 2-methylnaphthalene and $30,000 \mu\text{g}/\text{km}^{-1}$ of 1-methylnaphthalene were detected in the noncatalyst converter-equipped vehicles.

1-Methylnaphthalene and 2-methylnaphthalene have been reported in ambient air at average concentrations of 0.51 and $0.065 \mu\text{g}/\text{m}^3$, respectively (EPA 1988g). Most of the data reported are from source-dominated areas, where the highest concentrations were detected. Methylnaphthalene (isomer not specified) was detected (concentration not reported) in ambient air at a hazardous waste site in New Jersey (LaRegina et al. 1986). 2-Methylnaphthalene was also reported in indoor air at an average concentration of $1.5 \mu\text{g}/\text{m}^3$ (EPA 1988g).

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6.4.2 Water

Naphthalene has been detected in surface water and groundwater in the United States. An analysis of 1980–1982 data from the STORET database indicates that naphthalene was detectable in 7% of 630 ambient water samples (Staples et al. 1985). The median concentration for all samples was <10 µg/L. Analysis of earlier (1978–1980) STORET data for naphthalene showed concentrations in positive samples ranging from 0.005 to 17 µg/L (EPA 1982d). Naphthalene was also detected in 11% of 86 urban runoff samples at concentrations ranging from 0.8 to 2.3 µg/L (Cole et al. 1984). In a study of contaminants of an urban watershed of Chesapeake Bay, naphthalene was detected in the northeast and northwest branches of Anacostia River (an urban watershed of Chesapeake Bay) at a concentration range of 0.18–21.6 ng/L. 2-Methylnaphthalene was also detected at a concentration of 0.57–62.7 ng/L (Foster et al. 2000). The mean concentration of naphthalene found in the water samples taken from 31 freshwater and estuarine sites adjacent to, nearby, or downstream from potential pollutant sources in Florida was 33 mg/L (Miles and Delfino 1999).

Naphthalene was detected in fewer than 5% of the 208 wells sampled from a variety of urban setting across the United States (Koplin et al. 1997). Naphthalene was detected in 3% of the samples taken from urban and rural wells from 1985 to 1995 (Squillace et al. 1999).

Naphthalene is rarely detected in drinking water. Naphthalene was reported in drinking water supplies in one area in the United States at levels up to 1.4 µg/L (EPA 1982d). Low levels of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene were detected in drinking water samples taken from a chlorine dioxide disinfection pilot plant in Evansville, Indiana. These compounds were identified as organic disinfection byproducts produced by chlorine dioxide treatment (Richardson et al. 1994).

Naphthalene and 2-methylnaphthalene were detected in groundwater at five wood treatment facilities (Rosenfeld and Plumb 1991). Naphthalene was reported in 35% of samples at all five sites at an average concentration of 3,312 µg/L. 2-Methylnaphthalene was reported in 27% of samples at four sites at an average concentration of 563 µg/L. Naphthalene was reported in leachate or groundwater plume from industrial and municipal landfills at concentrations ranging from <10 to 18.69 mg/L and from 0.11 to 19 mg/L, respectively. The methylnaphthalene (isomer not specified) concentration reported at a municipal landfill was 0.033 mg/L (Brown and Donnelly 1988). Naphthalene was detected in the groundwater in 12.7% of the 479 U.S. waste disposal sites (Barbee 1994). Naphthalene was also reported in the leachate of a household hazardous waste disposal in sanitary landfill. The 4-year mean

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concentrations of naphthalene ranged from 128.9 to 496.6 $\mu\text{g/L}$ (Kinman et al. 1995). Naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene have been detected in groundwater at Gas Works Park, Seattle, Washington, in the range of 0.02–12, 0.02–1.1, and 0.03–1.4 mg/L , respectively (Turney and Goerlitz 1990). Gas Works Park is located on the site of a coal and oil gasification plant that ceased operation in 1956.

1-Methylnaphthalene and 2-methylnaphthalene were reported in an urban snow-pack in Michigan at concentrations of <0.05 – 0.177 and <0.05 – 0.251 $\mu\text{g/L}$, respectively (Boom and Marsalek 1988).

Naphthalene has been reported at a mean concentration of 6.3 ng/L in seawater in the south Atlantic Ocean (Cripps 1992).

6.4.3 Sediment and Soil

Naphthalene and methylnaphthalenes have been reported at low concentrations in uncontaminated soils and sediments and at higher concentrations near or within sources of contamination. Naphthalene has been reported in untreated agricultural soils at levels ranging from 0 to 3 $\mu\text{g/kg}$ (Wild et al. 1990). Naphthalene was detected in urban soil samples taken from Boston, Massachusetts, Providence, Rhode Island, and Springfield, Massachusetts at a mean concentration of 0.125 mg/kg (Bradley et al. 1994). Reported naphthalene concentrations in contaminated soils included 6.1 $\mu\text{g/g}$ in coal-tar contaminated soil (Yu et al. 1990), 16.7 mg/kg in soil from a former tar-oil refinery (Weissenfels et al. 1992) and up to 66 $\mu\text{g/kg}$ in sludge-treated soils (Wild et al. 1990). Methylnaphthalenes (isomer not specified) were reported at a concentration of 2.9 $\mu\text{g/g}$ in coal-tar contaminated soil (Yu et al. 1990). Hawthorne et al. have reported concentration of naphthalene to be 48 mg/kg in the soil from an unspecified manufactured gas plant in Midwestern United States (Hawthorne et al. 2001). Naphthalene and 2-methylnaphthalene have been detected in groundwater at Gas Works Park, Seattle, Washington, in the range of 0–46 and 0–6.3 mg/L , respectively (Turney and Goerlitz 1990). Gas Works Park is located on the site of a coal and oil gasification plant that ceased operation in 1956.

Naphthalene was reported as detectable in 7% of 267 sediment samples entered into the STORET database (1980–1982), with the median concentration for all samples of <500 $\mu\text{g/kg}$ (Staples et al. 1985). Another analysis of STORET data indicated that concentrations in positive sediment samples ranged from 0.02 to 496 $\mu\text{g/kg}$ (EPA 1982d). Naphthalene and methylnaphthalenes (isomers not specified) were

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detected in contaminated and noncontaminated estuarine sediments (Brooks et al. 1990). Average concentrations of naphthalene detected in samples taken at 10 and 25 miles from an offshore coastal multiwell drilling platform were 54.7 and 61.9 $\mu\text{g}/\text{kg}$, respectively while concentrations of methyl-naphthalenes were 50.4 and 55.3 $\mu\text{g}/\text{kg}$, respectively. Naphthalene and methyl-naphthalenes concentrations in nearby noncontaminated estuarine sediments were 2.1 and 1.9 $\mu\text{g}/\text{kg}$, respectively. Naphthalene was detected in 7% of 496 streambed sediment sites across the United States tested for the presence of semivolatile organic compounds. The maximum concentration of naphthalene measured was 4,900 $\mu\text{g}/\text{kg}$ dry weight (Lopes and Furlong 2001). Concentration of naphthalene detected decreased from 33 to 2.1 ng/g dry weight with increasing depth (0–148 cm) in the sediment core in Richardson Bay and from 18–4.1 ng/g dry weight with increasing depth (0–239 cm) in the sediment core in San Pablo Bay (Pereira et al. 1999). These bays are located in the San Francisco Bay which is the largest urbanized estuary on the west coast of the United States.

6.4.4 Other Environmental Media

Naphthalene is not generally reported in fish, but has been detected in shellfish in the United States. Naphthalene was not detected in 83 biota samples (median detection limit 2.5 mg/kg) reported from 1980–1982 in the STORET database (Staples et al. 1985). Reported naphthalene concentrations ranged from 5 to 176 ng/g in oysters, from 4 to 10 ng/g in mussels, and from <1 to 10 ng/g in clams from U.S. waters (Bender and Huggett 1989). In shore crabs collected from the San Francisco Bay area, average naphthalene concentrations were 7.4 ng/g (Miles and Roster 1999). Naphthalene constituted 75–80% of total polyaromatic hydrocarbons (PAHs) found in the muscle, liver, and gonads of American plaice and yellow tail flounder caught off the coast of Newfoundland (Hellou and Warren 1996). Naphthalene and methyl-naphthalene (isomer not specified) were detected in the muscle (1.5–3.1 ng/g wet weight), kidney (1.4–4.3 ng/g wet weight), liver (1.4–4.7 ng/g wet weight), and blubber (8.3–23.5 ng/g wet weight) of harp seals caught in southern Labrador on the eastern coast of Canada (Zitko et al. 1998). Naphthalene and methyl-naphthalenes (isomer not specified) were detected at concentrations of 7.15 and 65.11 $\mu\text{g}/\text{kg}$ of salmon tissue, respectively, and at 12.9 and 17.3 $\mu\text{g}/\text{kg}$ of mussels, respectively. Both the salmon and mussels were caught in Exxon Valdez spill affected Snug Harbor in the Prince William Sound (Neff and Burns 1996). Methyl-naphthalenes have occasionally been detected in fish from polluted waters. 2-Methyl-naphthalene was reported at concentrations ranging from 0.4 to 320 $\mu\text{g}/\text{g}$ in fish from Ohio waters, but neither isomer of methyl-naphthalene was detected in muscle tissue of fish from polluted areas of Puget Sound (GDCH 1992). Methyl-naphthalenes were also detected in oysters in Australia at <0.3–

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2 µg/g. Naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene were detected at mean concentrations of 1.98, 0.96, and 1.98 ng/g, respectively, in farmed salmon and at 2.15, 1.53, and 2.93 ng/g, respectively, in wild salmon from the Pacific coast (Easton et al. 2002).

Naphthalene was detected in 2 of 13,980 samples of foods analyzed in six states (Minyard and Roberts 1991). In a Lower Rio Grande Valley environmental study, naphthalene (median concentration, 2.159 µg/kg body weight) was detected in five of the nine duplicate-diet samples (Berry et al. 1997). Naphthalene (1–7 µg/kg) was also detected in fresh tree-ripened apricots, plums, and their interspecific hybrids (Gomez et al. 1993). Naphthalene concentrations from vegetables grown in an industrial area of Thessaloniki, Greece were measured to be 0.37–15 µg/kg dry weight in cabbage; 8.9–30 µg/kg dry weight in carrots; 6.3–35 µg/kg dry weight in leeks; 4.9–53 µg/kg dry weight in lettuce; and 27–63 µg/kg dry weight in endive (Kipopoulou et al. 1999). Naphthalene was among the volatile organic compounds identified in whole and ground sorghum (Seitz et al. 1999).

Naphthalene levels in sterilized milk drinks contained in low-density polyethylene (LDPE) bottles were shown to be low (0.02 µg/mL) at the time of purchase, increasing to 0.1 µg/mL 30 days later, and averaging 0.25 µg/mL at the expiration date of the milk (Lau et al. 1994). Residual naphthalene present in the LDPE packaging was hypothesized to be the source of naphthalene contamination. A later study by the same authors observed that the level of naphthalene in LDPE milk bottle material had been reduced to 0.1–0.4 µg/g due to the use of new packaging material (Lau et al. 1995).

No information was located that documented methylnaphthalenes in food products.

Naphthalene was detected in the gas phase (5,860 µg/kg of meat cooked) as well as the particle phase (1,440–1,690 µg/kg of cooked meat) in the emissions from the process of charbroiling hamburger meat over a natural gas grill (Schauer et al. 1999a). Naphthalene was detected at a concentration of 227 mg/kg of wood burned from the fireplace combustion of pine wood. 1-Methylnaphthalene was detected at concentrations of 10.6, 6.39, and 4.31 mg/kg of wood burned from the combustion of pine, oak, and eucalyptus wood respectively. 2-Methylnaphthalene was detected at concentrations of 15.0, 9.31, and 5.69 mg/kg of wood burned from combustion of pine, oak, and eucalyptus wood, respectively. Naphthalene was not measured from the oak and eucalyptus fires (Schauer et al. 2001). In another study, the respective median concentrations of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene were determined to be 22.57, 4.14, and 4.76 mg/kg of burned soft wood in the fireplace; 60.86, 12.71, and

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15.55 mg/kg for hardwood in the fireplace; and 34.96, 5.23 and 6.32 mg/kg for hardwood burned in a woodstove (McDonald et al. 2000).

Reported levels of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene in measured in the smoke from U.S. commercial unfiltered cigarettes were 3, 1, and 1 μg , respectively (Schmeltz et al. 1978). Levels in sidestream smoke were found to be higher; 46, 30, and 32 $\mu\text{g}/\text{cigarette}$, respectively (Schmeltz et al. 1976).

Naphthalene has been detected in ash from municipal refuse and hazardous waste incinerators (EPA 1989g; Shane et al. 1990). Naphthalene was detected in 7 of 8 municipal refuse ash samples at 6–28,000 $\mu\text{g}/\text{kg}$ (Shane et al. 1990) and in 5 of 18 hazardous waste incinerator ash samples at 0.17–41 mg/kg (EPA 1989g). Higher concentrations were detected in bottom ash than in fly ash (Shane et al. 1990).

Naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene were among the chemicals detected in Lower Manhattan in the aftermath of the destruction of the World Trade Center, New York City, New York on September 11th, 2001. Concentration of naphthalene ranged from 699 ng/m^3 on 9/26–9/27 to 42 ng/m^3 on 10/21–10/22. The concentration of 1-methylnaphthalene ranged from 178 to 100 ng/m^3 and that of 2-methylnaphthylene ranged from 267 to 165 ng/m^3 for the same days (Swartz et al. 2003).

6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

The general population is exposed to naphthalene mainly by inhalation of ambient and indoor air. The use of naphthalene-containing moth repellents and smoke from cigarettes are the main sources of naphthalene in indoor air. Other sources include kerosene heaters. Based on an urban/suburban average air concentration of 0.95 $\mu\text{g}/\text{m}^3$ and an inhalation rate of 20 m^3/day , it has been estimated that the average daily intake from ambient air is 19 μg (Howard 1989). Intake from indoor air may be higher, depending on the presence of indoor sources.

The estimated average daily intake from ambient air may be about 10 μg for 1-methylnaphthalene and 1 μg for 2-methylnaphthalene. These estimates are based on ambient air samples taken from 64 (1-methylnaphthalene) and 17 (2-methylnaphthalene) locations (EPA 1988g) and an assumed human daily intake of 20 m^3 . Naphthalene was one of the PAHs detected in an 8-home pilot study that was

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conducted in Columbus, Ohio to measure the PAH concentration profiles in house-dust. The average concentration of naphthalene was found to be dependant upon the method of extraction (2.8 mg/m³ by soxhlet extraction and 1.8 mg/m³ by sonication extraction) (Chuang et al. 1995). Concentrations of naphthalene detected in the indoor and outdoor air measured in 24 low-income homes in North Carolina ranged from 0.33 to 9.7 and from 0.57 to 1.82 µg/m³, respectively (Chuang et al. 1999). In a study reporting the concentrations of volatile organic compounds (VOCs) in a wide range of environments (i.e., homes, offices, restaurants, pubs, department stores, train and bus stations, heavily trafficked roadside locations, buses, trains and automobiles) in Birmingham, United Kingdom, naphthalene concentrations were found to range from 0.1 µg/m³ (labs) to 12.1 µg/m³ (heavily trafficked roadside) (Kim et al. 2001). A mean concentration of naphthalene was found to be 2.3 µg/m³ in a German environmental survey that monitored 113 adults aged 25–69 years, selected at random, for personal exposure to VOCs including naphthalene (Hoffman et al. 2000). Low levels of naphthalene (average concentration, 0.44 µg/m³) and 1-methylnaphthalene (average concentration 0.08 µg/m³) were found in the indoor air of 92 and 81% of single family homes and apartments monitored, respectively (Kostianen 1995). Naphthalene has been detected in the smoke from charbroiling meat (Schauer et al. 1999a) and from the smoke from domestic fireplaces and wood burning stoves (McDonald et al. 2000; Schauer et al. 2001).

Exposure to naphthalene may occur from ingestion of drinking water and/or food, but these exposures are expected to be much less than inhalation exposures for the general population. Estimated exposure from drinking water, assuming a water concentration range of 0.001–2 µg/L, is 0.002–4 µg/day (Howard 1989). Estimates for food were not calculated. In a Lower Rio Grande Valley environmental study, naphthalene (median concentration, 2.159 µg/kg body weight) was detected in five of the nine duplicate-diet samples (Berry et al. 1997). Naphthalene was also detected in fresh tree-ripened apricots, plums, and their interspecific hybrids (Gomez et al. 1993), in vegetables such as cabbage, carrots, leeks, lettuce, and endive (Kipopoulou et al. 1999), and in whole and ground sorghum (Seitz et al. 1999). It has also been found in fish such as American plaice, yellow tail flounder (Hellou and Warren 1996), and salmon (Neff and Burns 1996).

Accidental ingestion of household products containing naphthalene such as mothballs or deodorant blocks frequently occurs in children. In 1990, 2,400 cases of accidental naphthalene ingestion were reported to 72 Poison Control Centers in the United States (Woolf et al. 1993). Nearly 90% of these cases occurred in children under 6 years of age.

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Dermal exposure to naphthalene may occur from handling or wearing clothing stored in naphthalene-containing moth repellents. However, no data were located concerning the level of human exposure to naphthalene, 1-methylnaphthalene, or 2-methylnaphthalene via this exposure route. Experimental studies have shown that naphthalene can be dermally absorbed and systemically metabolized in rats (Turkall et al. 1994).

Naphthalene was detected in 40% of human adipose tissue samples at concentrations ranging from <9 to 63 $\mu\text{g}/\text{kg}$ in a National Human Adipose Tissue Survey (NHATS) (EPA 1986g). Naphthalene was also detected (concentrations not reported) in six of eight selected breast milk samples from women in four U.S. cities (Pellizzari et al. 1982).

Naphthalene exposure may also occur in the workplace. Bjorseth et al. (1978a, 1978b) have reported vapor levels of 11–1,100 $\mu\text{g}/\text{m}^3$ and from 0 (nondetected) to 44 $\mu\text{g}/\text{m}^3$ for naphthalene-containing particulate in a coke plant. Similar measurements in an aluminum reduction plant yielded somewhat lower levels of 0.72–310 $\mu\text{g}/\text{m}^3$ for vapor and 0.08–4 $\mu\text{g}/\text{m}^3$ for particulates. Higher levels would be anticipated in naphthalene-producing industries and naphthalene-using industries such as wood preserving, tanning, and ink and dye production. A NIOSH (1980) survey of worker exposures to polyaromatic hydrocarbons at a petroleum refinery in Tulsa, Oklahoma reported air concentrations of naphthalene as high as 10.2 $\mu\text{g}/\text{m}^3$ in an area sample and 19.3 $\mu\text{g}/\text{m}^3$ for a personal sample. For 2-methylnaphthalene, 17.6 $\mu\text{g}/\text{m}^3$ was the maximum area concentration reported and 31.9 $\mu\text{g}/\text{m}^3$ was the highest value for a personal sample. A National Occupational Exposure Survey (NOES) conducted by NIOSH estimated that 112,702 and 4,358 workers are potentially exposed to naphthalene and 2-methylnaphthalene, respectively (NIOSH 1991). The workers at greatest risk of exposure included mining machine operators, aircraft engine mechanics, and miscellaneous machine operators. The NOES data have become progressively dated, and as a consequence, less representative of current exposure situations. The number of workers exposed to naphthalene during its manufacture and subsequent use is estimated to be 250–500 in the UK and 1,500–2,000 in the European Union (EU). These estimates do not include operators handling creosote treated lumber or brush applicators or users of tar paints/membranes (EU 2002).

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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 naphthalene via the same routes that affect adults, such as inhalation of contaminated air, ingestion of contaminated groundwater used as a source of drinking water, ingestion of contaminated food, and dermal contact with contaminated soils or products treated with the compound. The EPA (1996c) calculated an estimated intake range of 0.0002–0.043 mg/kg/day of naphthalene for a 10-kg child, assuming an ingestion of 100 mg of soil per day. Assuming food ingestion of approximately 0.5–2.3 kg/day for children, an estimated daily intake of 204–940 ng/kg-day was calculated for a 10-kg child. An estimated average daily dose of 1,127 ng/kg-day was calculated, assuming an inhalation rate of 8.7 m³/day for a 10-kg child.

Small children are more likely than adults to come into intimate contact with yard dirt, lawns, and dust from carpets. Dislodgeable pesticide residues in carpets or on uncovered floors may present a relatively important exposure route for infants and toddlers through dermal contact and oral ingestion. The tendency of young children to ingest soil, either intentionally through pica or unintentionally through hand-to-mouth activity, is well documented. These behavioral traits can result in ingestion of naphthalene present in soil and dust. Naphthalene has been detected in the house-dust in an 8-home pilot study (Chuang et al. 1995).

Dermal exposure to naphthalene may occur from handling or wearing clothing stored in naphthalene-containing moth repellents. No studies are available that describe the dermal absorption of naphthalene in

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children. Experimental studies have shown that naphthalene can be dermally absorbed and systemically metabolized in rats (Turkall et al. 1994).

Inhalation exposure is a major source of exposure in both adults and children. Naphthalene has been detected in the indoor air of homes (Chuang et al. 1995, 1999; Kostianen 1995). Naphthalene has been detected in the smoke from charbroiling meat (Schauer et al. 1999a) and from the smoke from domestic fireplaces and wood burning stoves (McDonald et al. 2000; Schauer et al. 2001).

Naphthalene was among the chemicals detected at nine day care centers in Durham, Raleigh, and Chapel Hill, North Carolina (Wilson et al. 1999). Indoor and outdoor air was found to contain naphthalene at concentrations of 205 and 89.6 ng/m³, respectively. The concentrations were 0.011 ppm in soil, 0.008 ppm in dust, 0.94 ppb in liquid food, and 0.25 ppb in solid food samples. The differences in PAH concentrations between day care centers serving low-income clients and those serving middle-income clients were found to be small.

Naphthalene (mothballs) is commonly used as a moth repellent in clothes during storage and as a deodorizer in diaper pails. Acute hemolysis was reported in 21 children following a period of inhalation exposure of naphthalene. The source of naphthalene was woolen clothes and blankets that had been stored with mothballs over the summer (Valaes et al. 1963).

A potential source of exposure in infants is from the presence of naphthalene in breast milk or formula. Naphthalene was detected (concentrations not reported) in six of eight breast milk samples from women in four U.S. cities (Pellizzari et al. 1982).

Children may also be exposed to naphthalene from milk drinks that have been stored in LDPE bottles. Naphthalene concentrations of 0.02 µg/mL were found in milk drinks stored in LDPE bottles at the time of purchase, but increased to 0.1 µg/mL 30 days later and averaged 0.25 µg/mL at the expiration date of the milk drink (Lau et al. 1994). Residual naphthalene present in the LDPE packaging was hypothesized to be the source of naphthalene contamination. A later study by the same authors observed that the level of naphthalene in LDPE milk bottle material had been reduced to 0.1–0.4 µg/g due to new packaging material (Lau et al. 1995).

Accidental ingestion of household products containing naphthalene, such as mothballs or deodorant blocks, can occur in children. In 1990, 2,400 cases of accidental naphthalene ingestion were reported to

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72 Poison Control Centers in the United States (Woolf et al. 1993). Nearly 90% of these cases occurred in children under 6 years of age.

6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Members of the general population most likely to have high levels of exposure to naphthalene are users of naphthalene-containing moth repellents (including infants exposed to blankets or clothing stored in naphthalene-containing mothballs), smokers, and those in proximity to smokers. Workers in naphthalene-producing or naphthalene-using industries could be subject to heightened exposure, and individuals living or working near hazardous waste sites at which naphthalene has been detected could also be exposed to higher naphthalene concentrations if they came into contact with contaminated media.

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 naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene are 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 naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene.

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

6.8.1 Identification of Data Needs

Physical and Chemical Properties. The physical and chemical properties of naphthalene that are required to evaluate its behavior in the environment have been determined (EPA 1982e; HSDB 2004). Information that documented the physical and chemical properties of 1-methylnaphthalene and 2-methyl-

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naphthalene are also available (HSDB 2004). However, measured Henry's law constants and log K_{oc} values for methylnaphthalenes would allow more accurate prediction of environmental fate processes.

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 2002, became available in May of 2004. This database is updated yearly and should provide a list of industrial production facilities and emissions.

Naphthalene producers, production locations and volumes, uses, releases, and disposal practices are well documented (Lacson et al. 2000; SRI 2004; TRI02 2004). Disposal of naphthalene-containing wastes are regulated by EPA, and major spills or accidental releases must be reported to EPA. No data were located on production volume, releases, and disposal practices for 1-methylnaphthalene or 2-methylnaphthalene. This information would be helpful to predict the potential for human exposure to these chemicals.

Environmental Fate. Existing information indicates that most naphthalene is released to the atmosphere and undergoes rapid reaction with hydroxyl radicals (Atkinson et al. 1987; EPA 1982d; Howard 1989). Available data indicate that volatilization and biodegradation are important removal processes from water and soil (EPA 1982d; Howard 1989; Tabak et al. 1981; Wakeham et al. 1983). Additional studies on the rates of volatilization, degradation, and transport in groundwater would be helpful in assessing potential human exposure in the vicinity of industrial sources and chemical waste sites. Data describing the volatilization, biodegradation, and transport of 1-methylnaphthalene and 2-methylnaphthalene would be useful in predicting the potential for human exposure.

Bioavailability from Environmental Media. No studies were located on the bioavailability of naphthalene in various environmental media. Available toxicity data indicate that naphthalene present in contaminated air and ingested in drinking water or soil is probably absorbed. Confirmatory, quantitative data would be useful. Data on infants indicate that toxicologically significant amounts of naphthalene may be absorbed dermally from residues left on stored clothing, especially under circumstances where baby oil was used on the infants' skin (Schafer 1951). Quantitative studies of the dermal absorption of naphthalene from water and soil would be useful in determining potential exposure for populations living near hazardous waste sites.

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No data have been located pertaining to the bioavailability of 1-methylnaphthalene or 2-methylnaphthalene in environmental media. Studies in laboratory animals to assess the absorption of this compound via the oral, inhalation, and dermal routes would be useful before bioavailability from each medium can be reasonably estimated.

Food Chain Bioaccumulation. Naphthalene is often readily degraded in the environment and is easily metabolized by a wide variety of organisms. Studies indicate that although naphthalene may bioconcentrate to a moderate degree for brief periods, it will not significantly bioaccumulate in organisms due to metabolism, and thus, is unlikely to biomagnify through the food chain (Howard 1989; Thomann 1989). Naphthalene has been found to be present in fish and shellfish (Bender and Huggett 1989; Hellou and Warren 1996; Miles and Roster 1999; Minyard and Roberts 1991; Neff and Burns 1996; Zitko et al. 1998). It has also been located in the flesh of fresh fruits and vegetables (Gomez et al. 1993; Kipopoulou et al. 1999; Seitz et al. 1999). Data were not located on 1-methylnaphthalene and 2-methylnaphthalene levels in foods. Additional data on naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene concentrations in foods and processed foods would be useful to assess the extent of human exposure via the food chain.

Exposure Levels in Environmental Media. Reliable monitoring data for the levels of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene in contaminated media at hazardous waste sites are needed so that the information obtained on levels of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene in the environment can be used in combination with the known body burden of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

The concentrations of naphthalene in the air, water, and soil have been documented (Bradley et al. 1994; Chuang et al. 1999; EPA 1988g; Howard 1989; Miles and Delfino 1999; Richardson et al. 1994; Squillace et al. 1999; Wild et al. 1990; Yu et al. 1990; Zielinska et al. 1998). In addition, indoor air levels have been measured (Chuang et al. 1991; Hung et al. 1992; Wilson et al. 1989). Additional information regarding exposure levels of 1-methylnaphthalene and 2-methylnaphthalene in environmental media would be useful for deriving exposure estimates for the general population.

Reliable monitoring data for the levels of naphthalene in contaminated media at hazardous waste sites are needed so that the information obtained on levels of naphthalene in the environment can be used in

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combination with the known body burden of naphthalene to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

Exposure Levels in Humans. A national survey of adipose tissue samples indicates that about 40% of the study subjects had measurable levels of naphthalene (EPA 1986g). Naphthalene was also detected in six of eight samples of human milk (Pellizzari et al. 1982). Data on the effect of cigarette filters on naphthalene uptake by the adipose tissues would be useful. Naphthalene has been detected in house dust (Chuang et al. 1995).

No data on exposure levels in humans were located for 1-methylnaphthalene or 2-methylnaphthalene. This information would be useful to determine whether any significant exposure to these chemicals occurs.

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

Exposures of Children. No monitoring studies have been performed to investigate the exposure to, and the body burden of, naphthalene in children. No studies are available on the dermal absorption of naphthalene in infants and toddlers due to activities such as crawling, which will result in contact with the floor (carpet) and soil or from exposure to clothes stored with mothballs. Since naphthalene is likely to be adsorbed to these materials, more information would allow the estimation of a child's exposure to naphthalene to be more rigorously determined. Naphthalene has been detected in house dust (Chuang et al. 1995). The EPA has calculated estimated amounts of naphthalene inhaled and naphthalene ingested via the intake of food and soil for a 10-kg child (EPA 2002b). No studies on amounts of naphthalene present in foods eaten by children are available. Such studies may help to identify childhood-specific means of decreasing exposure to naphthalene.

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 naphthalene, 1-methylnaphthalene, or 2-methylnaphthalene were located. These substances are not currently one of the compounds for which a sub-registry has been established in the National Exposure Registry. These substances will be considered in the future when chemical selection is made for sub-registries to be established. The information that is

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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. These studies are summarized in Table 6-2.

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Table 6-2. Ongoing Studies on the Potential for Human Exposure to Naphthalene^a

Investigator	Affiliation	Research description	Sponsor
Nylander French LA	University of North Carolina, Chapel Hill, North Carolina	Dermal exposure to benzene and naphthalene	National Institutes of Environmental Health Science
Aitken MD	University of North Carolina, Chapel Hill, North Carolina	Bacterial chemotaxis to naphthalene desorbing from non-aqueous phase liquid	National Science Foundation, Environmental Remediation Program
Atkinson R; Winer AM	University of California, Riverside, California	Photochemical and thermal reactions of combustion related particulate organic matter: A combined chemical and microbiological approach	ER-74 Office of Scientific and Technical Information
Boyd SA	Michigan State University, East Lansing, Michigan	Physicochemical and microbiological factors influencing the bioavailability of organic contaminants in subsoils	U.S. Department of Energy, Energy Research
Bryers JD	University of Connecticut Health Center, Farmington, Connecticut	Substrata surface chemistry, conformation of contaminant upon absorption, and availability for biodegradation	National Science Foundation, Environmental Remediation Program
Kilduff JE	Rensselaer Polytechnic Institute, Troy, New York	Collaborative research: Sorption reversibility of hydrophobic compounds in geosorbents investigated with model sorbents	National Science Foundation, Environmental Remediation Program
Thompson AF	Connecticut Agricultural Experimental Station, New Haven, Connecticut	Collaborative research: Sorption reversibility of hydrophobic compounds in geosorbents investigated with model sorbents	National Science Foundation, Environmental Remediation Program
Pulliam Holoman TR	University of Maryland, College Park, Maryland	Anaerobic degradation of polycyclic aromatic hydrocarbons in marine harbor sediments	National Science Foundation, Environmental Remediation Program
Sayler GS	University of Tennessee, Knoxville, Tennessee	On-line monitoring of aerobic bioremediation with bioluminescent reporter microbes	U.S. Department of Energy, Energy Research
Zylstra GJ	Rutgers University, New Brunswick, New Jersey	Molecular analysis of polycyclic aromatic hydrocarbon degradation by mycobacteria	National Science Foundation, Biomolecular Processes Cluster

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Table 6-2. Ongoing Studies on the Potential for Human Exposure to Naphthalene^a

Investigator	Affiliation	Research description	Sponsor
Pignatello JJ	Connecticut Agricultural Experimental Station, New Haven, Connecticut	Chain-transfer complexation of aromatic compounds with soil organic matter	U.S. Department of Agriculture
Inskeep WP	Montana State University, Bozeman, Montana	Fate and transport of chemicals in soils: linking chemical transformations	U.S. Department of Agriculture
Madsen EL	Cornell University, Ithaca, New York	Observing microbial diversity and horizontal gene transfer in a shallow aquifer	U.S. Department of Agriculture
Hagblom MM	Rutgers University, New Brunswick, New Jersey	Microbial degradation of PAHs in the rhizosphere of salt-marsh plants	U.S. Department of Agriculture
Pignatello JJ	Connecticut Agricultural Experimental Station, New Haven, Connecticut	Nonideal (specific) sorption of organic chemicals in soil organic matter	U.S. Department of Agriculture
Ogram AV; Hornsby AC	University of Florida, Gainesville, Florida	Pesticides and other toxic organics in soil and their potential for ground and surface water contamination	U.S. Department of Agriculture
Huang W	Drexel University, Philadelphia, Pennsylvania	Black carbon in soils and sediments and its interactions with organic pollutants	U.S. Department of Agriculture
Huwe JK; Hakk H; Shappell NW; Shlever WL; Larsen GL; Smith DJ	Agricultural Research Service, Fargo, South Dakota	Dioxins and other environmental contaminants in food	U.S. Department of Agriculture
Xing B	University of Massachusetts, Amherst, Massachusetts	Effects of long-term tillage and cover crop systems on soil organic matter and pesticide sorption	U.S. Department of Agriculture
Chorover JD	Pennsylvania State University, University Park, Pennsylvania	Effects of mineral-organic interactions on chemical processes in soils	U.S. Department of Agriculture
Thompson ML; Sandor JA; Burras CL	Iowa State University, Ames, Iowa	Human impacts on soil; a pedogenic perspective	U.S. Department of Agriculture
Hyman MR	North Carolina State university, Raleigh, North Carolina	Physiology, biochemistry, and enzymology of microbial cometabolism	U.S. Department of Agriculture
Larson RA; Sims GK	University of Illinois, Urbana, Illinois	Phytoremediation of agrochemicals with aquatic and terrestrial plants	U.S. Department of Agriculture

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Table 6-2. Ongoing Studies on the Potential for Human Exposure to Naphthalene^a

Investigator	Affiliation	Research description	Sponsor
Simkins S	University of Massachusetts, Amherst, Massachusetts	Quantification of pesticide-derived organic carbon in microbial biomass and soil humic substances	U.S. Department of Agriculture
Pignatello JJ	Connecticut Agricultural Experimental Station, New Haven, Connecticut	Reducing the potential for environmental contamination by pesticides and other organic chemicals	U.S. Department of Agriculture
Scow KM	University of California, Davis, California	Reducing the potential for environmental contamination by pesticides and other organic chemicals	U.S. Department of Agriculture
Maier RM; Brusseau ML	University of Arizona, Tucson, Arizona	Reducing the potential for environmental contamination by pesticides and other organic chemicals	U.S. Department of Agriculture
Xing B	University of Massachusetts, Amherst, Massachusetts	Sorption of organic contaminants in soils; mechanisms and implications for desorption and bioavailability	U.S. Department of Agriculture
Rolston DE	University of California, Davis, California	Transport and transformation of trace gases in soil	U.S. Department of Agriculture

^aFEDRIP 2004