6. POTENTIAL FOR HUMAN EXPOSURE

6.1 OVERVIEW

o-Cresol, *m*-cresol, *p*-cresol, and mixed cresols have been identified in at least 210, 22, 310, and 70 of the 1,678 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL), respectively (HazDat 2006). However, the number of sites evaluated for cresols is not known. The frequency of these sites for *o*-, *m*-, *p*-, and mixed cresols can be seen in Figures 6-1, 6-2, and 6-3, and 6-4, respectively.

Cresols are widely occurring natural and anthropogenic products. Although cresols appear to be ubiquitous in the environment, their concentrations probably remain low due to their rapid removal rates in most environmental media. In air, cresols degrade rapidly because of reactions with photochemically produced hydroxyl radicals. Biodegradation is the dominant mechanism responsible for the fast breakdown of cresols in soil and water. Nevertheless, cresols may persist in extremely oligotrophic waters, in those with limited microbial communities, and/or those under anaerobic conditions, such as in some sediments and groundwater aquifers.

Based on the available information, the most common route of exposure for the general population is inhalation. Cresols are constantly emitted to air via automobile exhaust; consequently, people who live in urban and suburban settings may be constantly exposed to low levels of cresols in the atmosphere. Cresols are also emitted to ambient air during the combustion of coal, wood, and municipal solid waste. Therefore, residents near coal- and petroleum-fueled electricity-generating facilities, municipal solid waste incinerators, and industries with conventional furnace operations or large-scale incinerators may be exposed to cresols in air. People in residential areas where homes are heated with coal, oil, or wood may also be exposed to cresols in air. High levels of cresol exposure can result from active and passive inhalation of cigarette smoke (Wynder and Hoffmann 1967). Therefore, people who smoke or live with smokers are exposed to higher concentrations of cresol in the air.

Figure 6-1. Frequency of NPL Sites with *o*-Cresol Contamination

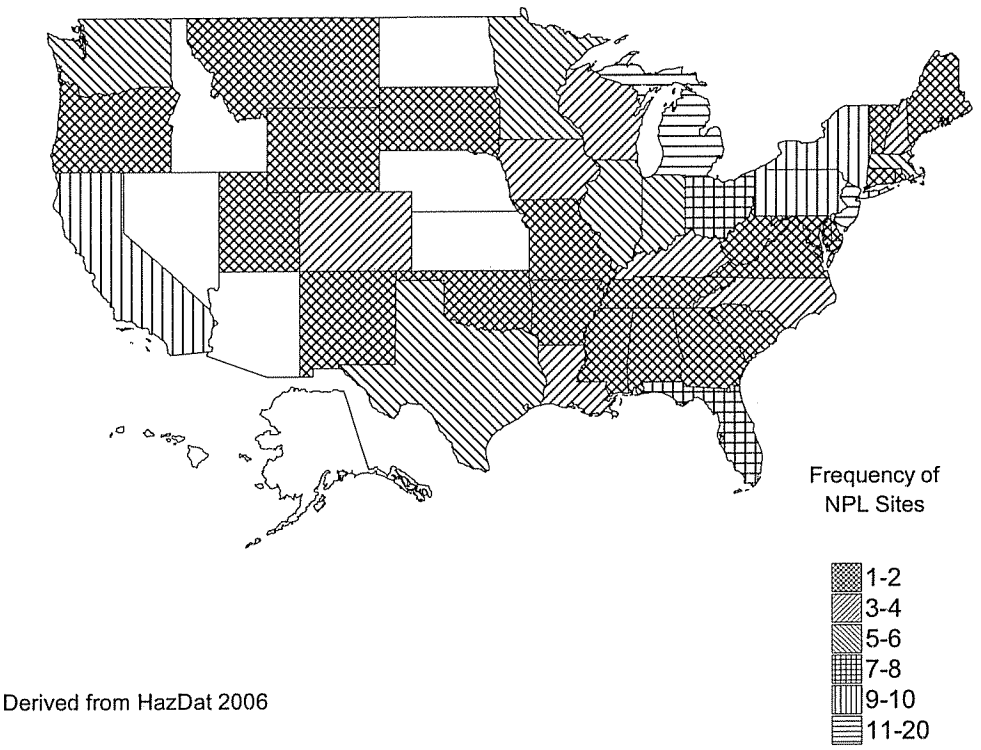
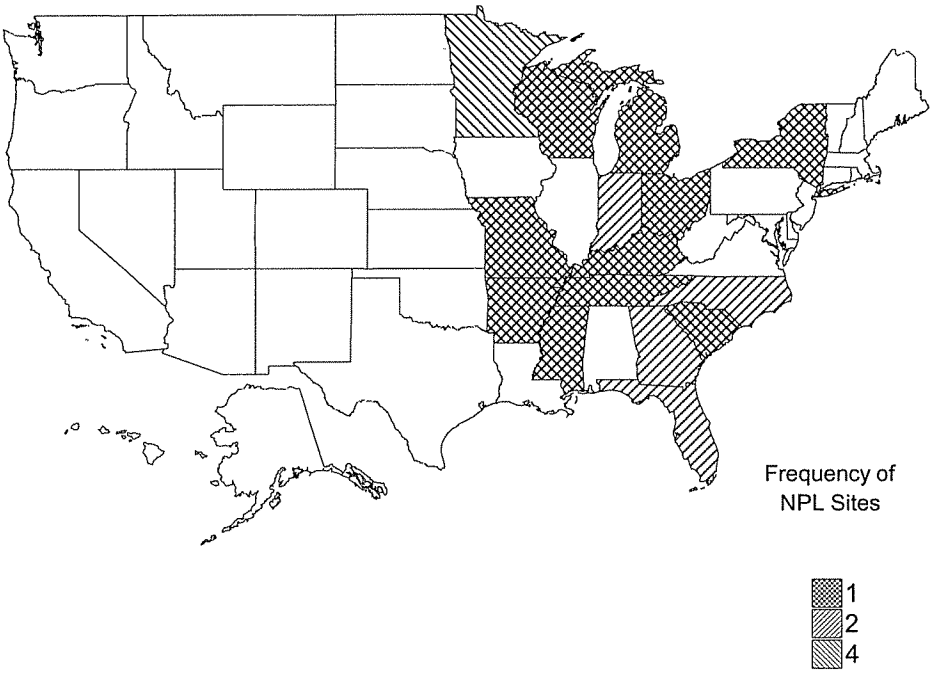


Figure 6-2. Frequency of NPL Sites with *m*-Cresol Contamination



Derived from HazDat 2006

Figure 6-3. Frequency of NPL Sites with *p*-Cresol Contamination

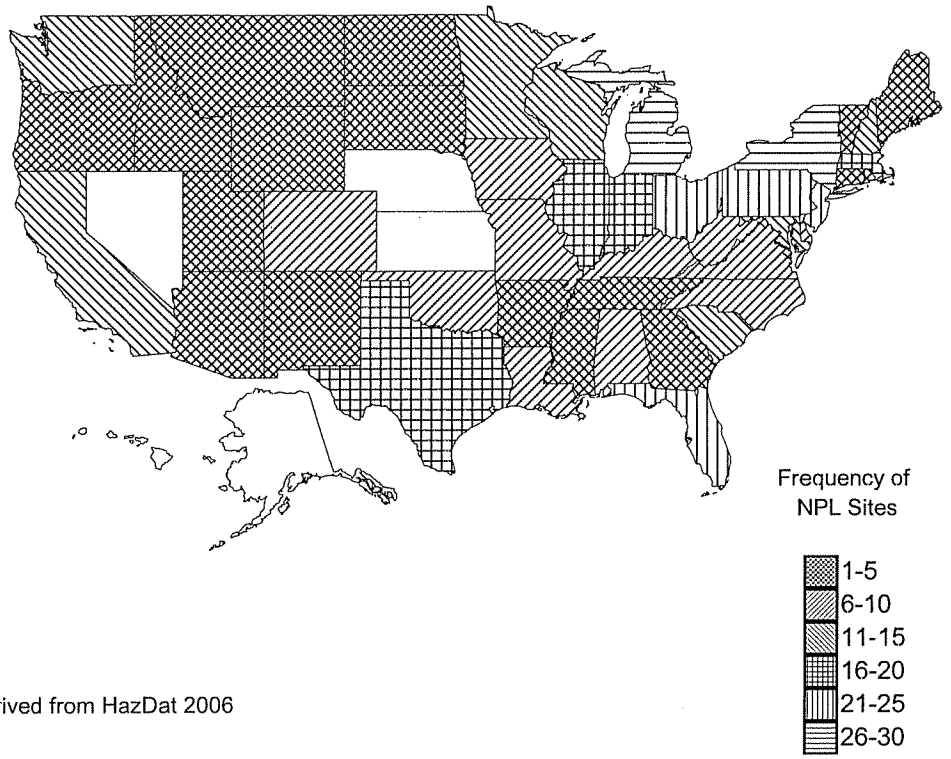
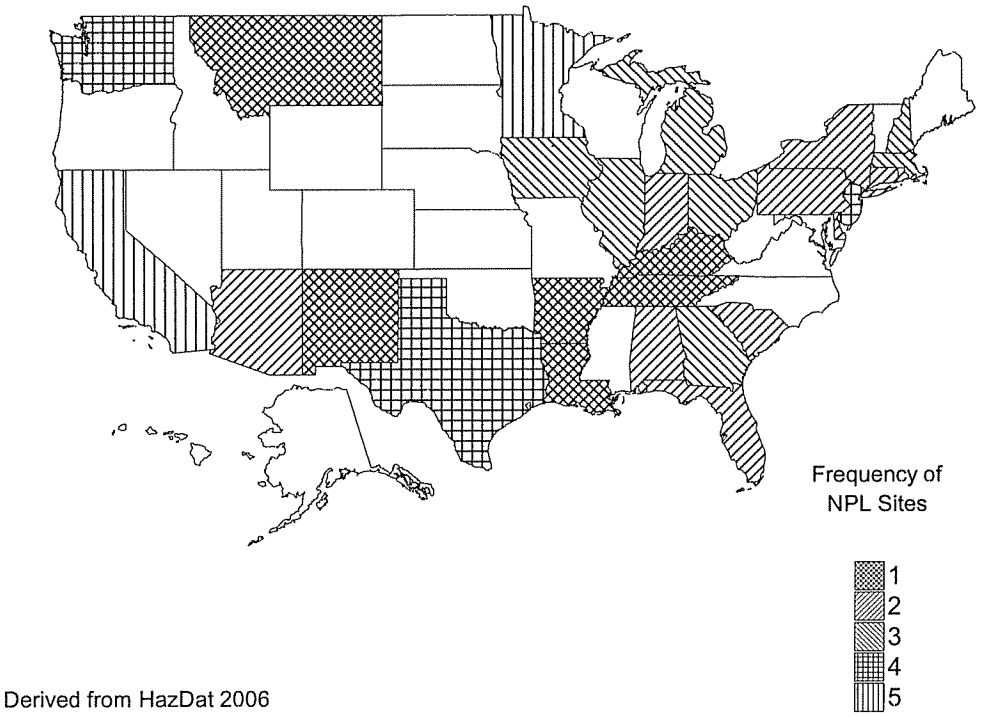


Figure 6-4. Frequency of NPL Sites with Cresols (Mixed Isomers) Contamination



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

6.2.1 Air

Estimated releases of 4,073 pounds (~1.9 metric tons) of *o*-cresol, 40.229 pounds (~18 metric tons) of *m*-cresol, 37,945 pounds (~17 metric tons) of *p*-cresol, and 926,379 pounds (~421 metric tons) of mixed isomers of cresol, to the atmosphere from 26, 31, 31, and 159 domestic manufacturing and processing facilities in 2004, accounted for about 1, 11, 15, and 63% of the estimated total environmental releases of *o*-cresol, *m*-cresol, *p*-cresol, and cresol mixed isomer from facilities required to report to the TRI (TRI04 2006), respectively. These releases are summarized in Tables 6-1 through 6-4.

A national emissions study conducted from 1990 to 1998 reported an estimated 11,000 tons/year released throughout the United States for all combined isomers of cresol (EPA 2000d). The emissions of total cresol isomers were 6,000 and 5,000 tons/year for urban and rural locations, respectively (EPA 2000d).

Cresols are a group of widely distributed natural compounds formed as metabolites of microbial activity and excreted in the urine of mammals (Fiege and Bayer 1987). Cresols occur in various plant lipid constituents, including oils from jasmine, cassia, Easter lily, ylang ylang, and *Yucca gloriosa* flowers, peppermint, eucalyptus, and camphor. Oils from conifers, oaks, and sandalwood trees also contain cresols (Fiege and Bayer 1987). Volatilization of natural cresols from urine and transpiration of plants

Table 6-1. Releases to the Environment from Facilities that Produce, Process, or Use *o*-Cresol[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
IL	2	10	No data	0	250	250	10	500	510
IN	1	690	No data	0	0	0	690	0	690
KY	2	481	No data	0	0	0	481	0	481
LA	2	10	0	0	0	0	10	0	10
MO	2	10	No data	0	0	0	10	0	10
NE	1	1	No data	0	5	11	1	16	17
NY	3	1,000	5	0	0	0	1,005	0	1,005
OH	3	131	0	0	0	0	131	0	131
TX	8	1,736	176	324,757	9	2	326,678	2	326,680
WI	2	4	0	0	0	0	4	0	4
Total	26	4,073	181	324,757	264	263	329,020	518	329,538

[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: TRI04 2006 (Data are from 2004)

Table 6-2. Releases to the Environment from Facilities that Produce, Process, or Use *m*-Cresol[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
AR	2	1	No data	0	0	0	1	0	1
IL	2	10	No data	0	250	250	10	500	510
IN	6	22,282	No data	0	0	0	22,282	0	22,282
KY	2	3,913	No data	0	0	0	3,913	0	3,913
MI	1	3	No data	0	0	0	3	0	3
MO	2	259	0	0	0	0	259	0	259
MS	1	2,970	No data	0	0	0	2,970	0	2,970
NC	1	4	No data	0	0	0	4	0	4
NY	1	255	5	0	0	0	260	0	260
OH	2	1,379	0	0	255	0	1,379	255	1,634
OK	1	0	No data	0	0	0	0	0	0
SC	3	163	No data	0	0	0	163	0	163
TN	1	1,537	No data	0	0	0	1,537	0	1,537
TX	5	7,424	2,535	331,140	179	52	341,099	231	341,330
WV	1	29	7	0	1	0	36	1	37
Total	31	40,229	2,547	331,140	685	302	373,916	987	374,903

[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: TRI04 2006 (Data are from 2004)

Table 6-3. Releases to the Environment from Facilities that Produce, Process, or Use *p*-Cresol[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
AR	1	1	No data	0	0	0	1	0	1
IL	2	10	No data	0	250	250	10	500	510
IN	6	14,064	No data	0	0	0	14,064	0	14,064
KY	2	2,933	No data	0	0	0	2,933	0	2,933
LA	3	3,604	0	2,227	0	0	5,831	0	5,831
MS	1	2,080	No data	0	0	0	2,080	0	2,080
NC	1	3	No data	0	0	0	3	0	3
NE	1	1	No data	0	5	11	1	16	17
NJ	1	8	No data	0	0	0	8	0	8
NY	1	10	5	0	0	0	15	0	15
OH	1	0	0	0	255	0	0	255	255
OK	1	0	No data	0	0	0	0	0	0
SC	1	18	No data	0	0	0	18	0	18
TN	1	1,020	No data	0	0	0	1,020	0	1,020
TX	7	14,171	374	206,758	217	14	221,430	104	221,534
WV	1	22	7	0	1	0	29	1	30
Total	31	37,945	386	208,985	728	275	247,443	876	248,319

[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: TRI04 2006 (Data are from 2004)

Table 6-4. Releases to the Environment from Facilities that Produce, Process, or Use Cresol (Mixed Isomers)[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	6	87,605	370	0	8	0	87,983	0	87,983
AR	4	42,539	39	0	14	0	42,580	12	42,592
CA	12	443	968	0	61	0	1,411	61	1,472
DE	1	0	55,369	0	0	0	55,369	0	55,369
FL	3	48,079	5	0	14	0	48,098	0	48,098
GA	7	101,622	11	0	7	0	101,640	0	101,640
IA	1	0	No data	0	0	0	0	0	0
ID	1	0	No data	0	0	0	No data	0	0
IL	9	1,564	145	0	1,814	5	1,709	1,819	3,528
IN	10	26,391	0	0	217	0	26,391	217	26,608
KS	1	301	0	0	0	0	301	0	301
KY	6	120,349	3	0	0	0	120,352	0	120,352
LA	15	21,780	1,978	83,996	220	98	107,785	288	108,073
MD	1	34,000	No data	0	0	0	34,000	0	34,000
ME	1	13,254	15	0	0	0	13,269	0	13,269
MI	2	9,427	549	0	1	4,633	9,977	4,633	14,610
MN	1	338	No data	0	452	3	338	455	793
MO	3	510	No data	0	0	0	510	0	510
MS	3	60,928	107	0	0	0	61,035	0	61,035
NC	3	83,176	40	0	340	0	83,216	340	83,556
NE	1	5	No data	0	250	261	5	511	516
NH	1	1,910	No data	0	0	0	1,910	0	1,910
NJ	2	1,553	22	0	772	0	2,347	0	2,347
NM	2	1,518	No data	0	0	852	1,518	852	2,370
NY	5	5,639	435	0	81	45	6,074	126	6,200
OH	8	26,337	240	10,230	14,950	0	36,806	14,951	51,757
OK	1	500	0	0	0	0	500	0	500
OR	1	0	No data	0	0	0	0	0	0
PA	4	9,114	9	0	14	18,000	9,134	18,003	27,137
SC	6	102,430	7	0	490	0	102,928	0	102,928
TN	2	22,996	21	0	0	0	23,017	0	23,017
TX	19	67,139	409	341,974	528	0	408,771	1,279	410,049
UT	3	500	500	0	6,264	41	7,250	55	7,305
VA	3	30,208	1	0	615	0	30,789	35	30,824
WA	6	2,817	243	0	2	0	3,062	0	3,062
WI	2	663	No data	0	0	0	663	0	663

Table 6-4. Releases to the Environment from Facilities that Produce, Process, or Use Cresol (Mixed Isomers)[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
WV	2	744	No data	0	805	0	744	805	1,549
WY	1	0	No data	0	2	0	0	2	2
Total	159	926,379	61,486	436,200	27,921	23,939	1,431,481	44,444	1,475,925

[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: TRI04 2006 (Data are from 2004)

may release cresols to the air. Cresols are also a product of combustion and can be released to the atmosphere from natural fires associated with lightning, spontaneous combustion, and volcanic activity (McKnight et al. 1982).

Cresols are natural components of crude oil and coal tar, from which they are recovered as fractional distillates. Cresols are also produced synthetically. The dominant anthropogenic sources for the release of cresols to the atmosphere are fugitive or accidental emissions during the manufacture, use, transport, and storage of cresols or associated products of the coal tar and petroleum industries.

Low levels of cresols are constantly emitted to the atmosphere in the exhaust from motor vehicle engines using petroleum based-fuels (Fraser et al. 1998; Hampton et al. 1982; Johnson et al. 1989; Seizinger and Dimitriades 1972). Using data collected from 7,060 vehicles entering a tunnel in Southern California, the emission rates (calculated as μg cresol emitted per liter of fuel consumed) of *o*-cresol, and *m/p*-cresol were calculated as 756.6 and 4,449.1 μg/L, respectively (Fraser et al. 1998). Cresols have been identified in stack emissions from municipal waste incinerators (Assmuth and Kalevi 1992; James et al. 1984; Jin et al. 1999; Junk and Ford 1980) and in emissions from the incineration of vegetable materials (Liberti et al. 1983). Cresols have also been identified as a component of fly ash from coal combustion (Junk and Ford 1980). Therefore, coal- and petroleum-fueled electricity-generating facilities are likely to emit cresols to the air. The combustion of wood (Hawthorne et al. 1988, 1989; Schauer et al. 2001) and cigarettes (Arrendale et al. 1982; Novotny et al. 1982) also emits cresols to the ambient air. Cresols are also formed in the atmosphere as a result of reactions between toluene and photochemically generated hydroxy radicals (Leone et al. 1985).

6.2.2 Water

Estimated releases of 181 pounds (~0.1 metric tons) of *o*-cresol, 2,547 pounds (~1.2 metric tons) of *m*-cresol, 386 pounds (~0.2 metric tons) of *p*-cresol, and 61,486 pounds (~28 metric tons) of mixed isomers of cresols to surface water from 26, 31, 31,and 159 domestic manufacturing and processing facilities in 2004, accounted for about 0.5, 0.7, 0.2, and 4.2% of the estimated total environmental releases of *o*-cresol, *m*-cresol, *p*-cresol, and cresol mixed isomer from facilities required to report to the TRI (TRI04 2006), respectively. These releases are summarized in Tables 6-1 through 6-4.

Cresols are widely distributed natural compounds. As discussed above, they are formed as metabolites of microbial activity and are excreted in the urine of humans (Needham et al. 1984) as well as other

mammals (Fiege and Bayer 1987). Cresols from human urine are biodegraded at municipal sewage treatment facilities prior to release to ambient waters. However, for combined septic and storm sewage systems, cresols may be released to surface waters during periods of precipitation when influent volumes exceed treatment plant capacities. Also, in rural and suburban areas where septic tanks are used (*o*- and *m*-cresols can resist anaerobic digestion), human excrement may be a nonpoint source release of cresols to groundwater.

Low levels of cresols are constantly emitted in the exhaust from motor vehicle engines using petroleum-based fuels (Hampton et al. 1982; Johnson et al. 1989; Seizinger and Dimitriades 1972). Therefore, waterways used for transportation and recreation are likely to receive cresols from ship and motorboat traffic. Waste water effluents from coal gasification (Giabbai et al. 1985; Neufeld et al. 1985) and liquefaction facilities (Fedorak and Hrudey 1986), shale oil production sites (Dobson et al. 1985; Hawthorne and Sievers 1984), refineries (Cardwell et al. 1986; Snider and Manning 1982), and a poultry processing plant (Andelman et al. 1984) also may release cresols to surface waters.

In general, cresols will degrade in surface waters very rapidly. However, cresols may persist in groundwater due to a lack of microbes and/or anaerobic conditions. Cresols are largely released to groundwater via landfills and hazardous waste sites. Tables 6-5 through 6-8 include monitoring data for these sources.

Coal liquefaction and other waste water may contain elevated levels of cresols. Effluent from coal gasification facilities contained *o*-cresol at a concentration of 586 mg/L (Fedorak and Hrudey 1986). Waste water effluents from coal gasification facilities contained *p*-cresol at concentrations of 880 mg/L (Neufeld et al. 1985) and 5.12 mg/L (Pellizzari et al. 1979). A coal liquefaction and a shale oil waste water effluent contained *p*-cresol at concentrations of 420 mg/L (Fedorak and Hrudey 1986) and 0.779 mg/L (Pellizzari et al. 1979), respectively. *p*-Cresol was emitted with the waste water of a poultry processing plant at concentrations ranging from 0.00214 to 0.0225 mg/L (Andelman et al. 1984). Waste water effluents from coal gasification facilities contained *m*-cresol at concentrations of 950 mg/L (Neufeld et al. 1985) and 2.67 mg/L (Pellizzari et al. 1979). A coal liquefaction and a shale oil waste water effluent contained *m*-cresol at concentrations of 1,230 mg/L (Fedorak and Hrudey 1986) and 0.561 mg/L (Pellizzari et al. 1979), respectively. Waste water effluents from coal gasification plants located in North Dakota contained *p*- and *m*-cresol at a combined concentration of 1,840 mg/L (Giabbai et al. 1985).

Table 6-5. Detection of *o*-Cresol in the Groundwater of Hazardous Waste Sites and Landfills

Type/location	Sampling dates	Number of samples	Number positive	Concentration	Reference
Waste sites, groundwater					
Hazardous waste/ Buffalo, New York	No data	No data	No data	2.3 mg/L	Weber and Matsumoto 1987
Pine tar manufacturing/ Gainesville, Florida	No data	No data	No data	3.08 mg/L	Drinkwater et al. 1986
Wood preserving/ Pensacola, Florida	March 1984	19	6	0.04–7.10 mg/L	Goerlitz et al. 1985
Coal gasification/Hoe Creek, Wyoming	No data	3	3	63–6,600 µg/L	Stuermer et al. 1982
Gas works Park/Seattle, Washington	December 1986	10	2	1–10 µg/L	Turney and Goerlitz 1990
American Creosote Works Facility/ Pensacola, Florida	March 1990	No data	No data	4.2 mg/L	Middaugh et al. 1991
Coal gasification/ Denmark	No data	12	8	10–77 µg/L	Johansen et al. 1997
Samara River/Ukraine (mine water)	1987–1990	No data	No data	1–10 µg/L	Goncharuk and Milyukin 1999
American Creosote Works Facility/ Pensacola, Florida (stream)	March 1990	No data	No data	0.0047 mg/L	Middaugh et al. 1991
Abandoned pine tar manufacturing plant/ Gainesville, Florida	No data	11	11	0.3–5,200 mg/L	McCreary et al. 1983
Effluent water					
American Creosote Works Facility/ Pensacola, Florida (feed water)	March 1990	No data	No data	10.95 mg/L	Middaugh et al. 1991
American Creosote Works Facility/ Pensacola, Florida (permeate water)	March 1990	No data	No data	0.157 mg/L	Middaugh et al. 1991
Industrial effluent/ Managua, Nicaragua	No data	4	1	418 µg/L	Bethune et al. 1996

Table 6-6. Detection of *m*-Cresol in the Groundwater of Hazardous Waste Sites and Landfills

Type/location	Sampling dates	Number of samples	Number positive	Concentration	Reference
Waste sites, groundwater					
Wood preserving/ Pensacola, Florida	March 1984	19	4	0.05–13.73 mg/L	Goerlitz at al. 1985
Infiltration of waste water, groundwater					
Municipal, secondary/ Port Devens, Massachusetts	No data	2	1	0.02 µg/L	Bedient et al. 1983; Hutchins et al. 1984
Samara River/Ukraine (mine water)	1987–1990	No data	No data	2.5–4 µg/L	Goncharuk and Milyukin 1999
Landfill, Groundwater					
Municipal/Southington, Connecticut	1982–1983	No data	No data	0.6 mg/L	Sawhney and Kozloski 1984
Gas works Park/Seattle, Washington	December 1986	10	1	1.5 mg/L	Turney and Goerlitz 1990
American Creosote Works Facility/ Pensacola, Florida	March 1990	No data	No data	2.5 mg/L	Middaugh et al. 1991
American Creosote Works Facility/ Pensacola, Florida (stream)	March 1990	No data	No data	0.0031 mg/L	Middaugh et al. 1991
American Creosote Works Facility/ Pensacola, Florida (feed water)	March 1990	No data	No data	11.3 mg/L	Middaugh et al. 1991
American Creosote Works Facility/ Pensacola, Florida (permeate water)	March 1990	No data	No data	0.271 mg/L	Middaugh et al. 1991
Industrial effluent/ Managua, Nicaragua	No data	4	1	349 µg/L	Bethune et al. 1996

Table 6-7. Detection of *p*-Cresol in the Groundwater of Hazardous Waste Sites and Landfills

Type/location	Sampling dates	Number of samples	Number positive	Concentration	Reference
Waste sites, groundwater					
Hazardous waste/ Buffalo, New York	No data	No data	No data	15 mg/L	Weber and Matsumoto 1987
Wood preserving/ Pensacola, Florida	March 1984	19	3	0.02–6.17 mg/L	Goerlitz et al. 1985
Gas Works Park/Seattle, Washington	December 1986	10	2	0.6 and 1.6 mg/L	Turney and Goerlitz 1990
American Creosote Works Facility/ Pensacola, Florida	March 1990	No data	No data	2 mg/L	Middaugh et al. 1991
Landfill, groundwater					
Municipal/Southington, Connecticut	1982–1983	No data	No data	1.5 mg/L	Sawhney and Kozloski 1984
Waste sites/surface water					
American Creosote Works Facility/ Pensacola, Florida (stream)	March 1990	No data	No data	0.0022 mg/L	Middaugh et al. 1991
Effluent water					
American Creosote Works Facility/ Pensacola, Florida (feed water)	March 1990	No data	No data	8.5 mg/L	Middaugh et al. 1991
American Creosote Works Facility/ Pensacola, Florida (permeate water)	March 1990	No data	No data	0.75 mg/L	Middaugh et al. 1991
Industrial effluent/ Managua, Nicaragua	No data	4	2	166 µg/L	Bethune et al. 1996

Table 6-8. Detection of *p*- and *m*-Cresol in the Groundwater of Hazardous Waste Sites and Landfills

Type/location	Sampling dates	Number of samples	Number positive	Concentration	Reference
Waste sites, groundwater					
Pine tar, manufacturing/ Gainesville, Florida	No data	No data	No data	5.17 mg/L	Drinkwater et al. 1986
Coal gasification/Hoe Creek, Wyoming	No data	3	3	9.6–16.000 µg/L	Stuermer et al. 1982
Abandoned pine tar manufacturing plant/ Gainesville, Florida	No data	11	<0.3	0.3–2,900 µg/L	McCreary et al. 1983
Coal gasification/ Denmark	No data	12	7	5–77 µg/L	Johansen et al. 1997
Landfill leachate/Sweden	No data	3	3	34 µg/L	Oman and Hynning 1993

p- and *m*-Cresol were detected at a combined average concentration of 1.0 mg/L for three samples of retort water from a shale oil production facility (Hawthorne and Sievers 1984). *o*-Cresol was detected at an average concentration of 1.1 mg/L for three samples of retort water from a shale oil production facility (Hawthorne and Sievers 1984).

6.2.3 Soil

Estimated releases of 264 pounds (~0.1 metric tons) of *o*-cresol, 685 pounds (~0.3 metric tons) of *m*-cresol, 728 pounds (~0.3 metric tons) of *p*-cresol, and 27,921 pounds (~13 metric tons) of mixed isomers of cresol to soils from 26, 31, 31, and 159 domestic manufacturing and processing facilities in 2004, accounted for about 0.1, 0.2, 0.3, and 1.9% of the estimated total environmental releases of *o*-cresol, *m*-cresol, *p*-cresol, and mixed isomers respectively, from facilities required to report to the TRI (TRI04 2006). An additional 324,757 pounds (~147 metric tons) of *o*-cresol, 331,140 pounds (~150 metric tons) of *m*-cresol, 208,985 pounds (~95 metric tons) of *p*-cresol, and 436,200 pounds (~198 metric tons) of mixed isomers of cresols constituting about 99, 88, 84, and 30% of the total environmental emissions for *o*-cresol, *m*-cresol, *p*-cresol, and mixed isomers respectively, were released via underground injection (TRI04 2006). These releases are summarized in Tables 6-1 through 6-4.

Cresols can enter soil from the same types of natural sources as described above. In fact, microbial activity may be an important contributor of cresols to soil. Poultry manure reportedly contained *p*-cresol at an average concentration of 11.7 mg/kg (Yasuhara 1987). Consequently, natural cresols are constantly released to soils via excrement, exocellular secretions, and necromass of living and former living organisms, where they are expected to degrade rapidly (Section 6.3.2.3). Also, rural and suburban septic tanks and grazing animals on pasture lands may contribute relatively large amounts of cresols to soil.

Cresols are released to soil at landfills and hazardous waste sites. In general, cresols will degrade in soil very rapidly. However, cresols may persist in soil under anaerobic conditions or due to the toxic effects of high concentrations of cresols or other associated compounds. Tables 6-5 through 6-8 include monitoring data for these sources. The land application of municipal sewage sludges that contain cresols may also release cresols to soil (Demirjian et al. 1984, 1987).

6.3 ENVIRONMENTAL FATE

6.3.1 Transport and Partitioning

The transport and partitioning of an organic compound in the environment is a function of the physical and chemical properties of that compound and the site-specific characteristics of the environment (e.g., percentage soil organic matter). Based on the environmental correlations with physical properties (Thomas 1982), the physical and chemical properties of the three isomeric cresols are sufficiently similar to indicate that similar transport and partitioning processes will be important for each isomer in the environment. Therefore, their potential for partitioning between the various environmental compartments will be discussed collectively.

In the atmosphere, the vapor pressure of the isomeric cresols, 0.11±0.30 mmHg at 25.5 °C (AIChE 1989, 2000; Chao et al. 1983), suggests that these compounds will exist predominantly in the vapor phase (Eisenreich et al. 1981) rather than being bonded to atmospheric particles. This is consistent with experimental studies that found all three isomers in the gas phase of urban air samples, but they were not present in the particulate samples collected at the same time (Cautreels and Van Cauwenbergh 1978) when the droplets are present, gas-phase creosote will predominantly be taken up. The relatively high water solubility of the cresol isomers, 21,520–25,950 mg/L (Yalkowsky et al. 1987), indicates that wet deposition may remove them from the atmosphere. This is confirmed by the detection of cresols in rain water (Section 6.4.2). The short atmospheric residence time expected for the cresols (Section 6.3.2.1) suggests that cresols will not be transported long distances from their initial point of release.

Calculated soil adsorption coefficients (K_{oc}) of 17.5–117 have been determined for the three isomeric cresols, and compare favorably with experimentally determined values ranging from 22 to 158 (Boyd 1982; Koch and Nagel 1988). The estimated values were derived by regression analysis based on the inherent hydrophobicity (octanol/water partition coefficient [K_{ow}]) of an organic compound. For the soils studied in these adsorption studies, this type of regression analysis successfully predicted the potential for the movement of cresols through soil, suggesting high to very high mobility in soil (Swann et al. 1983).

The mobility of the isomeric cresols cannot be adequately described by considering their tendency to partition from water. The hydroxyl function of cresol is capable of forming relatively strong hydrogen bonds with active sites in the soil, and its mobility will depend on the degree in which these bonds are formed (Artiola-Fortuny and Fuller 1982; Boyd 1982; Southworth and Keller 1986). This was the rationale presented to explain large values obtained in laboratory experiments, which obtained K_{oc} values

for isomeric cresol ranging from 115 to 3,420 in a study of three different soils (Southworth and Keller 1986). A K_{oc} value near 3,000 would suggest only slight mobility in soil (Swann et al. 1983). The amount of hydrogen bonding to sites in the soil will be strongly influenced by the pH of the surrounding medium, the type of soil, its iron oxide content, anion exchange capacity, and amount of organic matter present. From the literature, one cannot make generalized trends as to which soils provide active bonding sites for the cresol isomers. For example, *m*-cresol adsorbed strongly to a high-clay-content soil (Southworth and Keller 1986), but not to two others (Luh and Baker 1970).

In water, the isomeric cresols may eventually volatilize to the atmosphere, but volatilization is expected to be a slow process. Based on their Henry's law constants, which range from $1.2x10^{-6}$ to $8.65x10^{-7}$ atm-m^3/molecule (Gaffney et al. 1987; Hine and Mookerjee 1975), the volatilization half-life from a model river 1 m deep, flowing at 1 m/sec, with a wind velocity of 3 m/sec can be estimated to range from approximately 30 to 41 days (Thomas 1982).

Experimental bioconcentration factors (BCFs) of 14.1 for *o*-cresol (Sabljic 1987) and 19.9 for *m*-cresol (Freitag et al. 1982) indicate that the isomers of cresol will not bioconcentrate in fish and aquatic organisms to any significant extent. Also, cresols are not likely to bioconcentrate in humans. Similar to their behavior in soil, the isomeric cresols are not expected to adsorb to sediment and suspended organic matter, although the potential for this process exists.

6.3.2 Transformation and Degradation

All cresol isomers can be rapidly removed from environmental media. The dominant removal mechanism in air appears to be oxidation by hydroxyl radical during the day and nitrate radical at night, with half-lives on the order of a day. In water under aerobic conditions, biodegradation will be the dominant removal mechanism; half-lives will be on the order of a day to a week. Under anaerobic conditions, biodegradation should still be important, but half-lives should be on the order of weeks to months. In soil under aerobic conditions, biodegradation is also important, with half-lives on the order of a week or less.

6.3.2.1 Air

Cresols degrade rapidly in air. Removal during the day is dominated by the reaction with hydroxyl radical (HO•), while nighttime removal is dominated by the nitrate radical. Reaction with other oxidants

in air (e.g., ozone) will be much slower than reactions with hydroxyl or nitrate radical (Atkinson and Carter 1984).

Hydroxyl radicals react with cresols by attacking the carbon bearing the hydroxyl group. Degradation products from this reaction include nitrocresols and products of ring opening such as pyruvic acid, acetaldehyde, formaldehyde, peroxyacetylnitrate, and nitrocresol (Atkinson et al. 1980; Grosjean 1984, 1985). Products may vary, depending on whether the reaction takes place in the gas or particle phase (Grosjean 1984). Second-order rate constants for *o*-, *p*-, and *m*-cresol of $4.0x10^{-11}$, $4.4x10^{-11}$, and $5.7x10^{-11}$ cm^3 $molecule^{-1}$ sec^{-1}, respectively, were determined (Atkinson 1985). Using $5x10^5$ molecules cm^3 as an average tropospheric hydroxyl radical concentration (Atkinson 1985) and the reaction rate constants presented above, the atmospheric half-lives for *o*-, *p*-, and *m*-cresol were calculated to be 9.63, 8.75, and 6.76 hours, respectively.

At night, hydroxyl radical concentrations decrease and nitrate radical concentrations increase (Platt et al. 1984), making nitrate radical reactions more important than hydroxyl radical reactions. Nitrate radicals attack cresols by removing the hydroxyl hydrogen, yielding a phenoxy radical. The average second-order rate constants for the reactions of *o*-, *p*-, and *m*-cresol and the nitrate radical are $1.01x10^{-11}$, $0.70x10^{-11}$, and $1.08x10^{-11}$ cm^3 $molecule^{-1}$ sec^{-1}, respectively (Atkinson et al. 1984; Carter et al. 1981). The half-lives for these reactions, assuming an average night-time nitrate radical concentration of $2.4x10^8$ molecules cm^3, are 4.8, 4.5, and 6.9 minutes for *o*-, *m*-, and *p*-cresols, respectively (Atkinson et al. 1984; Carter et al. 1981).

In addition to degradation by hydroxyl and nitrate radicals, all three cresol molecules absorb small amounts of UV light with wavelengths above 290 nm (Sadtler 1960a, 1960b, 1966). Therefore, direct photolysis is also possible; however, the photolysis rate is slow compared to the rate of reaction with atmospheric radicals.

6.3.2.2 Water

Dilute cresols have been tested for biodegradability in numerous screening tests and sewage treatment plant simulation tests, as well as in surface water, groundwater, estuarine water, and sea water. Most tests indicate that the cresol isomers rapidly and completely degrade to simpler molecules under aerobic conditions in fresh water. Degradation is slower in salt water and under anaerobic conditions.

All cresol isomers were found to degrade rapidly in biodegradation screening and sewage treatment plant simulation studies with half-lives between <24 hours and <7 days (Alexander and Lustigman 1966; Babeu and Vaishnav 1987; Baird et al. 1974; Chambers et al. 1963; EPA 1979; Heukelekian and Rand 1955; Ludzack and Ettinger 1960; Lund and Rodriguez 1984; Malaney 1960; Malaney and McKinney 1966; McKinney et al. 1956; Pauli and Franke 1972; Pitter 1976; Tabak et al. 1964; Young et al. 1968). In these studies, degradation was rapid with both acclimated and unacclimated inocula; initial concentrations ranged from 0.5 to >500 ppm. Degradation generally was slower at the higher concentrations; however, under sewage treatment plant conditions, high cresol concentrations can be degraded (e.g., Chudoba et al. [1968] reported >99% removal of starting material [4,448 ppm of *p*-cresol] in 3 days under sewage treatment plant conditions). The available screening tests indicate that the cresols are readily degraded by microorganisms and activated sludge.

Very little information is available concerning the differences in the biodegradability of the cresol isomers. Based on the results of one study (Visser et al. 1977), biodegradability of their isomers appears to exist in the order: *p*-cresol > *o*-cresol > *m*-cresol. Aerobic degradation under these conditions appears to be fast, with the initial step being the rate-limiting step. No intermediate products have been reported using grab samples and the inoculum (EPA 1978; Spain and van Veld 1983).

Aerobic biodegradation in salt water (estuarine and sea water) appears to be slower than in fresh water; insufficient information is available to estimate anaerobic degradation in salt water. Factors governing biodegradation of *m*- and *p*-cresol in salt water include spatial and temporal variations (e.g., salinity and temperature) (Bartholomew and Pfaender 1983; Palumbo et al. 1988; Pfaender and Bartholomew 1982a, 1982b; Spain and van Veld 1983; van Veld and Spain 1983), substrate concentration (Palumbo et al. 1988; Spain and van Veld 1983), and the presence or absence of sediment (van Veld and Spain 1983). Almost no information is available for *o*-cresol, although one biological oxygen demand (BOD) test in saline water suggested rapid degradation (Takemoto et al. 1981).

In contrast to aerobic conditions, cresols do not appear to degrade rapidly in anaerobic fresh water sediments, although very little information is available. Horowitz et al. (1982) reported that the cresol isomers in anoxic sediments from Wintergreen Lake in Kalamazoo County, Michigan, had degradation times in excess of 29 weeks. The authors also stated that, as described above for anaerobic sludges, the *m*- and *p*-cresol isomers showed the most degradation, while *o*-cresol resisted degradation.

In anaerobic groundwater samples and groundwater samples with aquifer materials, cresol isomers display the same pattern of degradation *p*-cresol > *m*-cresol > *o*-cresol, where *p*-cresol is the most readily biodegradable of the three isomers, seen in anaerobic sewage sludge experiments. Thomas et al. (1989) reported that *o*-cresol concentrations decreased, then increased, in a groundwater sample from a creosote-contaminated site. The authors suggested that *o*-cresol may be a metabolite of some other chemical present during the multi-component study.

The degradation pathway of *p*-cresol in groundwater appears to proceed by oxidation of the methyl group to first give the corresponding benzaldehyde, then benzoic acid (Kuhn et al. 1988; Smolenski and Suflita 1987; Suflita et al. 1988, 1989). The hydroxybenzoic acid then can be either decarboxylated or dehydroxylated to phenol or benzoic acid, respectively.

There are no hydrolyzable functional groups on cresol, so hydrolysis is not an important environmental fate process. In addition to biodegradation, chemical oxidation (including by superoxide, singlet oxygen, hydroxyl radical, and organic peroxy radicals) and photolysis may be removal pathways in the environment, but do not appear to be as fast as biodegradation under most conditions. Faust and Holgné (1987) reported that the irradiation of water containing fulvic acid produced a transient oxidant that oxidized *o*- and *p*-cresol. The transient radical was suggested to be an organic peroxy species. Irradiation of water without fulvic acid produced almost no degradation of *p*-cresol in 3 hours; the addition of fulvic acids caused rapid disappearance with half-times of about 50 minutes (EPA 1978). In water from Greifensee (a polluted, eutrophic, pre-alpine Swiss lake) at pH 8, calculated half-lives for the top meter of water (where light of the necessary wavelength is present) are 11 and 4.4 days for *o*- and *p*-cresol, respectively. Singlet oxygen is also produced by solar irradiation on natural waters and can react with cresols. A rate constant of 3.7×10^{-8} M^{-1} sec^{-1} for *p*-cresol reaction with singlet oxygen was produced in the laboratory by irradiation of water containing rose bengal (Scully and Hoigne 1987). Using a singlet oxygen concentration of 4×10^{-14} M (corresponding to the concentration in water at noon on a summer day), these authors calculated a half-life of 500 hours. EPA (1978) studied the direct photolysis of *p*-cresol in water. In pure water and using solar irradiation in April, EPA (1978) reported half-lives of approximately 35 days.

While the above data indicate that oxidative and photolytic processes occur during degradation of cresols in water, it is difficult to estimate the half-lives for these under environmental conditions. Since environmental waters vary significantly in clarity (and hence, in their ability to transmit light), as well as their concentration of fulvic substances, half-lives are expected to vary considerably. Additionally, the

absorbance of cresols changes with the pH of the water (EPA 1978). Thus, the amount of light absorbed at a specific wavelength by cresols will change with pH, as will the degradation rates. EPA (1978) estimated a half-life of *p*-cresol in environmental waters from direct photolysis of 300–400 days under summer light conditions. This, with the other estimates presented above, suggests that chemical oxidation from light-produced radicals and direct photolysis will not be a significant removal mechanism under most environmental conditions.

In addition to oxidants generated by light, Stone (1987) reported that ferric iron [Fe(III)] and manganese [Mn(III/IV)] oxides are capable of oxidizing *p*-cresol. Fe(III) and Mn(III/IV) oxides are common species found in surface water particulate and soils, as well as in dust and ash. Rate constants for *p*-cresol ranged from 10^{-9} to 10^{-6} mol/L-min for pH of 7.8–4.2, respectively. In the environment and at low pH values, these species may oxidize cresols with half-lives on the order of several hours.

6.3.2.3 Sediment and Soil

Cresol degradation in soil has been reported by Medvedev and Davidov (1981a, 1981b), Namkoong et al. (1988), and Dobbins and Pfaender (1988). Dobbins and Pfaender (1988) and Namkoong et al. (1988) found that the data for cresol degradation fit first-order kinetics, but with very different rates. Dobbins and Pfaender (1988) found that CO_2 from *m*-cresol degradation evolved slowly when *m*-cresol was incubated in water slurries of surface and subsurface soils from a pristine location. Degradation was followed by trapping radioactive carbon dioxide, and overall mass balances were performed by comparing radioactivity remaining in the soil with the trapped CO_2. In surface soils, first-order rate constants based on CO_2 evolution were 7.55×10^{-5}–6.31×10^{-4} $hour^{-1}$, which yields half-lives from 46 days to about 1 year.

By contrast, Namkoong et al. (1988) reported a rapid degradation of all cresol isomers in surface soils from an uncultivated grassland site. Degradation was followed by analyzing for the parent substance, and first-order kinetics were followed. *o*-Cresol reportedly had a half-life of about 1.6 days, while *p*-cresol degraded too fast to allow measurement of a rate constant. *m*-Cresol reportedly had a half-life of about 0.6 days. Medvedev and Davidov (1981a, 1981b) reported the same relative rates for the three isomers in a soil from the Soviet Union but did not report absolute rates. Times to disappearance in the soil were reportedly 16, 9, and 27 days for *o*-, *p*-, and *m*-cresol, respectively. These authors were unable to detect any secondary products from cresol metabolism. The differences in the rates reported by Namkoong et al. (1988) and Dobbins and Pfaender (1988) appear to be the result of the different analytical methods used.

Namkoong et al. (1988) used gas chromatography to determine the rate of cresol disappearance, while Dobbins and Pfaender (1988) used CO_2 evolution to determine the rate of carbon dioxide appearance. Thus, based on the available information, cresols degrade rapidly in soils, possibly becoming incorporated into soil microorganisms, but they mineralize slowly. Indeed, Dobbins and Pfaender (1988) noted that significant amounts of radioactivity were bound to the soil, which supports the explanation that cresols or cresol metabolites are incorporated.

6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to cresols depends in part on the reliability of supporting analytical data from environmental samples and biological specimens. Concentrations of cresols 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 cresol 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 cresols in a variety of environmental media are detailed in Chapter 7.

6.4.1 Air

Monitoring data have not shown cresols to be widely occurring atmospheric pollutants. A national emissions study conducted from 1990 to 1998 reported an estimated ambient concentration average of 31.7 ng/m^3 (EPA 2000d). In an analysis of contaminants of the air in southern California in August 1987, background levels of p-cresol and o-cresol were found in concentrations of 0.02–0.07 and 0.09–0.30 ppb (Harley and Cass 1994). The National Ambient Volatile Organic Compounds (VOCs) Database, a compilation of published and unpublished air monitoring data from 1970 to 1987, contained very little information on the cresols (EPA 1988e). The database contained only information for *o*-cresol in source-dominated atmospheres (air surrounding a facility or known release of the chemical in question). The median air concentration of *o*-cresol at source-dominated sites is 1.62 μg/m^3 for 32 samples (EPA 1988e). The median atmospheric concentration of *o*-cresol (10 samples collected at three unspecified sites in the United States) was 1.5 μg/m^3, a range of 0.5–20 μg/m^3 was reported for *p*-cresol (62 samples collected at 11 unspecified sites in the United States), and *m*-cresol was not detected in any of the three samples studied (Kelly et al. 1994). On September 8–9, 1993, 46.77 and 90.53 ng/m^3 of *o*-cresol and a mixture of *p*- and *m*-cresol, respectively, were detected in vapor-phase semivolatile organics over Southern

California during a major photochemical smog event (Fraser et al. 1998). Cresol was detected in the ambient air of Upland, California; however, specific isomers were not identified (Kolber et al. 1981).

All three isomers of cresol have been identified, but not quantified, in gas samples taken from various municipal landfills in southern Finland (Assmuth and Kalevi 1992). In coal gas effluent, *p*- and *m*-cresol were found in concentrations of 11.6 and 7.09 mg/L, respectively (Jin et al. 1999). *p*-Cresol was detected in the emissions at waste incineration plants in Germany at a concentration of 0.43 μg/m^3 (Jay and Stieglitz 1995). *p*-Cresol was indentified in the air adjacent to municipal incinerators, waste collection centers, and sewage treatment plants around Southampton, England in concentrations ranging from <0.1 to 24.5 μg/m^3 (Leach 1999).

In a study of air emissions from burning pine, oak, and eucalyptus, *o*-cresol was detected in the gas phase for all three samples at concentrations of 89.6, 47.7, and 37.8 mg/kg wood burned, respectively, and in the particle phase of oak and eucalyptus at concentrations of 0.018 and 0.006 mg/kg wood burned, respectively. A mixture of *p*- and *m*-cresol was detected in the gas phase for pine, oak, and eucalyptus in concentrations of 380, 179, and 110 mg/kg wood burned, respectively, and in the particle phase of all three wood types at concentrations of 0.5, 0.21, and 0.055 mg/kg wood burned, respectively (Schauer et al. 2001).

The absence of data does not necessarily indicate a lack of cresol emissions into ambient air. In general, cresols are highly reactive with hydroxyl and nitrate radicals in the day and night, respectively, and atmospheric half-lives for cresols are short. Scavenging by water may further reduce the atmospheric residence time of cresols (see Section 6.3.2.1).

6.4.2 Water

According to the EPA Storage and Retrieval Database (STORET), five water samples in Utah contained cresol at levels below quantification and one sample contained 2.9 μg/L of cresol in 2002–2006 (EPA 2006j). Information from this database is of limited value because it is difficult to determine the purpose and circumstances of the studies contained in the database. In a national study of organic contaminants in 139 U.S. streams located in 30 states from 1999 to 2000, *p*-cresol was detected in 24.7% of the samples taken with a maximum concentration of 0.54 μg/L and a mean concentration of 0.05 μg/L (Kolpin et al. 2002). In a study of public groundwater at superfund sites, *o*-cresol and *p*-cresol were detected with

maximum concentrations of 390 and 150 μg/L, respectively; however, neither was detected in well fields or finished water from treatment plants (Canter and Sabatini 1994).

o-Cresol was detected in fresh water samples from Spirit Lake, Washington, on August 7, 1980 and from South Fork Castle Lake and Smith Creek, Washington, on September 11, 1980 at unreported concentrations (McKnight et al. 1982). The presence of cresols attributed to the Mount St. Helens eruption on May 18, 1980 was most likely a result of incomplete combustion of plant materials (McKnight et al. 1982). Whether or not the cresols originated from wood fires or the actual eruption was not clarified.

p-Cresol was detected in surface water with a frequency of occurrence of 1.5% and with a geometric mean concentration of 11 μg/L for positive samples (CLPSD 1988). *p*-Cresol was identified as a contaminant of mixed water and sediment samples from the Tennessee River (Gordon and Goodley 1971) at a concentration of 200 μg/L (Goodley and Gordon 1976). *p*-Cresol also was detected in fresh water samples from Spirit Lake, Washington, on August 7, 1980 at unreported concentrations (McKnight et al. 1982).

m-Cresol was detected with a frequency of occurrence of 0.9% in surface water (CLPSD 1988). In addition, *m*-cresol was listed as a contaminant of the St. Joseph River in the Lake Michigan Basin (Great Lakes Water Quality Board 1983). *m*-Cresol was detected in fresh water samples from Spirit Lake, Washington, on August 7, 1980 at unreported concentrations (McKnight et al. 1982).

Industrial effluents are a source of groundwater exposure to cresols. While human exposure to these waters is unlikely, it is important to note these releases to groundwater. Unspecified isomers of cresol were detected from one of seven sample sites along the Delaware River at a concentration of 20 μg/L. This was a result of industrial waste water effluent discharged by the Philadelphia Northeast Sewage Treatment Plant, which discharges secondary effluent into the river (Hites 1979; Sheldon and Hites 1979). For Delaware River water from August 1976 to March 1977, the summer and winter average concentrations of unspecified isomers of cresols that were not traceable to any source were "not detected" and 2 μg/L, respectively; this suggested that rapid biodegradation prevents cresol detection during the warmer months (Sheldon and Hites 1978).

Tables 6-5 through 6-8 summarize the literature data on cresols found in groundwater and their respective anthropogenic sources.

Rain water at Portland, Oregon, contained *o*-cresol at concentrations ranging from 0.240 to 2.80 µg/L, with an average concentration of 1.02 µg/L for seven rainfalls between February 12, 1984 and April 12, 1984. In addition to this study, combined *p*- and *m*-cresol was detected in rain in Portland, Oregon at concentrations >1.1 µg/L (Grosjean 1991). Combined *p*- and *m*-cresol concentrations ranged from 0.380 to 2.00 µg/L, with an average concentration of >1.10 µg/L (Leuenberger et al. 1985). *o*-Cresol was detected in rain water from a rural site (Grepden, Switzerland) on April 3, 1986, at concentrations ranging from not detected to 1.3 µg/L. Combined *p*- and *m*-cresol concentrations ranged from 0.65 to 9.3 µg/L (Czuczwa et al. 1987). Combined *p*-and *m*-cresol were detected in rain and cloud water in Vosges Mountains in France at concentrations ranging from 0.47 to 2.23 µg/L (Levsen et al. 1993). *p*- and *m*-Cresol were also detected in concentrations ranging from 0.6 to 3.6 µg/L in cloud water samples taken from Mt. Brocken in Germany during June 1994 (Luttke et al. 1999). *p*-Cresol was found in snow samples from Finland, Moscow, and Siberia at concentrations 0.04, 0.004–0.06, and 0.29 µg/kg (Poliakova et al. 2000). *o*-Cresol was found in snow samples from Finland and Moscow in concentration of 0.07 and 0.03 µg/kg, respectively (Poliakova et al. 2000).

Cresols are formed when various aromatic compounds are metabolized. Therefore, cresols are expected to be in municipal waste water. *p*-Cresol was detected in five of nine municipal waste water plants in western Virginia with concentrations ranging from 0.18 to 0.86 µg/sample (Dietrich et al. 1993).

The absence of monitoring data does not necessarily indicate a lack of cresols in the environment. Cresols are widely occurring natural and anthropogenic products. However, biodegradation is probably the dominant mechanism responsible for the rapid removal of cresols from surface waters (see Section 6.3.2.2). Nevertheless, cresols may persist in extremely oligotrophic waters, in waters with limited microbial communities, and/or under anaerobic conditions such as in some sediments and groundwater aquifers.

6.4.3 Sediment and Soil

o-Cresol was detected in 3.7% of the soil samples in the Contract Laboratory Program Statistical Database (CLPSD) (CLPSD 1988). *p*- and *m*-Cresol were also detected with frequencies of occurrence of 4.4 and 0.9%, and geometric mean concentrations of 257 and 1,105 µg/kg for the positive samples, respectively (CLPSD 1988). *o*-Cresol was detected at maximum concentrations of 12,000, 21,000,

34,000, and 55,000 µg/kg in the soil of an abandoned pine tar manufacturing plant in Gainesville, Florida at four separate sites (McCreary et al. 1983).

Cresols are an excretory product of mammals and an intermediate biotransformation product of natural aromatics such as lignin constituents (Fiege and Bayer 1987). Soil microorganisms are capable of metabolizing cresols, and any anthropogenic release of cresol, other than massive spills, is likely to be rapidly degraded in soil (Section 6.3.2.3).

Cresols have been detected in various sediment samples. Reviewing data from the EPA STORET database from 2002 to 2006, *p*-cresol was identified, but not quantified, in 88 sediment samples from various locations in South Carolina (EPA 2006j). In Roane County, Tennessee, *p*-cresol was detected in two sediment samples at concentrations of 1,233 and 127 ppb. In a study of streambed sediment in 20 major river basins of the United States from 1992 to1995, *p*-cresol was identified in 37.8% of the sites with a maximum value of 4,800 µg/kg dry weight; however, 90% of the positive samples contained ≤430 µg/kg dry weight (Lopes and Furlong 2001). *o*- and *p*-Cresol were identified, but not quantified, in sediment samples obtained from the Elbe River of the German Bight (Schwarzbauer et al. 2000).

6.4.4 Other Environmental Media

As discussed above, cresols are widely distributed natural compounds. They are formed as metabolites of microbial activity and are excreted in the urine of animals. Various plant lipid constituents, including many oils, contain cresols. Cresols have also been detected in certain foods and beverages such as tomatoes, tomato ketchup, cooked asparagus, various cheeses, butter, oil, red wine, distilled spirits, raw and roasted coffee, black tea, smoked foods, tobacco, and tobacco smoke (Fiege and Bayer 1987). However, very few monitoring data for cresols in food were found in the literature. *p*-Cresol has been detected in fermented soybean curds at concentrations ranging from 52.0 to 67.3 µg/kg (Chung 1999) and *o*-cresol has been detected in big eyed herring fermented fish at a mean concentration of 18.6 µg/kg (Cha and Cadwallader 1995).

Both *o*-cresol and *p*-cresol have been detected in eggs of birds of the Selenga river estuary in Lake Baikal, Russia, one of the largest fresh natural water sources in the world. Concentrations ranged from 208 to <10 µg/kg dry weight and from 540 to <10 µg/kg dry weight for *o*- and *p*-cresol, respectively (Lebedev et al. 1998).

All three cresol isomers were identified as volatile emissions of fried bacon (Ho et al. 1983). Various brands of Scotch whiskey, whiskeys made outside of Scotland, cognac, armagnac, brandy other than cognac and armagnac, and white and dark rums contained cresol at concentrations of 0.01–0.20 ppm, 0.01–0.07 ppm, trace to 0.02 ppm, trace to 0.02 ppm, trace to 0.02 ppm, and trace to 0.20 ppm, respectively (Lehtonen 1983).

Cresols are emitted in cigarette smoke. The total concentration of *o*-cresol and combined *m*-cresol and *p*-cresol in cigarette smoke was reported to range from approximately 14 to 26 μg/cigarette and from 41 to 82 μg/cigarette, respectively (Wynder and Hoffmann 1967). Depending upon the rate of ventilation, *o*-cresol was detected in cigarette smoke at levels of 7.1–37 μg/cigarette, while combined *m*-cresol and *p*-cresol isomers were emitted at a rate of 12.3–68 μg/cigarette (Singer et al. 2002). The average cresol concentration in a 45 cubic meter chamber after six cigarettes had been smoked ranged from 0.17 to 3.9 $\mu g/m^3$ depending on the brand and type of cigarette (Nelson et al. 1998). In another study, *o*-, *m*-, and *p*-cresol were emitted from mainstream cigarette smoke at mean rates of 3.31, 2.55, and 6.36 μg/cigarette, respectively (Rustemeier et al. 2002). Under steady-state conditions in a furnished 50 cubic meter room, the exposure relevant emission factors (EREFs) of *o*-, *m*-, and *p*-cresol were 22–41, 16–35, and 32–72 μg/cigarette, respectively, depending upon the ventilation of the building (Singer et al. 2003). These EREFs measure not only the initial exposure to environmental tobacco smoke, but also the potential for exposure from the re-emission of chemicals from absorbing surfaces such as wallboard, carpeting, and other room furnishings.

6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

Inhalation exposure is likely to be the most common route of exposure for the general population to cresols. However, since cresols have a short residence time in both day- and night-time air; atmospheric levels are probably low despite their ubiquitous nature.

Cresols have been identified as components of automobile exhaust (Hampton et al. 1982; Johnson et al. 1989; Seizinger and Dimitriades 1972), and may volatilize from gasoline and diesel fuels used to power motor vehicles. Vehicular traffic in urban and suburban settings provides a constant source of cresols to the atmosphere. Hence, urban and suburban populations may be constantly exposed to atmospheric cresols. Cresols are also emitted to ambient air during the combustion of coal (Junk and Ford 1980), wood (Hawthorne et al. 1988, 1989), municipal solid waste (James et al. 1984; Junk and Ford 1980), and cigarettes (Arrendale et al. 1982; Novotny et al. 1982). Therefore, residents near coal- and petroleum-

fueled electricity-generating facilities, municipal solid waste incinerators, and industries with conventional furnace operations or large-scale incinerators may be exposed to cresols in air. People in residential areas where homes are heated with coal, oil, or wood may also be exposed to cresols in air.

Exposure to cresol may occur in atmospheres containing toluene. Cresols are formed in the atmosphere during photochemical reactions between toluene and photochemically generated hydroxy radicals (Leone et al. 1985).

Cigarette smoke is also a source of cresol exposure. One estimate indicated that an individual who smokes two packs of cigarettes a day may inhale 3 μg/day of total cresol (Wynder and Hoffmann 1967). Other estimates are somewhat higher; for instance, Nazaroff and Singer (2004) estimated that nonsmokers who live with a person who smokes nine cigarettes/day may inhale 2–5 μg/day of cresols through inhalation of second-hand smoke.

Ingestion of certain foods may be as prevalent or more prevalent a route of exposure than inhalation. However, more quantitative data on the occurrence of cresols in food would be required to make a comparison. Cresols have been detected in tomatoes and tomato ketchup, cooked asparagus, various cheeses, butter, and oil (Fiege and Bayer 1987). Beverages such as red wine and distilled spirits (Lehtonen 1983), raw and roasted coffee, and black tea contain cresols (Fiege and Bayer 1987). Fried (Ho et al. 1983), smoked, and barbecued foods also may contain cresols (Fiege and Bayer 1987). For people with groundwater wells near landfills or hazardous waste sites, drinking water may be an important source of exposure; individuals living near hazardous waste sites or cresol production facilities may also be exposed. Quantitative information for both foods and drinking water was lacking, and the respective average daily intakes were not calculated.

Dermal contact to cresols may occur during recreational activities at natural waterways containing either naturally or anthropogenically generated cresols. However, cresols are expected to degrade rapidly in surface water and this is not likely to be a major source of exposure.

According to the National Occupational Exposure Survey (NOES) conducted by NIOSH in the workplace between 1981 and 1983, 10,985 (483 are female), 21,313 (16,798 are female), 5,615 (1,174 are female), and 132,742 (28,184 are female) workers were potentially exposed to *o*-, *p*-, *m*-, and the mixture of isomers, respectively (NIOSH 1989). The NOES database does not contain information on the frequency, concentration, or duration of exposure of workers to any of the chemicals listed therein. These surveys

provide estimates of the number of workers potentially exposed to the chemicals in the workplace. The most probable routes of occupational exposure are inhalation and dermal contact at places where cresols and/or cresol-containing compounds are produced or used.

Very little information pertaining to occupational exposure to cresols was located in the literature. Occupational exposure to cresols has been documented in laboratories and coal gasification facilities (Needham et al. 1984), during paint and varnish application (Angerer and Wulf 1985), during application of insulation lacquers to copper wires, and in wood-preserving facilities (Nieminen and Heikkila 1986). During the creosote impregnation of wood, workers were exposed to cresol concentrations <0.1 mg/m^3 (Heikkila et al. 1987). Workers of a bench scale coal conversion process were exposed to atmospheric levels of cresols <0.1 ppm in 1981 and 1982 (Dreibelbis et al. 1985).

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).

No data regarding environmental cresol exposure in children were found. No reports or studies of cresol in baby food or breast milk were found. The most likely route of exposure to cresols for children is through inhalation of ambient air. Children who live in areas of high traffic or with adults who smoke are more likely to be exposed to cresols through inhalation.

6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

High levels of exposure to cresols are most likely to occur in occupational settings where cresols are either produced or used. Intake by inhalation or dermal contact is the most probable route of high exposure to cresols. Cigarette smokers or persons who reside with smokers are likely to be exposed to higher amounts of cresols than the nonsmoking general population

People who work at manufacturing facilities that process coal or coal tar may have an increased risk for cresol exposure. In a study of 76 male workers aged 22–58 years of age employed at a coke plant in Poland, slightly elevated levels of *o*-cresol and *m/p*-cresol were detected in the urine of employees when compared to a group of 34 nonoccupationally exposed individuals (Bieniek 1997). The concentrations of *o*-cresol and *m/p*-cresol in the urine of subjects working in the high temperature tar distillation process were 0.54 and 18.14 mg/L, respectively, while the nonexposed control group had levels of 0.041 and 14.38 mg/L for *o*-cresol and *m/p*-cresol, respectively (Bieniek 1997). The time-weighted geometric mean concentrations of *o*-cresol and *m/p*-cresol in the breathing zone at the plant were reported as 0.09 and 0.13 mg/m^3, respectively (Bieniek 1997).

Workers at gas stations, or those involved in distillation of crude tar, oil, and other plants that produce cresols as side-products are likely to have increased exposure to cresols. However, there are no monitoring data to give the exact exposure.

Cresols are metabolites of other aromatic compounds. *o*-Cresol is a metabolite of toluene and therefore, exposure to toluene may increase exposure to *o*-cresol. Toluene is a major component of glue. In a Japanese study, people who sniffed glue as a form of intoxication had a mean value of 7.31 mg *o*-cresol/g creatinine in their urine as opposed to 0.095 and 0.016 mg *o*-cresol/g creatinine for industrial workers and those who did not sniff glue (Yamazaki et al. 1992). Workers who were occupationally exposed to toluene at a median concentration of 284.4 mg/m^3 in workplace air had a median urinary *o*-cresol level of 2.1 mg/g creatinine (Angerer and Kramer 1997). Workers at a rotogravure printing plant, who were exposed to toluene at levels ranging from 8 to 496 mg/m^3 in workplace air, had mean *o*-cresol urinary excretion levels ranging from 0.080 to 2.37 mmol *o*-cresol/mol creatinine (0.076–2.26 mg *o*-cresol/g creatinine) (Nise 1992). These *o*-cresol excretory levels were correlated with toluene exposure levels and smoking habits of the employees.

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 cresols 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 cresols.

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 necessary to estimate the fate and transport of cresols in the environment have been described for all isomers (AIChE 1989, 2000; Amoore and Hautala 1983; Artiola-Fortuny and Fuller 1982; Boyd 1982; Chao et al. 1983; Freitag et al. 1985; Gaffney et al. 1987; Hansch and Leo 1985; Hine and Mookerjee 1975; Lewis 2001; Lide 2005; OHM/TADS 1989; Riddick et al. 1986; Verschueren 1983; Windholz et al. 1983; Yalkowsky et al. 1987). Knowledge of some of these properties was required to describe the fate and transport of cresols because adequate experimental data were not available. The database was sufficient to perform the necessary estimates (Thomas 1982).

Production, Import/Export, Use, Release, and Disposal. According to the Emergency Planning and Community Right-to-Know Act of 1986, 42 U.S.C. Section 11023, industries are required to submit substance release and off-site transfer information to the EPA. The TRI, which contains this information for 2004, became available in May of 2006. This database is updated yearly and should provide a list of industrial production facilities and emissions.

Current production volumes and demand for cresylics are available (CMR 2004; USITC 2006), as are historical and predictive production volume information (CMR 2004; USITC 2006). Information on the

uses of cresols is available, including the use as a chemical intermediate and wood preservative. Information on the release of cresols to the environment (Andelman et al. 1984; Arrendale et al. 1982; Cardwell et al.1986; Dobson et al. 1985; Fedorak and Hrudey 1986; Giabbai et al. 1985; Hampton et al. 1982; Hawthorne and Sievers 1984; Hawthorne et al. 1988, 1989; James et al. 1984; Johnson et al. 1989; Junk and Ford 1980; Leone et al. 1985; Liberti et al. 1983; Neufeld et al. 1985; Novotny et al. 1982; Pellizzari et al. 1979; Seizinger and Dimitriades 1972; Snider and Manning 1982) from manufacturing, production, and use (TRI04 2006) and to the workplace, as well as their presence in foods and other natural sources, is available (Fiege and Bayer 1987; McKnight et al. 1982; Needham et al. 1984). Disposal methods are also well described.

Environmental Fate. Information concerning the partitioning of cresols in the environment is available; cresols occur in all environmental media. Information on the transport of cresols in environmental media is also available; however, the confounding influence of pH on soil transport makes assessing soil leaching difficult. An extensive database is available describing the aerobic (Alexander and Lustigman 1966; Babeu and Vaishnav 1987; Baird et al. 1974; Chambers et al. 1963; EPA 1979; Heukelekian and Rand 1955; Ludzack and Ettinger 1960; Lund and Rodriguez 1984; Malaney 1960; Malaney and McKinney 1966; McKinney et al. 1956; Pauli and Franke 1972; Pitter 1976; Tabak et al. 1964; Young et al. 1968) and anaerobic (Battersby and Wilson 1988, 1989; Boyd et al. 1983; EPA 1981; Fedorak and Hrudey 1984; Horowitz et al. 1982; Wang et al. 1988, 1989) degradation of cresols in water. Data exist regarding the biodegradation of cresols in soils (Dobbins and Pfaender 1988; Medvedev and Davidov 1981a, 1981b; Namkoong et al. 1988). The atmospheric fate of cresol isomers is well described and suggests that cresols are rapidly degraded in air (Atkinson 1985; Atkinson et al. 1980, 1984; Carter et al. 1981; Grosjean 1984, 1985; Platt et al. 1984). No data needs are identified at this time.

Bioavailability from Environmental Media. Case reports of people who have experienced cresol poisoning following oral and dermal exposure indicate that all cresols can be absorbed by these routes (Cason 1959; Chan et al. 1971; Green 1975). However, no information is available regarding oral or dermal absorption of cresols in water and soil matrices, or plant material. Studies in animals have shown that cresols can be absorbed from contaminated air by inhalation but have not attempted to quantify this absorption. Studies of absorption of cresols from air, water, soil, and plant material are required to determine the rate and extent of absorption from each of these media and comparison of the potential hazard posed by cresols contained in each.

Food Chain Bioaccumulation. Few data are available describing the food chain bioaccumulation of cresols. The available experimental data (Freitag et al. 1985) are consistent with estimated values obtained from regression equations which suggest that it will not bioconcentrate to any significant extent (Thomas 1982). Information concerning the potential for biomagnification has not been described, although the log K_{ow} values are small and biomagnification is expected to be insignificant. Therefore, no data needs exist at this time.

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

Cresol levels in groundwater (Bedient et al. 1983; Drinkwater et al. 1986; Goerlitz et al. 1985; Oliveira and Sitar 1985; Ram et al. 1985; Sawhney and Kozlowski 1984; Stuermer et al. 1982; Weber and Matsumoto 1987) and surface water (CLPSD 1988; Great Lakes Water Quality Board 1983; Kolpin et al. 2002) are available. Data exist regarding the level of cresols in atmospheric samples including rain water and clouds (Fraser et al. 1998; Grosjean 1991; Kelly et al. 1994; Leuenberger et al. 1985; Levsen et al. 1993; Luttke et al. 1999). Cresols have infrequently been identified in foods (Chung 1999; Fiege and Bayer 1987), as well as in soil and sediment samples (Lopes and Furlong 2001; McCreary et al. 1983). Continued monitoring data in air, water, soil, and foods is necessary in order to assess the potential for human exposure from environmental media. Of particular value would be more quantitative data on the cresol levels in various foods.

Exposure Levels in Humans. Cresols are naturally occurring substances that are widely distributed in the environment. Humans excrete, on average, 87 mg of *p*-cresol per day in urine (Fiege and Bayer 1987). Cresols may also be present as a result of the metabolic breakdown of other organic compounds, such as toluene (Needham et al. 1984). As such, positive detections of cresols in human biological samples do not necessarily indicate exposure solely to cresol. Information concerning the number of persons potentially exposed to cresols near waste sites and manufacturing, production, and use facilities, however, is not available. High production and widespread use make the potential for human exposure high. A data need exists to rigorously establish cresol exposure levels in humans. There are insufficient data regarding body burden of cresol, partially due to the rapid metabolism and lack of bioaccumulation.

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

Exposures of Children. There are limited, if any, data relating to exposures of children to cresols. Some of the factors that would increase the risk of children exposure include living with a smoker, and living near gas stations, heavy traffic areas, and companies that use and/or produce cresol. A data need exists to establish cresol exposure in children.

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 cresols 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

The Federal Research in Progress (FEDRIP 2006) database provided no additional information of ongoing studies that may fill in some of the data needs identified in Section 6.8.1.