5. POTENTIAL FOR HUMAN EXPOSURE

5.1 OVERVIEW

Small amounts of cadmium enter the environment from the natural weathering of minerals, forest fires, and volcanic emissions, but most is released by human activities such as mining and smelting operations, fuel combustion, disposal of metal-containing products, and application of phosphate fertilizer or sewage sludges (Elinder 1985a). It has been estimated that worldwide anthropogenic emissions of cadmium exceed natural ones by a factor close to ten (Elinder 1992; IARC 1993). Primary and secondary metal production, industrial applications, manufacture of phosphate fertilizers, waste incineration, and coal, wood, and oil combustion can all contribute cadmium to the atmosphere (Elinder 1985a). Recent pollutant emission control measures have reduced the output from these and other industrial sources in the United States.

Atmospheric cadmium is in the form of particulate matter, which may consist of very small particles if it is produced by combustion processes. The principal chemical species in air is cadmium oxide, although some cadmium salts, such as cadmium chloride, can enter the air, especially during incineration (IARC 1993). These are stable compounds that do not undergo significant chemical transformation. The chief fate of airborne cadmium is to be dispersed by the wind and, subsequently, deposited by wet or dry processes (Elinder 1985a).

In surface water and groundwater, cadmium can exist as the hydrated ion, or as ionic complexes with other inorganic or organic substances. While soluble forms may migrate in water, cadmium is relatively nonmobile in insoluble complexes or adsorbed to sediments. Similarly, cadmium in soil may exist in soluble form in soil water, or in insoluble complexes with inorganic and organic soil constituents. Cadmium in soil tends to be more available when the soil pH is low. Cadmium is taken up and retained by aquatic and terrestrial plants and is concentrated in the liver and kidney of animals that eat the plants (Elinder 1985a).

Human exposure to cadmium can result from consumption of food, drinking water, or incidental ingestion of soil or dust contaminated with cadmium; from inhalation of cadmium-containing particles from ambient air; from inhalation of cigarette smoke, which contains cadmium taken up by tobacco; or from working in an occupation involving exposure to cadmium fumes and dust (Elinder 1985a). For nonsmokers, ingestion

of food is the largest source of cadmium exposures. Most drinking water contains only very low levels of cadmium and is usually not an important route of exposure, although water may leach cadmium from plumbing. Concentrations of cadmium in ambient air are generally less than $5x10^{-6}$ mg/m^3, but concentrations up to $5x\ 10^{-4}$ mg/m^3 have been detected in air near cadmium-emitting facilities (Elinder 1985a).

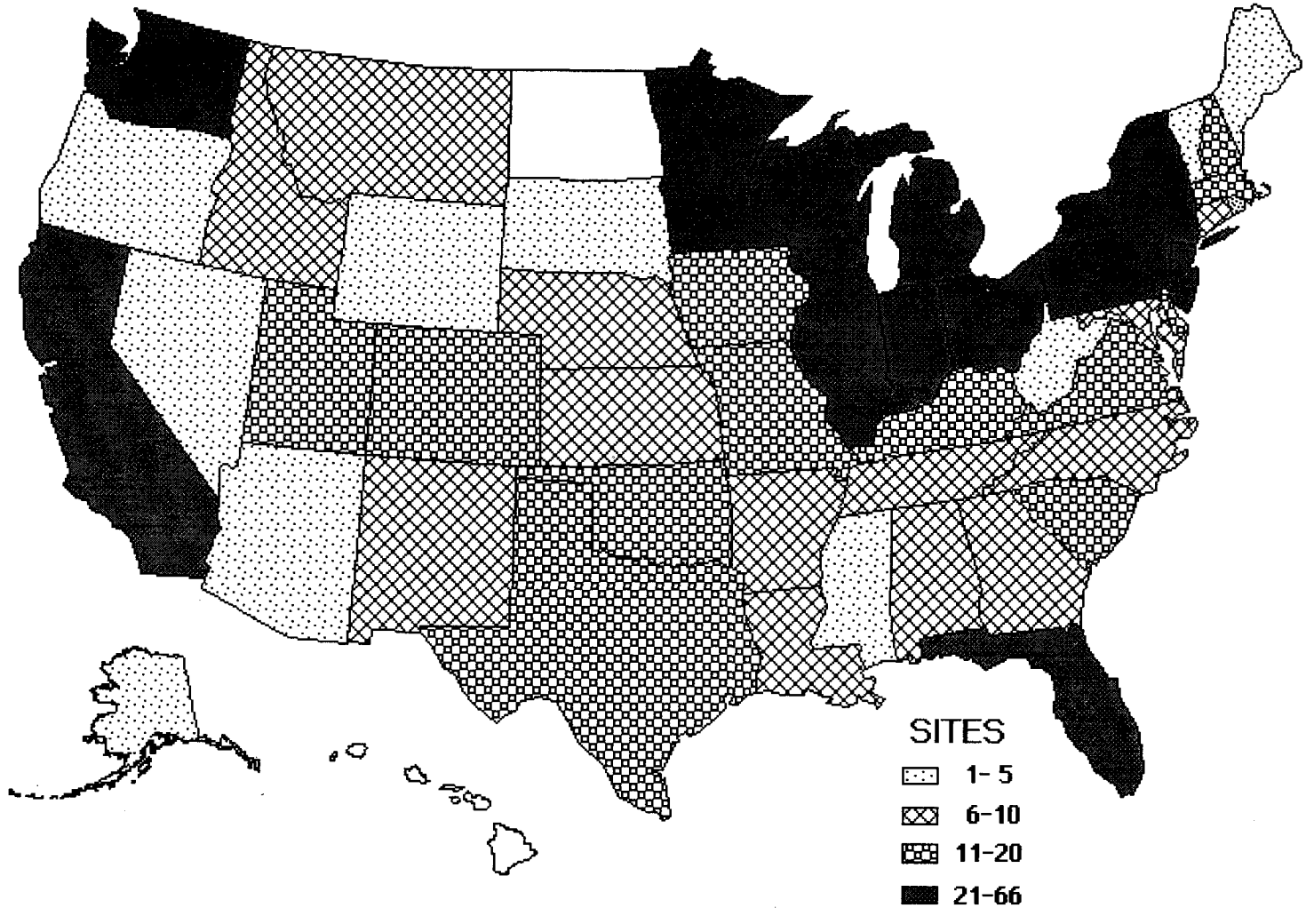
Levels of cadmium in soil may be increasing as a result of the application of municipal sludge or phosphate fertilizers, and this may result in greater human exposures from food chain accumulation in plants and animals. Dietary exposure may increase as acid precipitation lowers the soil pH. Grain and cereal products usually contribute the greatest percentage of dietary cadmium; potatoes, leafy vegetables, and root vegetables also contain relatively high levels. Organ meats (liver and kidney) and shellfish can also contribute to cadmium intake for individuals who consume large amounts of these items. Smoking is an important source of cadmium exposure and typically doubles the total daily absorption of cadmium (Elinder 1985a).

Cadmium has been identified in at least 776 of 1,467 current or former EPA National Priorities List (NPL) hazardous wastes sites (HazDat 1998). However, the number of sites evaluated for cadmium is not known. The frequency of these sites within the United States can be seen in Figure 5-l.

5.2 RELEASES TO THE ENVIRONMENT

According to the Toxics Release Inventory (TRI), in 1996, a total of 2,996,610 pounds (1,359,262 kg) of cadmium was released to the environment from 113 large processing facilities (TRI961998). Table 5-l lists amounts released from these facilities. In addition, an estimated 3,137 pounds (1,423 kg) were released by manufacturing and processing facilities to publicly owned treatment works (POTWs) and an estimated 2,273,306 pounds (1,031,172 kg) were transferred offsite (TRI961998). The TRI data should be used with caution since only certain types of facilities are required to report. Therefore, this is not an exhaustive list. Facilities are required to report data to TRI if they have 10 or more full-time employees, if the facility is classified under Standard Industrial Classification (SIC) codes 20 through 39, if the facility manufactures or processes more than 25,000 pounds of the chemical, or otherwise uses more than 10,000 pounds of the chemical in the calendar year (EPA 1995).

Figure 5-1. Frequency of NPL Sites with Cadmium Contamination



Derived from HazDat 1998

Table 5-1. Releases to the Environment from Facilities That Manufacture or Process Cadmium

			Reported amounts released in pounds per year [a]						
STATE [b]	CITY	FACILITY	AIR [c]	WATER	LAND	UNDERGROUND INJECTION	POTW TRANSFER	OFF-SITE WASTE TRANSFER	TOTAL ENVIRONMENT [d]
AL	ARAB	HALL CHEMICAL CO.	0	0	0	0	5	0	5
AL	BIRMINGHAM	BIRMINGHAM STEEL CORP.	1,073	0	0	0	0	21,312	22,385
AL	DECATUR	MONSANTO CO.	0	85	85	0	0	36,700	36,870
AL	TROY	SANDERS LEAD CO. INC.	10	250	250	0	250	1,074	1,834
AL	TUSCALOOSA	TUSCALOOSA STEEL CORP.	0	0	0	0	0	250	250
AR	BLYTHEVILLE	NUCOR-YAMATO STEEL CO.	2	0	0	0	0	43,181	43,183
AR	FORT SMITH	GNB TECHS. INC.	6	2	0	0	0	18,967	18,975
AZ	CLAYPOOL	CYPRUS MIAMI MINING CORP.	1,000	0	53,500	0	0	2,000	56,500
AZ	HAYDEN	ASARCO INC.	358	0	4,083	0	5	48,587	53,033
AZ	SAN MANUEL	BHP COPPER METALS CO.	500	0	35,894	0	0	30,284	66,678
CA	COMPTON	EME INC.	0	0	0	0	4	0	4
CA	PACOIMA	BURBANK PLATING SERVICES CORP.	5	0	0	0	250	5,100	5,355
CA	SUN VALLEY	ALERT PLATING CO.	10	0	0	0	5	798	813
CO	COLORADO SPRINGS	EAGLE-PICHER IND. INC.	248	0	0	0	0	16,926	17,174
CT	ANSONIA	ANSONIA COPPER & BRASS INC.	390	1	0	0	0	1,891	2,282
CT	FAIRFIELD	HANDY & HARMAN	45	3	0	0	0	8,700	8,748
CT	STRATFORD	FLOW POLYMERS INC.	10	0	0	0	0	2,346	2,356
CT	STRATFORD	SYNTHETIC PRODS. CO.	255	0	0	0	0	1,872	2,127
FL	ALACHUA	EVEREADY BATTERY CO. INC.	971	5	0	0	0	95,200	96,176
FL	JACKSONVILLE	JEFFERSON SMURFIT CORP.	0	0	0	0	0	650	650
GA	ATLANTA	ARMSTRONG GLASS CO. INC.	0	0	0	0	0	5	5
GA	VALDOSTA	SAFT AMERICA INC.	29	7	0	0	6	142,557	142,599
IA	BLOOMFIELD	BLOOMFIELD FNDY. INC.	10	0	0	0	0	5	15
ID	POCATELLO	FMC CORP.	340	0	337,964	0	0	37	338,341
IL	CHICAGO HEIGHTS	CALUMET STEEL CO.	7	0	0	0	1	1,700	1,708
IL	ELK GROVE VILLAGE	API IND. INC.	5	0	0	0	250	43,000	43,255
IL	ELK GROVE VILLAGE	THREE J'S IND. INC.	10	0	0	0	5	1,100	1,115
IL	HARTFORD	CHEMETCO INC.	1,000	5	0	0	0	0	1,005
IL	KANKAKEE	GNB TECHS. INC.	3	0	0	0	0	4,896	4,899
IL	SAUGET	BIG RIVER ZINC CORP.	1,332	0	0	0	5	18,991	20,328
IN	EDINBURGH	UNITED TECHS. AUTOMOTIVE INC.	5	0	0	0	0	2,250	2,255
IN	HAMMOND	JUPITER ALUMINUM CORP.	0	0	0	0	0	2,107	2,107
IN	MOUNT VERNON	GE PLASTICS CO.	27	0	0	0	0	2,954	2,981
KS	HOISINGTON	ESSEX GROUP INC.	0	0	0	0	0	5,850	5,850
KY	JEFFERSONTOWN	CONDEA VISTA CO.	122	0	0	0	22	50	194
KY	LOUISVILLE	ENGELHARD CORP.	755	0	50,700	0	250	50,750	102,455
KY	WILDER	NEWPORT STEEL CORP.	16	0	0	0	0	2,900	2,916
LA	BATCHELOR	NAN YA PLASTICS CORP. AMERICA	0	0	0	0	0	5	5
LA	SHREVEPORT	LIBBEY GLASS INC.	0	0	1,878	0	188	1,878	3,944
MA	ATTLEBORO	ATTLEBORO REFINING CO. INC.	500	0	0	0	0	14,864	15,364
MA	ATTLEBORO	CHEMET CORP.	3	0	0	0	1	6,140	6,144
MD	BALTIMORE	SCM GLIDCO ORGANICS CORP.	5	7	0	0	13	38,105	38,130
MI	DEARBORN	ROUGE STEEL CO.	250	250	0	0	0	7,226	7,726
MI	DETROIT	AJAX METAL PROCESSING INC.	0	0	0	0	250	1,205	1,455
MI	JACKSON	DIECAST CORP.	250	0	0	0	0	500	750

Table 5-1. Releases to the Environment from Facilities That Manufacture or Process Cadmium (continued)

			Reported amounts released in pounds per year [a]						
STATE [b]	CITY	FACILITY	AIR [c]	WATER	LAND	UNDERGROUND INJECTION	POTW TRANSFER	OFF-SITE WASTE TRANSFER	TOTAL ENVIRONMENT [d]
MI	JACKSON	ELM PLATING CO.	5	0	0	0	5	10	20
MO	ANNAPOLIS	ASARCO INC.	1,312	2	7,520	0	0	0	8,834
MO	HERCULANEUM	DOE RUN CO.	8,871	13	5,703	0	49	0	14,636
MO	SAINT PETERS	M. A. HANNA COLOR	48	0	0	0	0	957	1,005
MS	CORINTH	IPC CORINTH DIV. INC.	1	0	0	0	0	223	224
MS	PRAIRIE	NORTH AMERICAN PLASTICS INC.	5	0	0	0	0	0	5
MT	EAST HELENA	ASARCO INC.	9,773	190	22,108	0	3	174,637	206,711
NC	PINE HALL	KOBE COPPER PRODS. INC.	12	0	2,100	0	0	52,500	54,612
NE	FAIRBURY	AMERICAN MICROTRACE CORP.	0	77	0	0	0	24,738	24,815
NE	LINCOLN	YANKEE HILL BRICK MFG. CO.	0	0	3,000	0	0	0	3,000
NE	OMAHA	LUCENT TECHS. INC.	1	0	0	0	2	57	60
NJ	MILLVILLE	DURAND GLASS MFG. CO.	10	0	0	0	0	333	343
NJ	NEW BRUNSWICK	AKCROS CHEMICALS AMERICA	5	0	0	0	1	496	502
NJ	RIVERSIDE	METAL IND. CORP.	5	0	0	0	0	0	5
NJ	SOUTH PLAINFIELD	DEGUSSA CORP.	4	0	0	0	5	0	9
NJ	UNION	M.C. CANFIELD INC.	2	0	0	0	5	1	8
NJ	WOODBRIDGE	GENTEK BUILDING PRODS.	0	0	0	0	0	8	8
NM	HURLEY	CHINO MINES CO.	11,533	0	106,581	0	0	0	118,114
NY	BROOKLYN	BELMONT METALS INC.	250	0	0	0	0	0	250
NY	BROOKLYN	NEY SMELTING & REFINING CO.	1	0	0	0	0	0	1
NY	HERKIMER	H. M. QUACKENBUSH INC.	0	0	0	0	250	8,109	8,359
NY	*HORSEHEADS*	*THOMAS & BETTS*	0	0	0	0	5	4,256	4,261
NY	SIDNEY	AMPHENOL CORP.	0	48	0	0	0	3,976	4,024
OH	CLEVELAND	BARKER PRODS.	0	0	800	0	16	800	1,616
OH	CLEVELAND	ERIEVIEW METAL TREATING CO.	0	0	0	0	5	14,672	14,677
OH	CLEVELAND	FERRO CORP.	123	0	0	0	17	253	393
OH	CLEVELAND	N & W METAL FINISHING INC.	0	0	0	0	250	19,203	19,453
OH	CLEVELAND	RIVER RECYCLING IND. INC.	15	0	0	0	0	753	768
OH	DAYTON	HOHMAN PLATING & MFG. INC.	500	0	0	0	60	2,490	3,050
OH	DOVER	DOVER CHEMICAL CORP.	39	0	0	0	0	1,481	1,520
OH	MIDDLETOWN	AK STEEL CORP.	10	0	0	0	0	0	10
OH	MINERVA	GENERAL COLOR & CHEMICAL CO.	1,980	0	0	0	250	0	2,230
OH	TOLEDO	LIBBEY GLASS INC.	0	1	0	0	52	2,558	2,611
OH	WALTON HILLS	FERRO CORP.	500	0	0	0	9	814	1,323
OH	YOUNGSTOWN	NORTH STAR STEEL	67	0	0	0	3	6,586	6,656
OK	BARTLESVILLE	ZINC CORP. OF AMERICA	1	0	40	82	0	564,700	564,823
OK	MUSKOGEE	YAFFE IRON & METAL CO. INC.	0	0	0	0	0	27,604	27,604
OK	*SAND SPRINGS*	*SHEFFIELD STEEL CORP.*	*250*	*0*	*0*	*0*	*0*	*10,392*	*10,642*
OK	SAPULPA	BARTLETT-COLLINS GLASS CO.	0	0	0	0	0	1,958	1,958
OK	TULSA	SINCLAIR OIL CORP.	0	5	5	0	0	0	10
PA	BRIDGEVILLE	GE CO.	453	100	0	0	0	37,300	37,853
PA	ELLWOOD CITY	INTERNATIONAL METALS	3,479	2,745	0	0	5	164,000	170,229
PA	JEANNETTE	GENCORP INC.	67	2	0	0	0	2,187	2,256
PA	JOHNSTOWN	JOHNSTOWN CORP.	0	0	0	0	0	10	10
PA	MONACA	ZINC CORP. OF AMERICA	593	30	0	0	0	142,736	143,359

Table 5-1. Releases to the Environment from Facilities That Manufacture or Process Cadmium (continued)

			Reported amounts released in pounds per year [a]						
STATE [b]	CITY	FACILITY	AIR [c]	WATER	LAND	UNDERGROUND INJECTION	POTW TRANSFER	OFF-SITE WASTE TRANSFER	TOTAL ENVIRONMENT [d]
PA	MOUNTAIN TOP	HPG INTL. INC.	243	0	0	0	0	0	243
PA	PHILADELPHIA	FRANKLIN SMELTING & REFINING	1,000	250	0	0	0	0	1,250
PA	PITTSBURGH	FERRO CORP.	10	0	0	0	5	40	55
PA	POTTSVILLE	WORLD RESOURCES CO.	10	0	0	0	5	0	15
PA	READING	GENERAL BATTERY CORP.	9	37	0	0	0	6,150	6,196
PA	WASHINGTON	CERDEC CORP.	243	4	0	0	9	3,374	3,630
PR	ARECIBO	CUTLER-HAMMER DE PUERTO RICO	2,732	0	0	0	0	0	2,732
RI	WARWICK	ENGELHARD CORP.	0	0	0	0	1	603	604
SC	ABBEVILLE	PIRELLI CABLE CORP.	0	0	0	0	0	4,613	4,613
SC	DARLINGTON	NUCOR STEEL	500	0	0	0	0	24,752	25,252
TN	JACKSON	AMERISTEEL CORP.	48	5	0	0	0	9,939	9,992
TN	SPARTA	ALLIED-SIGNAL INC.	5	0	0	0	0	5	10
TX	EL PASO	ASARCO INC.	646	0	255	0	5	135,750	136,656
TX	FORT WORTH	TANDY WIRE & CABLE	0	0	0	0	0	6	6
TX	HOUSTON	SOUTHWESTERN PLATING CO. INC.	0	0	0	0	5	4,610	4,615
TX	JEWETT	NUCOR STEEL	114	0	1,000	0	0	21,530	22,644
TX	WACO	MARATHON POWER TECHS. CO.	10	250	0	0	600	42,800	43,660
UT	MAGNA	KENNECOTT UTAH COPPER	255	250	24,005	0	0	5,350	29,860
UT	PLYMOUTH	NUCOR STEEL	115	0	1,046	0	0	36,201	37,362
UT	VINEYARD	GENEVA STEEL	2	0	750	0	0	0	752
VA	BLACKSBURG	FEDERAL-MOGUL CORP.	14	0	0	0	4	10,071	10,089
WA	VANCOUVER	BOC GASES	0	0	761	0	0	761	1,522
WI	MILWAUKEE	MASTER LOCK CO.	10	0	0	0	1	11,040	11,051
		TOTALS	55,433	4,624	660,028	82	3,137	2,273,306	2,996,610

Source: TRI96 1998

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

[b] Post office state abbreviations used

[c] The sum of fugitive and stack releases are included in releases to air by a given facility

[d] The sum of all releases of the chemical to air, land, and water, and underground injection wells; and transfers off-site by a given facility

POTW = publicly owned treatment works

Additional releases of cadmium to the environment occur from natural sources and from processes such as combustion of fossil fuel, incineration of municipal or industrial wastes, or land application of sewage sludge or fertilizer (EPA 1985a). Quantitative information on releases of cadmium to specific environmental media is discussed below.

5.2.1 Air

Cadmium is released to the atmosphere from both natural and anthropogenic sources. Cadmium is widely distributed in the earth's crust and, consequently, may be released to the air from entrainment of dust particles, volcanic eruptions, or other natural phenomena (EPA 1985a). However, industrial activities are the main sources of cadmium release to air (EPA 1985a, 1985d), and emissions from anthropogenic sources have been found to exceed those of natural origin by an order of magnitude (IARC 1993). Major industrial sources of cadmium emissions include zinc, lead, copper, and cadmium smelting operations; coal and oil-fired boiler; pigment manufacturing plants; and municipal and sewage sludge incinerators (EPA 1985d; Wilber et al. 1992). It has been suggested that coal and oil used in classical thermal power plants are responsible for 50% of the total cadmium emitted to the atmosphere (Thornton 1992). Emission rates of cadmium from solid waste incinerators have been found to range from 20 to 2,000 $\mu g/m^3$ from the stacks of traditional incinerators and from 10 to 40 $\mu g/m^3$ from advanced incinerators. These emissions could result in deposition rates of l-40 and 0.02-0.8 $\mu g/m^3$ per day, respectively (IARC 1993). Additional sources that contribute negligible amounts of cadmium are rubber tire wear, motor oil combustion, cement manufacturing, and fertilizer and fungicide application (Wilber et al. 1992). Total atmospheric emissions of cadmium were estimated to be 1.4 million pounds annually in the early 1980s (EPA 1985d), with about 400,000 pounds from smelting operations, manufacturing plants, and incinerators, and 1 million pounds from fossil fuel combustion. Atmospheric cadmium occurs mainly in the forms of cadmium oxide and cadmium chloride (NTP 1991). According to TRI96 (1998), an estimated total of 55,433 pounds (25,144 kg) of cadmium, amounting to 1.8% of the total environmental release, was discharged to the air from manufacturing and processing facilities in the United States in 1996. Table 5-1 lists amounts released from these facilities. The TRI data should be used with caution because only certain types of facilities are required to report. This is not an exhaustive list. The total atmospheric release reported in 1996 is higher than the release of 15,290 pounds reported in 1993, but is lower than the release of 120,000 pounds reported in 1988.

Atmospheric emissions of cadmium are being reduced by controls necessary to meet the requirements of particulate emissions regulations (EPA 1985d). In addition, EPA has proposed risk-based regulations for cadmium emissions from hazardous waste incinerators (EPA 1990a). Therefore, although there may be an increase in fossil fuel combustion and waste incineration, it does not appear likely that overall cadmium emissions to air will increase substantially.

There is a potential for release of cadmium to air from hazardous waste sites. Cadmium has been detected in air samples collected at 33 of the 776 NPL hazardous waste sites where cadmium has been detected in some environmental medium (HazDat 1998). The HazDat information used includes data from NPL sites only.

5.2.2 Water

Cadmium may be released to water by natural weathering processes, by discharge from industrial facilities or sewage treatment plants, or by leaching from landfills or soil (EPA 1981, 1985a; IJC 1989). Cadmium may also leach into drinking water supplies from pipes in the distribution system (Elinder 1985a). According to TRI96 (1998), an estimated total of 4,624 pounds (2,097 kg) of cadmium, amounting to 0.2% of the total environmental release, was discharged to water from manufacturing and processing facilities in the United States in 1996. However, an additional 3,137 pounds (1,423 kg) were released indirectly to POTWs and some of this volume may have been released to surface water. Only 82 pounds (37 kg) were released to underground injection wells. The TRI data should be used with caution since only certain facilities are required to report. This is not an exhaustive list.

Smelting of nonferrous metal ores has been estimated to be the largest anthropogenic source of cadmium released into the aquatic environment. Cadmium contamination can result from entry into aquifers of mine drainage water, waste water, tailing pond overflow, and rainwater runoff from mine areas (IARC 1993). The upper Clark Fork River in Montana is contaminated with large amounts of cadmium from past mining activities between 1880 and 1972. While mining wastes are no longer released into the river, an estimated 14.5 million m^3 of tailings have been incorporated into the river bed, floodplain, and reservoir sediments (Canfield et al. 1994). Other human sources include spent solutions from plating operations and phosphate fertilizers. Cadmium constitutes up to 35 mg/kg of phosphorous pentoxide in the United States (IARC 1993). Atmospheric fallout of cadmium to aquatic systems is another major source of cadmium to the environment (IARC 1993; Muntau and Baudo 1992).

A large proportion of the cadmium load in the aquatic environment is due to diffuse pollution originating from many different sources rather than from point sources. In the estuarine portion of the Hudson River, it has been found that more cadmium was released from agricultural and urban run-off than from industrial and municipal sewage treatment plants (Muntau and Baudo 1992).

There is also a potential for release of cadmium to water from hazardous waste sites. Cadmium has been detected in surface water samples collected at 263 of the 776 NPL hazardous waste sites, in leachate samples collected at 100 of the 776 hazardous waste sites, and in groundwater samples collected at 541 of the 776 NPL hazardous waste sites where cadmium has been detected in some environmental medium (HazDat 1998). The HazDat information used includes data from NPL sites only.

5.2.3 Soil

Land disposal of cadmium-containing wastes (including batteries), land application of sewage sludge, and the use of phosphate fertilizers are the principal sources of cadmium releases to soil (Elinder 1985a; EPA 1985d; IARC 1993). According to TRI96 (1998), an estimated total of 660,028 pounds (299,389 kg) of cadmium, amounting to 22.0% of the total environmental release, was discharged to land from manufacturing and processing facilities in the United States in 1996. The total cadmium released to land in 1996 is significantly higher than the release of 56,665 pounds reported in 1993. Some of the estimated 2,273,306 pounds of cadmium waste transferred offsite also may be ultimately disposed to land. The TRI data should be used with caution since only certain facilities are required to report. This is not an exhaustive list.

EPA estimated that about 31% of the 11 billion pounds of sewage sludge produced annually in the United States is landspread (EPA 1985a). Estimated cadmium concentrations in sewage sludge range from less than 1 μg/g to more than 1,000 μg/g (EPA 1985a). Although EPA has set limits (EPA 1993) on the cadmium content of sludge applied to land (maximum permitted cadmium concentration of 85 mg/kg in sewage sludge; maximum cadmium concentration of 39 mg/kg in “clean” sewage sludge; maximum annual cadmium loading of 1.9 kg-ha^{-1}·yr^{-1}; and maximum cumulative cadmium loading of 39 kg/ha), significant amounts of cadmium are still likely to be transferred to soil by this practice.

Phosphate fertilizers are a major source of cadmium input to agricultural soils (EPA 1985a). The natural cadmium concentration in phosphates ranges from 3 to 100 μg/g (EPA 1985a; Singh 1994). The

concentration of cadmium in phosphate fertilizers ranges from 0.05 to 170 mg/kg (ppm) (Singh 1994). It is estimated that 880,000 pounds of phosphate fertilizer were used in the United States in 1980 (EPA 1985a). Continuous fertilization with a high rate of triple super-phosphate (1,175 kg P·ha-1· yr^{-1}) for a period of 36 years resulted in a 14-fold increase in cadmium content of surface soils (Singh 1994).

Wet and dry deposition of cadmium from the atmosphere may also contribute sizable amounts of cadmium to soil in the areas surrounding sources of atmospheric emissions, such as incinerators and vehicular traffic, which may release cadmium from burned fuel and tire wear (EPA 1985a; Mielke et al. 1991).

There is also a potential for release of cadmium to soil from hazardous waste sites. Cadmium has been detected in soil samples collected at 433 of the 776 NPL hazardous waste sites, in soil gas samples collected at 1 of the 776 NPL hazardous waste sites, and in sediment samples collected at 274 of the 776 NPL hazardous waste sites where cadmium has been detected in some environmental medium (HazDat 1998). The HazDat information used includes data from NPL sites only.

5.3 ENVIRONMENTAL FATE

5.3.1 Transport and Partitioning

Cadmium and cadmium compounds have negligible vapor pressures (see Table 3-2), but may exist in air as suspended particulate matter derived from sea spray, industrial emissions, combustion of fossil fuels, or the erosion of soils (Elinder 1985a; Keitz 1980). In processes that involve extremely high temperatures (e.g., the iron and steel industries), cadmium can volatilize and be emitted as a vapor (Wilber et al. 1992). Cadmium emitted to the atmosphere from combustion processes is usually associated with very small particulates that are in the respirable range (<10 μm) and are subject to long-range transport. These cadmium pollutants may be transported from a hundred to a few thousand kilometers and have a typical atmospheric residence time of about l-10 days before deposition occurs (Keitz 1980). Larger cadmium containing particles from smelters and other pollutant sources are also removed from the atmosphere by gravitational settling, with substantial deposition in areas downwind of the pollutant source. Cadmium deposition in urban areas is about one order of magnitude higher than in rural areas of the United States (Keitz 1980).

Cadmium-containing particulates may dissolve in atmospheric water droplets and be removed from air by wet deposition. The reported median concentration of cadmium in precipitation is about 0.7 μg/L in rural and urban areas (Keitz 1980). Scudlark et al. (1994) measured an average atmospheric wet flux of cadmium to 2 sites in the Chesapeake Bay area of 48 μg m^{-2} yr^{-1} .

Cadmium is more mobile in aquatic environments than most other heavy metals (e.g., lead). In most natural surface waters, the affinities of complexing ligands for cadmium generally follow the order of humic acids > CO_3^{2-} > OH^- ≥ Cl^- ≥ SO_4^{2-} (Callahan et al. 1979). In unpolluted natural waters, most cadmium transported in the water column will exist in the dissolved state as the hydrated ion $Cd(H_2O)_6^{2+}$. Minor amounts of cadmium are transported with the coarse particulates, and only a small fraction is transported with the colloids. In unpolluted waters, cadmium can be removed from solution by exchange of cadmium for calcium in the lattice structure of carbonate minerals (Callahan et al. 1979). In polluted or organic-rich waters, adsorption of cadmium by humic substances and other organic complexing agents plays a dominant role in transport, partitioning, and remobilization of cadmium (Callahan et al. 1979). Cadmium concentration in water is inversely related to the pH and the concentration of organic material in the water (Callahan et al. 1979). Because cadmium exists only in the +2 oxidation state in water, aqueous cadmium is not strongly influenced by the oxidizing or reducing potential of the water. However, under reducing conditions, cadmium may form cadmium sulfide, which is poorly soluble and tends to precipitate (EPA 1983c; McComish and Ong 1988). Free (ionic) cadmium seems to be the toxic form and becomes much more prevalent at low salinity (Sprague 1986). Cadmium has a relatively long residence time in aquatic systems. In Lake Michigan, a mean residence time of 4-10 years was calculated for cadmium compared to 22 years calculated for mercury (Wester et al. 1992).

Precipitation and sorption to mineral surfaces, hydrous metal oxides, and organic materials are the most important processes for removal of cadmium to bed sediments. Humic acid is the major component of sediment responsible for adsorption. Sorption increases as the pH increases (Callahan et al. 1979). Sediment bacteria may also assist in the partitioning of cadmium from water to sediments (Burke and Pfister 1988). Both cadmium-sensitive and cadmium-resistant bacteria reduced the cadmium concentration in the water column from 1 ppm to between 0.2 and 0.6 ppm, with a corresponding increase in cadmium concentration in the sediments in the simulated environment (Burke and Pfister 1988). Studies indicate that concentrations of cadmium in sediments are at least one order of magnitude higher than in the overlying water (Callahan et al. 1979). The mode of sorption of cadmium to sediments is important in determining its disposition to remobilize. Cadmium associated with carbonate minerals, precipitated as stable solid

compounds or co-precipitated with hydrous iron oxides, is less likely to be mobilized by resuspension of sediments or biological activity. Cadmium that is adsorbed to mineral surfaces such as clay, or to organic materials, is more easily bioaccumulated or released in the dissolved state when the sediment is disturbed (Callahan et al. 1979). Cadmium may redissolve from sediments under varying ambient conditions of pH, salinity, and redox potential (Callahan et al. 1979; Eisler 1985; Feijtel et al. 1988; Muntau and Baudo 1992). Cadmium is not known to form volatile compounds in the aquatic environment, so partitioning from water to the atmosphere does not occur (Callahan et al. 1979).

Debusk et al. (1996) studied the retention and compartmentalization of lead and cadmium in wetland microcosms. Differences between measured concentrations in inflow and outflow samples indicated that approximately half of the added cadmium was retained in the wetland microcosms. Experiments showed that nearly all trace metals were present in the sediments as sulfides, limiting their bioavailability and toxicity. The results of their analyses and a lack of noticeable biological effects suggested that in wetlands containing organic sediments, the sediment chemistry dominates cycling of the trace metals,

In soils, pH, oxidation-reduction reactions, and formation of complexes are important factors affecting the mobility of cadmium (Bermond and Bourgeois 1992; Herrero and Martin 1993). Cadmium can participate in exchange reactions on the negatively charged surface of clay minerals. In acid soils, the reaction is reversible. However, adsorption increases with pH and may become irreversible (Herrero and Martin 1993). Cadmium also may precipitate as insoluble cadmium compounds, or form complexes or chelates by interaction with organic matter. Available data suggest that organic matter is more effective than inorganic constituents in keeping cadmium unavailable (McBride 1995). Examples of cadmium compounds found in soil are $Cd_3(PO_4)_2$, $CdCO_3$, and $Cd(OH)_2$ (Herrero and Martin 1993). These compounds are formed as the pH rises. It has been found that about 90% of cadmium in soils remains in the top 15 cm (Anonymous 1994).

The mobility and plant availability of cadmium in wetland soils are substantially different from upland soils. Cadmium tends to be retained more strongly in wetland soils and is more available to plants under upland conditions (Gambrell 1994). Debusk et al. (1996) compared heavy metal uptake by cattails and duckweed wetland microcosms and found that duckweed, on a whole-plant basis, accumulates cadmium more effectively than cattail does. The potential cadmium removal rate for duckweed is 2-4 mg Cd/m^2/day.

Cadmium in soils may leach into water, especially under acidic conditions (Callahan et al. 1979; Elinder 1985a). Roy et al. (1993) demonstrated that Cl complexation in the leachate of ash from a municipal solid waste incinerator can result in a decrease in cadmium sorption by two common clays, kaolinite and illite. They also found that cationic competitive sorption enhances mobility in soils. Cadmium-containing soil particles may also be entrained into the air or eroded into water, resulting in dispersion of cadmium into these media (EPA 1985a). Contamination of soil by cadmium is of concern because the cadmium is taken up efficiently by plants and, therefore, enters the food chain for humans and other animals. A low soil pH, which is becoming prevalent in many areas of the world due to acid rain, increases the uptake of cadmium by plants (Elinder 1992).

Aquatic and terrestrial organisms bioaccumulate cadmium (Handy 1992a, 1992b; Kuroshima 1992; Naqui and Howell 1993; Roseman et al. 1994; Suresh et al. 1993). Cadmium concentrates in freshwater and marine animals to concentrations hundreds to thousands of times higher than in the water (Callahan et al. 1979). Reported bioconcentration factors (BCFs) range from 113 to 18,000 for invertebrates (EPA 1985d; van Hattum et al. 1989), from 3 to 4,190 for fresh water aquatic organisms (ASTER 1995), and from 5 to 3,160 for saltwater aquatic organisms (ASTER 1994). Bioconcentration in fish depends on the pH and the humus content of the water (John et al. 1987). Because of their high ability to accumulate metals, some aquatic plants have been suggested for use in pollution control. For example, it has been suggested that the rapidly-growing water hyacinth *Eichhornia crussipes* could be used to remove cadmium from domestic and industrial effluents (Ding et al. 1994; Muntau and Baudo 1992).

The data indicate that cadmium bioaccumulates in all levels of the food chain. Cadmium accumulation has been reported in grasses and food crops, and in earthworms, poultry, cattle, horses, and wildlife (Alloway et al. 1990; Beyer et al. 1987; Gochfeld and Burger 1982; Kalac et al. 1996; Munshower 1977; Ornes and Sajwan 1993; Rutzke et al. 1993; Sileo and Beyer 1985; Vos et al. 1990). The metal burden of a crop depends on uptake by the root system, direct foliar uptake and translocation within the plant, and surface deposition of particulate matter (Nwosu et al. 1995). In general, cadmium accumulates in the leaves of plants and, therefore, is more of a risk in leafy vegetables grown in contaminated soil than in seed or root crops (Alloway et al. 1990). He and Singh (1994) report that, for plants grown in the same soil, accumulation of cadmium decreased in the order: leafy vegetables > root vegetables > grain crops. Alloway et al. (1990) also demonstrated that uptake of cadmium decreased in the order: lettuces, cabbages, radishes, and carrots. Nwosu et al. (1995) investigated the uptake of Cd and Pb in lettuce and radish grown in loam soil spiked with known mixtures of $CdCl_2$ and $Pb(NO_3)_2$. They found that the mean uptake

of Cd by lettuce and radish increased as the concentrations of Cd and Pb in the soil increased. Their results supported previous findings that cadmium is absorbed by passive diffusion and translocated freely in the soil. The observed decline in Cd uptake by lettuce at 400 mg/kg could be attributed to saturation of the active binding sites on the plant root system or by early toxicological responses of the plant root. The study also supported earlier findings that radish did not accumulate as much cadmium as lettuce.

Some studies have concluded that soil pH is the major factor influencing plant uptake of cadmium from soils (Smith 1994). Liming of soil raises the pH, increasing cadmium adsorption to the soil and reducing bioavailability (He and Singh 1994; Thornton 1992). One study found that in peeled potato tubers, potato peelings, oat straw, and ryegrass, cadmium concentrations generally decreased as simple linear functions of increasing soil pH over the range of pH values measured (pH 3.9-7.6) (Smith 1994). Soil type also affects uptake of cadmium by plants. For soils with the same total cadmium content, cadmium has been found to be more soluble and more plant-available in sandy soil than in clay soil (He and Singh 1994). Similarly, cadmium mobility and bioavailability are higher in noncalcareous than in calcareous soils (Thornton 1992).

Since cadmium accumulates largely in the liver and kidneys of vertebrates and not in the muscle tissue (Harrison and Klaverkamp 1990; Sileo and Beyer 1985; Vos et al. 1990), and intestinal absorption of cadmium is low, biomagnification through the food chain may not be significant (Sprague 1986). In a study of marine organisms from the Tyrrhenian Sea, no evidence of cadmium biomagnification was found along pelagic or benthic food webs (Bargagli 1993). Although some data indicate increased cadmium concentrations in animals at the top of the food chain, comparisons among animals at different trophic levels are difficult, and the data available on biomagnification are not conclusive (Beyer 1986; Gochfeld and Burger 1982). Nevertheless, uptake of cadmium from soil by feed crops may result in high levels of cadmium in beef and poultry (especially in the liver and kidneys). This accumulation of cadmium in the food chain has important implications for human exposure to cadmium, whether or not significant biomagnification occurs.

Boularbah et al. (1992) isolated 6 cadmium-resistant bacterial strains from a soil receiving dredged sediments and containing 50 mg Cd/kg. The isolates tolerated higher cadmium concentrations than the control strain and accumulated cadmium at concentrations ranging from 0 to 100 mg/L. One of the isolates, Bacillus brevis, was found to be the most resistant to cadmium, with the ability to accumulate up to 70 mg Cd/g of cells dry weight (d/w), and may have some use in reclamation of metal-contaminated soils.

5.3.2 Transformation and Degradation

5.3.2.1 Air

Little information is available on the atmospheric reaction of cadmium (Keitz 1980). The common cadmium compounds found in air (oxide, sulfate, chloride) are stable and not subject to photochemical reactions (Keitz 1980). Cadmium sulfide may photolyze to cadmium sulfate in aqueous aerosols (Konig et al. 1992). Transformation of cadmium among types of compounds in the atmosphere is mainly by dissolution in water or dilute acids (Keitz 1980).

5.3.2.2 Water

In fresh water, cadmium is present primarily as the cadmium(+2) ion and Cd(OH), and CdCO, complexes, although at high concentrations of organic material, more than half may occur in organic complexes (McComish and Ong 1988; NTP 1991). Some cadmium compounds, such as cadmium sulfide, cadmium carbonate, and cadmium oxide, are practically insoluble in water. However, water-insoluble compounds can be changed to water-soluble salts by interaction with acids or light and oxygen. For example, aqueous suspensions of cadmium sulfide can gradually photoxidize to soluble cadmium (IARC 1993). Cadmium complexation with chloride ion increases with salinity until, in normal seawater, cadmium exists almost entirely as chloride species ($CdCl^+$, $CdCl_2$, $CdCl\ 3^-$) with a minor portion as Cd^{2+} (NTP 1991). In reducing environments, cadmium precipitates as cadmium sulfide (McComish and Ong 1988). Photolysis is not an important mechanism in the aquatic fate of cadmium compounds (EPA 1983c), nor is biological methylation likely to occur (Callahan et al. 1979).

5.3.2.3 Sediment and Soil

Transformation processes for cadmium in soil are mediated by sorption from and desorption to water, and include precipitation, dissolution, complexation, and ion exchange (McComish and Ong 1988). Important factors affecting transformation in soil include the cation exchange capacity, the pH, and the content of clay minerals, carbonate minerals, oxides, organic matter, and oxygen (McComish and Ong 1988).

5.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

Reliable evaluation of the potential for human exposure to cadmium depends, in part, on the reliability of supporting analytical data from environmental samples and biological specimens. In reviewing data on cadmium levels monitored in the environment, it should also be noted that the amount of the cadmium compound identified analytically is not necessarily equivalent to the amount that is bioavailable.

5.4.1 Air

Mean levels of cadmium in ambient air range from less than $1x10^{-6}$ mg/m^3 in remote areas to $3x10^{-6}$-4xl0^{-5} mg/m^3 in U.S. urban areas (Davidson et al. 1985; Eisler 1985; Elinder 1985a, 1992; EPA 1981; IARC 1993; Pirrone et al. 1996; Saltzman et al. 1985). Atmospheric concentrations of cadmium are generally highest in the vicinity of cadmium-emitting industries such as smelters, municipal incinerators, or fossil fuel combustion facilities (Elinder 1985a; Pirrone et al. 1996). The mean annual concentration of airborne cadmium in an area about 1 km from a zinc smelter in Colorado was 0.023 μg/m^3 ($2.3x10^{-5}$ mg/m^3) (IARC 1993). Sweet et al. (1993) conducted a study of airborne inhalable particulate matter (PM-I0) over a 2-year period in two urban/industrial areas (southeast Chicago and East St. Louis) and one rural area in Illinois. Air quality at the two urban locations is among the worst in Illinois in terms of criteria pollutants, and EPA has designated southeast Chicago as a nonattainment area. No cadmium was detected in fine particles (<2.5 μm) from the rural Illinois site (detection limit=4 ng/m^3); cadmium in coarse particles (2.5-10 μm) from this area ranged from <4 to 4.3 ng/m^3 (average <4 ng/m^3). In southeast Chicago, cadmium concentrations ranged from <4 to 9.7 ng/m^3 (average <4 ng/m^3) in fine particles and from <4 to 5.5 ng/m^3 (average <4 ng/m^3) in course particles. Cadmium concentrations in the East St. Louis area were 5-10 times higher, with a range of <4 to 115 ng/m^3 (average 15(24) ng/m^3) for fine particles and a range of <4-97 ng/m^3 (average 10(18) ng/m^3) for course particles. Annual average concentrations of atmospheric cadmium over three Great Lakes reflect the influence of industrialization and urbanization; Lake Erie's levels of 0.6 ng/m^3 were higher than fine particle concentrations of 0.2 ng/m^3 over Lake Michigan and <0.2 ng/m^3 over Lake Superior (Sweet et al. 1998). In the Lake Michigan Urban Air Toxics Study of dry deposition of metals, the flux of cadmium on the south side of Chicago was reported at about 0.01 mg/m^2 per day and levels in rural Michigan and over Lake Michigan were far lower (Holsen et al. 1993).

5.4.2 Water

Reported background levels of cadmium in unpolluted waters vary somewhat. Elinder (1992) reports that cadmium concentrations in water from the open sea range from 0.02 to 0.1 μg/L, while Eisler (1985) reports a range of 0.01-0.1 parts per billion (ppb) (μg/L). Sprague (1986) reports a cadmium concentration of 0.12 (μg/L) in deep ocean water, but adds that the concentration near the surface many decrease due to uptake of cadmium by organisms in the water. IARC (1993) reports that the concentration of cadmium dissolved in surface waters of the open ocean is <0.005 μg/L. Eisler reports that cadmium concentrations range from 0.05 to 0.2 ppb (μg/L) in fresh water and up to 0.05 in coastal seawater. Elinder (1992) reports that both fresh and coastal waters typically have cadmium concentrations less than 0.1 μg/L but that concentrations may exceed 1 μg/L in waters from areas with cadmium- and zinc-bearing mineral formations (Elinder 1992). Thornton (1992) reports that waters from the vicinity of cadmium bearing mineral deposits may have cadmium concentrations of 1,000 μg/L or more.

In a study of the water quality of the Mississippi River and its main tributaries, the U.S. Geological Survey (USGS) found cadmium concentrations ranging from 0.3 to 8 μg/L during July-August 1987; 0.05-0.9 μg/L during November-December 1987; and 0.2-6 μg/L during May-June 1988 (Taylor et al. 1990).

The cadmium concentration of natural surface water and groundwater is usually less than 1 μg/L (Elinder 1985a, 1992). Groundwater in New Jersey has an estimated median level of 1 μg Ccl/L with a high level of 405 μg/L. In a survey of groundwater surrounding waste sites, a concentration of 6,000 μg Cd/L was found (NTP 1991). The National Urban Runoff Program measured cadmium concentrations in urban storm water runoff; concentrations ranged from 0.1 to 14 μg/L in 55% of samples that were positive for cadmium (Cole et al. 1984). Cadmium in highway run-off has been detected at levels of 0.0-0.06 mg/L (0.0-60 μg/L). I n a survey of public drinking water supplies, the U.S. Public Health Service found that 4 of the 2,595 samples from 969 water systems had cadmium concentrations greater than 10 μg/L (EPA 1981). The average value was 3 μg/L. Most drinking water supplies in the United States probably do not contain more than 1 μg/L of cadmium (IARC 1993; Konz and Walker 1979), but the concentration may increase up to 10 μg/L as a result of industrial discharge or leaching from metal or plastic pipes (IARC 1993). Cadmium has been detected in water samples collected from all of the Great Lakes (IJC 1983). Cadmium has been detected in 100% of surface water and groundwater samples in a survey in New Jersey at a median concentration of 1 μg/L, and a maximum concentration of 405 μg/L (Page 1981).

5.4.3 Sediment and Soil

Cadmium concentrations in nonpolluted soil are highly variable, depending on sources of minerals and organic material. Eisler (1985) reports cadmium concentrations of 10-l,000 ppb (0.01-l ppm) in soils of nonvolcanic origin and up to 4,500 ppb (4.5 ppm) in soils of volcanic origin. Mean levels in unpolluted topsoil in the United States are approximately 0.25 ppm (EPA 1985a). Contamination of topsoil is likely the mechanism for the greatest human exposure to cadmium, mediated through uptake of soil cadmium into edible plants and tobacco (EPA 1985a). Topsoil concentrations are often more than twice as high as subsoil levels as the result of atmospheric fallout and contamination (Pierce et al. 1982). It has been reported that 90% of the cadmium in soils remains in the top 15 cm (Anonymous 1994). Markedly elevated levels may occur in topsoils near sources of contamination. For example, in the vicinity of a smelter in Helena, Montana, average soil values were 72 ppm within 1 km and 1.4 ppm between 18 and 60 km (EPA 1981). Total cadmium concentrations in soil samples taken from a SuperFund site in southeast Kansas ranged from 15 to 86 mg/kg (ppm). In the same study, soil samples were extracted with diethylenetriaminepentaacetic acid (DPTA) to approximate the plant-available metal concentrations. Extractable cadmium concentrations ranged from 0.6 to 10 mg/kg (ppm) (Abdel-Sahib et al. 1994). Soil cadmium levels in five Minnesota cities were highest in areas with the most vehicular traffic (>2 ppm in about 10% of inner-city samples) and also showed a pattern consistent with past deposition from a sewage sludge incinerator (Mielke et al. 1991). Cadmium levels up to 800 mg/kg (ppm) have been reported for soils in polluted areas (IARC 1993). Cadmium content in marine sediments ranges from 0.1 to 1.0 μg/g (ppm) in the Atlantic and Pacific oceans (Thornton 1992). Surficial sediments collected from 18 locations in three major tributaries to Newark Bay, New Jersey, had a mean cadmium concentration of 10±6 mg/kg (ppm) dry weight (Bonnevie et al. 1994). The highest cadmium concentrations were found in the Ironbound section of the Passaic River, a heavily industrialized area (29 mg/kg and 14 mg/kg), and in the Arthur Kill on the northwest side of Prall’s Island (15 mg/kg). An investigation of metals distribution in sediments along the Hudson River estuary revealed that cadmium concentrations in suspension were higher than in the bottom sediments by a factor of 30 (Gibbs 1994).

Soil samples collected from a depth of 0-15 cm along the banks of the Willamette River in Corvallis, Oregon, had a mean cadmium concentration of 1.866 mg/kg (ppm) (Nwosu et al. 1995).

Soils derived from dredged material in confined disposal facilities in the Great Lakes Region had cadmium concentrations (dry weight) of <1.9-32 ppm (Beyer and Stafford 1993). In an analytical survey of sewage

sludges from 16 large cities in the United States, cadmium concentrations ranged from 2.72 to 242 ppm (dry weight) (Gutenmann et al. 1994). The cadmium content of 242 ppm is far above the recommended concentration limit if the sludge is to be applied to agricultural land. All other sludges had cadmium contents ≤ 14.7 ppm.

Methods for decontamination of cadmium-polluted soil include leaching with acid, base, or chelating agents, and resin absorption of leachate (Urlings et al. 1988; Van Gestel et al. 1988). However, the increase in bioavailability caused by such treatment methods may result in no net decrease in cadmium content of plants grown on treated soil (Van Gestel et al. 1988).

5.4.4 Other Environmental Media

Cadmium has been detected in nearly all samples of food analyzed with sufficiently sensitive methods (Elinder 1985a). In foods obtained from unpolluted areas, the cadmium concentration is usually lower than 0.1 mg/kg fresh weight. Milk, dairy products, eggs, beef, and fish usually contain <0.01 mg/kg (ppm) while higher concentrations, 0.01-0.10 mg/kg, are typically found in vegetables, fruits, and grains (Elinder 1992). As part of the U.S. Food and Drug Administration (FDA) Total Diet Study, average concentrations of cadmium in 12 food groups were analyzed from samples collected in 27 American cities. Cadmium was found in nearly all samples, with lowest levels in beverages and fruits, and highest levels in leafy vegetables and potatoes (Gartrell et al. 1986). Table 5-2 summarizes the data from this study. Cadmium was detected in only 1 of 13,085 samples of foods collected and analyzed by 10 state food laboratories in fiscal year 1989, and the level was not considered significant (i.e., above tolerance or no tolerance set). However, no detection limit was given (Minyard and Roberts 1991). Watanabe et al. (1996) measured the cadmium content in rice samples from various areas in the world during the period from 1990 to 1995. Twenty-nine samples collected in the United States had a geometric mean of 7.43 ng Cd/g, with a standard deviation of 2.11 ng Cd/g. Shellfish, liver, and kidney meats have higher concentrations than other fish or meat (up to 1 ppm) (Elinder 1985a; IARC 1993; Schmitt and Brumbaugh 1990). Particularly high concentrations of cadmium of 2-30 mg/kg (ppm) fresh weight have been found in the edible brown meat of marine shellfish (Elinder 1992). Cadmium concentrations up to 8 μg/g in oysters and 3 μg/g in salmon flesh have been reported (IARC 1993). Sprague (1986) has reviewed tissue concentrations of cadmium for marine molluscs and crustaceans. They found that drills were higher in cadmium (average, 26 μg/g dry weight) than almost all other mollusks, although scallops and whelks also tended to be high. Clams were relatively low in cadmium (average, 0.5-l.0 μg/g dry weight). Oysters from polluted areas averaged 18 μg/g dry

Table 5-2. Cadmium Content in Selected Foods

Type of food	Average concentration (ppm)	Range of concentration (ppm)
Potatoes	0.0421	0.016–0.142
Leafy vegetables	0.0328	0.016–0.061
Grain and cereal products	0.0237	0.002–0.033
Root vegetables	0.0159	trace–0.028
Garden fruits	0.0171	trace–0.093
Oils and fats	0.0108	trace–0.033
Sugar and adjuncts	0.0109	trace–0.053
Meat, fish, and poultry	0.0057	trace–0.014
Legume vegetable	0.0044	trace–0.016
Dairy products	0.0035	trace–0.016
Fruits	0.0021	trace–0.012
Beverages	0.0013	trace
All groups		trace–0.142

Source: adapted from Gartrell et al. 1986

weight. The average concentration of cadmium in clams from polluted areas was only 2.7 μg/g dry weight, but this was significantly higher than levels in clams from clean areas. In Fiscal Year (FY) 1985/l 986, the FDA conducted a survey of cadmium, lead, and other elements in fresh clams and oysters collected from U.S. coastal areas used for shellfish production. Average cadmium levels (wet weight) were 0.09±0.06 mg/kg (ppm) (n=75) in hardshell clams, 0.05±0.04 mg/kg (n=59) in softshell clams, 0.5l±0.31 mg/kg (n=104) in Eastern oysters, and l.l±0.6 mg/kg (n=40) in Pacific oysters (Capar and Yess 1996). In FY91, FDA analyzed 5 samples of domestic clams and 24 samples of domestic oysters (collected from both coasts) for cadmium and found average concentrations of 0.06 and 0.62 mg/kg, respectively. Although no conclusions can be drawn in light of the small numbers of FY91 samples, these results to not appear to be appreciably different from those of the FY85/86 survey (Capar and Yess 1996).

Vahter et al. (1996) studied the dietary intake and uptake of cadmium in non-smoking women consuming a mixed diet low in shellfish (n=34) or with shellfish once a week or more (n=17). The shellfish diets, with a median of 22 μg Cd/day, contained twice as much cadmium as the mixed diets, which had a median of 10.5 μg Cd/day. In spite of the differences in the daily intake of cadmium, there were no statistically significant differences in the blood cadmium concentrations of the shellfish group (0.25 μg/L) and the mixed diet group (0.23 μg/L) or in the urinary cadmium concentrations of the shellfish and mixed diet groups (0.10 μg/L in both groups). These results indicate a lower absorption of cadmium in the shellfish group than in the mixed diet group or a difference in kinetics. The authors suggested that a higher gastrointestinal absorption of cadmium in the mixed diet group could be explained in part by their lower body iron stores as measured by the concentrations of serum ferritin (S-fer). A median S-fer concentration of 18 μg/L was measured for the mixed diet group compared to a median of 31 μg/L for the shellfish group.

Cadmium is accumulated mainly in the hepatopancreas (digestive gland) of the crab, and cadmium levels as high as 30-50 ppm have been detected in this edible part of the animal. Cadmium levels as high as 10 ppm also have been measured in some species of wild-growing edible mushrooms (Lind et al. 1995). Lind et al. (1995) conducted a feeding study in mice to determine the bioavailability of cadmium from crab hepatopancreas and mushroom in relation to organic cadmium. The cadmium accumulation in the liver and kidney of the mice was used as an estimate of the intestinal absorption. The group that was fed crab accumulated less cadmium in the liver and kidney than the groups fed mushrooms or inorganic cadmium salt. They concluded from the results of the study that cadmium from boiled crab has a lower bio-availability for absorption in the gastrointestinal tract of mice than inorganic cadmium and cadmium

from dried mushrooms. Almost all (99%) of the cadmium in the boiled crab hepatopancreas was associated with insoluble ligands, probably denatured protein. In fresh crab hepatopancreas, most of the cadmium is in a soluble form bound to metallothionein (Lind et al. 1995).

Significant concentrations of cadmium have been observed in fish living in stormwater ponds in Florida, especially in the redear sunfish, a bottom feeder (Campbell 1994). The mean cadmium concentration in redear sunfish living in stormwater ponds was 1.64 mg/kg wet weight compared to 0.198 mg/kg for redear sunfish living in control ponds. Similarly, the mean cadmium concentration in largemouth bass living in stormwater ponds was 3.16 mg/kg wet weight compared to 0.241 mg/kg for largemouth bass living in control ponds. Red drum, flounder, and seatrout collected from South Carolina estuaries during the period 1990-93 had consistently low cadmium levels throughout the sampling area and with respect to species (Mathews 1994). The mean concentration for all fillets and whole fish was 86.2 ppb wet weight, with 70.7% (n=164) of the samples having <25 ppb.

Cadmium concentrations of 0.5 ppm or more have been found in rice grown in cadmium-polluted areas of Japan (Nogawa et al. 1989) and China (Shiwen et al. 1990). Tobacco also concentrates cadmium from the soil, and cadmium content of cigarettes typically ranges from 1 to 2 μg/cigarette (Elinder 1985a, 1992). Some food crops, including confectionery sunflowers, have a propensity to take up cadmium from the soil in which they are grown and deposit it in the kernels. In a study to determine the cadmium burden of persons who report regular consumption of sunflower kernels, Reeves and Vanderpool (l 997) analyzed 19 different lots of sunflower kernels from the 1995 crop grown in the northern Great Plains region of North Dakota and Minnesota. They found a range of 0.33-0.67 μg Cd/g, with a mean±standard deviation of 0.48±0.11 μg/g fresh weight. The study showed that high intakes of sunflower kernels increased the intake of cadmium. However, the amount of cadmium in whole blood or in red blood cells was not affected by cadmium intake. The authors pointed out that an increased intake of sunflowers will increase not only the cadmium intake but also the intake of copper and phytate. In turn, this could reduce the availability of cadmium from this food source.

In mammals and birds, cadmium has been found in the livers and kidneys at concentrations of 0.1-2 mg/kg (ppm) and l-10 mg/kg wet weight, respectively (Elinder 1992). Animals with a long life span have very high concentrations of cadmium in their organs. Concentrations of nearly 200 mg/kg have been found in the renal cortices of old horses (Elinder 1992). Elevated cadmium levels in deer livers have prompted

several states to issue consumption advisories. Reported cadmium concentrations range from co.002 to 23 mg/kg (ppm) (dry weight) for deer livers from Connecticut, New Jersey, Illinois, and Maine, with mean concentrations of I .7, 4, 0.4, and 1.3 ppm, respectively (Musante et al. 1993).

The hepatopancreas of lobsters collected from a dredge soil dump site in Long Island Sound off New Haven, Connecticut, contained mean concentrations of 10.7 ppm cadmium in the 1970s and 8.8 ppm in 1989. Samples from another dump site off New London, Connecticut, had mean levels of 3.5 ppm in the 1970s and 3.1 ppm in 1989. Neither change in concentration with time was significant. The soft tissue of channeled whelk collected from the New Haven site contained mean cadmium concentrations of 9.3 ppm and 11.3 ppm in the 1970s and 1989, respectively. Samples from the New London site had mean cadmium concentrations of 6.0 ppm in the 1970s and 5.1 ppm in 1989. There were no statistically significant temporal changes in concentration at either site, but there were significant differences in concentrations between sites (Greig and Pereira 1993).

Eisler (1985) examined the concentrations of cadmium in a variety of aquatic and terrestrial flora and fauna and identified six trends: (1) in general, marine biota contained significantly higher cadmium residues than their freshwater or terrestrial counterparts; (2) cadmium tends to concentrate in the viscera of vertebrates, especially in the liver and kidneys; (3) cadmium concentrations are higher in older organisms than in younger ones, especially in carnivores and marine vertebrates; (4) higher concentrations for individuals of a single species collected at various locations are almost always associated with proximity to industrial/urban areas or point-source discharges of cadmium-containing wastes; (5) background levels of cadmium in crops and other plants are generally <l .0 mg/kg (ppm); and (6) cadmium concentrations in biota are dependent upon the species analyzed, the season of collection, ambient cadmium levels, and the sex of the organism.

The cadmium content of coals varies widely; concentrations of 0.01-180 μg/g (ppm) have been reported for the United States (Thornton 1992; Wilber et al. 1992).

5.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

The primary routes of human exposure to cadmium and cadmium compounds are inhalation, dermal contact, and ingestion (NTP 1991). For nonsmoking members of the general population, food is generally the greatest source of cadmium exposure. The intake of cadmium, therefore, depends upon the food items

that comprise a person's diet and may be highly variable. Sources of cadmium contamination of food by cadmium include phosphate fertilizers and sewage sludge applied to agricultural land; cadmium-plated utensils and galvanized equipment used in food processing and preparation; enamel and pottery glazes with cadmium-based pigments; and stabilizers used in food-contact plastics (Galal-Gorchev 1993). In the United States, adult intake of cadmium from food has recently been estimated to be about 30 μg/day based on the Total Diet Study, with the largest contribution from grain, cereal products, potatoes, and other vegetables (Gartrell et al. 1986). Thornton (1992) reports a typical dietary intake of 0.23 mg/week of cadmium. Somewhat lower estimates are obtained for adults using measured fecal excretion as an estimate of intake (Bunker et al. 1984; Kjellstrom et al. 1978). Assuming gastrointestinal absorption to be 5-10%, the amount of cadmium absorbed from the diet would be approximately l-3 μg/day. A decrease in soil pH due to acid precipitation may result in an increase in dietary cadmium (NTP 1991). Except in the vicinity of cadmium-emitting industries or incinerators, the intake of cadmium from drinking water or ambient air is of minor significance (Elinder 1985a). In 1988, the Joint FAO/WHO Expert Committee on Food Additives (JECFA) established a Proposed Tolerable Weekly Intake (PTWI) of cadmium of 7 μg/kg body weight for adults as well as infants and children. JECFA also estimated the dietary intake of cadmium to be usually l-4 μg/kg body weight/week and cautioned that there is only a small safety margin between normal dietary exposure and exposure that produces adverse effects (Galal-Gorchev 1993). The WHO guideline for all forms of cadmium in drinking water is 5 μg/L (WHO 1984a). The maximal level of cadmium in drinking water and the permissible level in bottled water in the United States is 10 μg/L (IARC 1993). Near sources of cadmium pollution, individuals may inhale l-75 μg of cadmium daily. Assuming 25% absorption from the lungs, this dose of 0.25-l.9 μg of cadmium per day may contribute significantly to cadmium intake (Elinder 1985a). Cadmium accumulates mainly in the kidneys and liver, with these organs accounting for roughly 70% of the total body burden (Armstrong et al. 1992). Elinder (1992) reports an average concentration of approximately 29 ng Cd/kg wet weight for human renal cortex. IARC (1993) reports that the total body burden of nonoccupationally exposed adult subjects has been estimated to range from 9.5 to 50 mg in the United States and Europe.

It has been estimated that tobacco smokers are exposed to 1.7 μg cadmium per cigarette (NTP 1991). The amount of cadmium absorbed from smoking one pack of cigarettes per day is about l-3 μg/day (Lewis et al. 1972a; Nordberg et al. 1985), roughly the same as from the diet. This large contribution is due to the greater absorption of cadmium from the lungs than from the gastrointestinal tract (Elinder 1985a). Direct measurement of cadmium levels in body tissues confirms that smoking roughly doubles cadmium body burden in comparison to not smoking, with kidney concentrations averaging 15-20 μg/g wet weight for

nonsmokers and 30–40 µg/g wet weight for heavy smokers at the age of 50–60 (Ellis et al. 1979; Hammer et al. 1973; Lewis et al. 1972a, 1972b; NTP 1991). Ellis et al. (1979) found an increase in kidney cadmium of 0.11±0.05 mg per pack-year of smoking and an increase in liver cadmium concentration of 0.077±0.065 µg/g per pack-year. Because excretion of cadmium is very slow, half-lives of cadmium in the body are correspondingly long (17–38 years) (Wester et al. 1992).

Wester et al. (1992) investigated the percutaneous absorption of cadmium chloride from water and soil into and through human skin. They found that 116 ppb cadmium in water applied to two human cadaver skin sources at two volumes of 5 µL/cm^2 penetrated the skin to concentrations of 8.8 ±0.6% and 12.7 ±11.7% of the applied dose. The percentage doses absorbed into plasma were 0.5±0.2% and 0.6±0.6%, respectively. Cadmium in soil (13 ppb) applied to two human cadaver skin sources at doses of 0.04 g soil/cm^2 penetrated the skin at concentrations of 0.6±0.02% and 0.13±0.05%. The percentage doses absorbed into plasma were 0.01±0.01% and 0.07±0.03%. Their calculations suggest that a daily whole body exposure to cadmium at 116 ppb (as in bathing or swimming) will result in a daily systemic intake of approximately 10 µg cadmium.

Workers in a variety of occupations may be exposed to cadmium and cadmium compounds. Occupations with potential exposure to cadmium are listed below (IARC 1993). An asterisk indicates an activity with high risk because atmospheric concentrations of cadmium are high and the number of workers employed is significant.

Occupations with Potential Exposure to Cadmium and Cadmium Compounds

Alloy production*	Phosphorous production
Battery production*	Pigment production and use*
Brazing	Plastics production*
Coating	Plating
Diamond cutting	Printing
Dry color formulation	Semiconductor and superconductor production
Electroplating	Sensors production
Electrical contacts production	Smelting and refining*
Enameling	Solar cells production
Engraving	Soldering
Glasswork	Stabilizer production
Laser cutting	Textile printing
Metallizing	Thin film production
Paint production and use	Transistors production
Pesticide production and use	Welding

Highest levels of exposure would be expected to occur in operations involving heating cadmium-containing products by smelting, welding, soldering, or electroplating, and also in operations associated with producing cadmium powders (OSHA 1990). The primary route of occupational exposure is through inhalation of dust and fumes, and also incidental ingestion of dust from contaminated hands, cigarettes, or food (Adamsson et al. 1979; NTP 1991).

Concentrations of airborne cadmium found in the workplace vary considerably with the type of industry and the specific working conditions. Processes that involve high temperatures can generate cadmium oxide fumes that are absorbed very efficiently through the lungs (IARC 1993). Deposition and absorption of dust containing different compounds depend upon particle size (IARC 1993).

These exposures can be controlled through use of personal protective equipment and good industrial hygiene practices, and through operating procedures designed to reduce workplace emissions of cadmium (OSHA 1990). As an example of cadmium emissions reduction, cadmium air concentrations in the solution room of a U.S. cadmium production facility were approximately 3,000 $\mu g/m^3$ before 1955, 1,500 $\mu g/m^3$ from 1955 to 1964, and 150 $\mu g/m^3$ subsequently (IARC 1993).

Data from the National Occupational Exposure Survey (NOES), conducted by NIOSH from 1981 to 1983, estimated the number of workers potentially exposed to various chemicals in the workplace during the same period (NIOSH 1989). Data for various forms of cadmium included in the survey are summarized below:

Chemical	Number of workers potentially exposed
Cadmium sulfide	42564
Cadmium oxide	15731
Cadmium	4748
Cadmium sulfate	1313
1:1 cadmium salt of carbonic acid	164
Cadmium (form unknown)	88966
Total	153486

The NOES database does not contain information on the frequency, level, or duration of exposure of workers to any of the chemicals listed. It provides only estimates of workers potentially exposed to the chemicals.

In a 1987 report, OSHA estimated that 213,000 workers were exposed to cadmium in the workplace at levels equal to or greater than 1 μg/m^3 (NTP 1991). Of these workers, 65% were exposed to cadmium at concentrations of l-39 μg/m^3, 21% were exposed to concentrations of 40-99 μg/m^3, and 14% were exposed to concentrations greater than 100 ug/m^3. In the proposed rule for occupational exposure to cadmium, OSHA (1990) estimated that approximately 512,000 workers in the United States were exposed to cadmium, of whom approximately 70% were exposed below a time-weighted average (TWA) of 5 μg/m^3 and 81% below a TWA of 20 μg/m^3.

The OSHA final rule has established a permissible exposure limit (PEL of 5 μg/m^3 for occupational exposure to airborne cadmium (OSHA 1992). Hazardous waste workers in New Jersey have blood and urinary cadmium levels within the range of the general population and thus appear not to experience significant cadmium exposure from working at hazardous waste sites (Gochfeld et al. 1991). The American Conference of Governmental and Industrial Hygienists (ACGIH) has set their biological exposure index (BEI) at 10 μg/L (Aurelio et al. 1993).

5.6 EXPOSURES OF CHILDREN

This section focuses on exposures from conception to maturity at 18 years in humans and briefly considers potential pre-conception exposure to germ cells. Differences from adults in susceptibility to hazardous substances are discussed in Section 2.6, 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, and 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; they put things in their mouths; they may ingest inappropriate things such as dirt or paint chips; they spend more time outdoors. Children also are closer to the ground, and they do not have the judgement of adults in avoiding hazards (NRC 1993).

The placenta may act as a partial barrier to fetal exposure to cadmium. Cadmium concentration has been found to be approximately half as high in cord blood as in maternal blood in several studies including both smoking and nonsmoking women (Kuhnert et al. 1982; Lauwerys et al. 1978; Truska et al. 1989). Accumulation of cadmium in the placenta at levels about 10 times higher than maternal blood cadmium concentration has been found in studies of women in Belgium (Roels et al. 1978) and the United States (Kuhnert et al. 1982); however, in a recent study in Czechoslovakia, the concentration of cadmium in the placenta was found to be less than in either maternal or cord blood (Truska et al. 1989). Baranowska (1995) also measured the concentrations of cadmium and lead in human placenta and in maternal and neonatal (cord) blood to assess the influence of a strongly polluted environment on the content of metals in tissues and on the permeability of the placenta to cadmium and lead. Samples for the study were collected from women living in the industrial district of Upper Silesia, one of the most polluted regions in Poland. The mean (range) concentration of cadmium in the air was 11.3 (2.1-25.4) ng/m^3 (0.011 [.002-.025] μg/m^3). The mean concentrations of cadmium were 4.90 ng/mL (0.005 μg/mL) in venous blood, 0.11 μg/g in placenta, and 1.13 ng/mL (0.001 μg/mL) in cord blood. Lead concentrations were 72.50 ng/mL (.072 μg/rnL) in venous blood, 0.50 μg/g in placenta, and 38.31 ng/mL (0.038 μg/mL) in cord blood. The researcher concluded that the placenta is a better barrier for cadmium than for lead, based upon the relative decrease in metal concentrations from placenta to cord blood. The mechanism by which the placenta transports the essential metals, copper and zinc, while limiting the transport of cadmium is unknown, but may involve the approximately 1,000-fold higher concentration of zinc in the placenta and the higher affinity of cadmium than zinc for metallothionein (Goyer et al. 1992). Timing and level of cadmium exposure may influence the uptake of cadmium by the placenta, perhaps explaining the conflicting human studies. Galicia-Garcia et al. (1995) performed analyses of cadmium in maternal, cord, and newborn blood for 50 births in a Mexico City hospital. Multiple regression analyses applied to the data indicated a significant association between cord and newborn blood and between cord and maternal blood, but not among maternal and newborn blood. Birth weight of the newborns was found to be inversely associated with cord blood cadmium levels and smoking habits.

Children are most likely to be exposed to cadmium in food or water. Most ingested cadmium passes through the gastrointestinal tract without being absorbed. Only about one-twentieth of the total ingested cadmium (in food or water) is absorbed in adult humans (Ellis et al. 1979; Flanasen et al. 1978; McLellan et al. 1978; Morgan and Sherlock 1984; Newton et al. 1984; Rahola et al. 1973). The retention of cadmium in the gut slowly decreases over a period of l-3 weeks after ingestion in adults (Rahola et al. 1973). There are no data on gastrointestinal absorption of cadmium in children, although very limited

evidence exists that cadmium absorption from the gut may be greater in young animals. Oral absorption is discussed in more detail in Section 2.3.1.2. A study performed in Cincinnati, Ohio, investigated cadmium in human milk and found a mean concentration of 19 ppb (0.019 ppm) (Jensen 1983). Reported levels of cadmium in infant foods in Canada ranged from 0.00053 ppm in juices to 0.034 ppm in dry infant cereals (Debeka and McKenzie 1988). Except in the vicinity of cadmium-emitting industries or incinerators, the intake of cadmium from drinking water or ambient air is of minor significance (Elinder 1985a). Near sources of pollution, children may inhale 1-75 μg/day (Elinder 1985a). Children in the homes of parents who smoke also can be exposed to cadmium through the inhalation of environmental tobacco smoke. Although no data were found, children playing near hazardous waste sites could be exposed to cadmium in soil by hand-to-mouth activity and/or soil pica. No case studies were found on accidental poisoning of children by swallowing cadmium-containing batteries or by ingesting cadmium-containing household pesticides, which also are potential routes of exposure. No information was found concerning differences in the weight-adjusted intakes of cadmium by children.

In the Workers' Home Contamination Study conducted under the Workers' Family Protection Act (DHHS 1995), several studies were identified that reported home contamination with cadmium originating from parental occupation in a lead smelter. In a study of 396 children of ages l-9 years living less than 900 m from a primary lead smelter, 380 children (96%) had blood cadmium (CdB) levels greater than 0.0089 μg/L (Carvalho et al. 1986). The geometric mean and standard deviation were 0.087 and 2.5 μg/L, respectively. No significant relationship was found between parental occupation in the smelter and CdB in children, but a significant relationship was found between presence of smelter dross in the house and elevated CdB in children. Higher CdB was significantly associated with shorter distance from the home to the smelter. In a similar study of 263 children (ages l-9 years), living less than 900 m from a primary lead smelter, the mean cadmium in hair was significantly higher at 6.0 ppm for children whose fathers worked in lead smelters than the concentration of 3.7 ppm for children whose fathers had other jobs (Carvalho et al. 1989). In a study of 9 children from families of lead workers and 195 children (ages 4-17 years) from other families, the children from the families of lead workers had significantly higher geometric mean urinary cadmium (CdU) (0.34k2.6 μg/L) than children from other families (0.1322.2 μg/L). The CdB levels of children from families of lead workers were higher than those of the children from other families, but the difference was not statistically significant (Brockhous et al. 1988). Maravelias et al. (1989) measured the CdBs of 514 children (ages 5-12) from four schools located within various distances (500-1500 m) from a lead smelter. The average CdB was 0.36 μg/L, with a range of 0.1-3.1 μg/L.

Children from the school closest to the smelter had higher CdB levels than children from other schools, but no relationship was found between children's CdB and parental employment in the smelter.

5.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

The greatest potential for above-average exposure of the general population to cadmium is from smoking, which may double the exposure of a typical individual. Passive smoking does not appear to increase blood cadmium concentrations (Willers et al. 1988). Smokers with additional occupational exposure are at highest risk (Elinder 1985a). Individuals living near zinc or lead smelting operations, municipal incinerators, or other industrial processes emitting cadmium to the air will also have above-average exposure (Elinder 1985a). Exposures through inhalation are diminishing due to pollution controls at such facilities, but exposure resulting from soil contamination may continue to be significant. Persons who have corrosive drinking water and cadmium-containing plumbing, who habitually consume cadmium concentrating foods (kidney, liver, and shellfish), or who ingest grains or vegetables grown in soils treated with municipal sludge or phosphate fertilizer all may have increased exposure (Elinder 1985a). Multiple pathways of exposure may exist for populations at hazardous waste sites contaminated with cadmium (ingestion of contaminated drinking water or garden vegetables, inhalation of airborne dust, incidental ingestion of contaminated soil).

Persons who consume large quantities of sunflower kernels can be exposed to higher levels of cadmium, Reeves and Vanderpool(l 997) identified specific groups of men who were likely to consume sunflower kernels. The groups included baseball and softball players, delivery and long-distance drivers, and line workers in sunflower kernel processing plants.

Recreational and subsistence fishers that consume appreciably higher amounts of locally caught fish from contaminated waterbodies may be exposed to higher levels of cadmium associated with dietary intake (EPA 1993a). Cadmium contamination has triggered the issuance of several human health advisories. As of December 1997, cadmium was identified as the causative pollutant in five fish and shellfish consumption advisories in New York and another in New Jersey. EPA is considering including cadmium as a target analyte and has recommended that this metal be monitored in fish and shellfish tissue samples collected as part of state toxics monitoring programs. EPA recommends that residue data obtained from these monitoring programs be used by states to conduct rick assessments to determine the need for issuing fish and shellfish consumption advisories for the protection of the general public as well as recreational and

subsistence fishers Under the same program, EPA has issued a statewide advisory in Maine for cadmium in moose (EPA 1998).

5.8 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 cadmium is available. Where adequate information is not available, ATSDR, in conjunction with the 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 cadmium.

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.

5.8.1 Identification of Data Needs

Physical and Chemical Properties. The chemical and physical properties of cadmium and its salts are known well enough to permit estimation of the environmental fate of the compounds (Elinder 1985a, 1992). Additional information on properties does not appear to be crucial for evaluating potential fate.

Production, Import/Export, Use, Release, and Disposal. The production volume, producers, import/export quantities, and uses of cadmium in the United States are well documented (ABMS 1994; IARC 1993; SRI 1994; TRI961998; U.S. Bureau of Mines 1990). Production volumes have responded to demand over the past decade and there is no indication of expected significant changes (U.S. Bureau of Mines 1990). Disposal of cadmium-containing wastes is regulated by the federal government, and data are available for industrial disposal practices (EPA 1982a; HSDB 1994; U.S. Bureau of Mines 1990). Most releases of cadmium are not from production of the metal or its compounds, but from combustion or smelter emissions, land application of sewage sludge and fertilizers, and other sources; estimates of these

releases have been made (TRI961998). However, no data were located to allow estimates of the quantities of products containing cadmium that are deposited in municipal landfills. Information on current disposal practices for cadmium-containing materials would assist in evaluating potential total human exposure to cadmium.

According to the Emergency Planning and Community Right-to-Know Act of 1986,42 U.S.C. Section 11023, industries are required to submit chemical release and off-site transfer information to the EPA. The Toxics Release Inventory (TRI), which contains this information for 1996, became available in May of 1998. This database will be updated yearly and should provide a list of industrial production facilities and emissions.

Environmental Fate. Cadmium partitioning among media occurs, and this partitioning depends on local environmental conditions (Elinder 1985a, 1992). Cadmium may be subject to long-range transport in air and water (Keitz 1980). Cadmium is persistent in all media, although it may form organic complexes in soil and water under certain environmental conditions (Callahan et al. 1979). These processes, which are important for determining the environmental fate of cadmium, seem to be relatively well understood. Therefore, additional information on environmental fate does not appear to be essential to evaluate potential human exposure to cadmium.

Bioavailability from Environmental Media. Factors that control the bioavailability of cadmium from air, water, soil, and food have been investigated. Intestinal absorption of cadmium from food is low, about 510% (McLellan et al. 1978; Newton et al. 1984; Rahola et al. 1973), but the absorption of cadmium from soil is not known. Absorption from the lungs is somewhat greater, averaging about 25% (Nordberg et al. 1985). Estimates of dermal absorption of cadmium from soil and water on human skin have been made (Wester et al. 1992). There is some evidence that bioavailability of cadmium to plants and worms from contaminated soil is greater following remediation (Van Gestel et al. 1988). Additional information on the factors influencing bioavailability, particularly from remediated soil, are needed to assess residual risk to populations in the vicinity of reclaimed hazardous waste sites.

Food Chain Bioaccumulation. Sufficient data are available to indicate that cadmium is concentrated in plants, aquatic organisms, and animals (Alloway et al. 1990; Beyer 1986; Handy 1992a, 1992b; Kuroshima 1992; Naqui and Howell 1993; Roseman et al. 1994; Suresh et al. 1993; Vos et al. 1990). In vertebrates, cadmium accumulates in the liver and kidneys (Harrison and Klaverkamp 1990; Sileo and Beyer 1985; Vos et al. 1990). There is strong evidence for food chain bioaccumulation, but the potential for biomagnification is uncertain. Additional studies on biomagnification are needed to provide data for more accurate evaluation of the environmental impact of cadmium contamination.

Exposure Levels in Environmental Media. Extensive monitoring data are available for cadmium in all environmental media (Elinder 1985a, 1992). Cadmium has been detected in air, water, soil, plants, and food in many areas of the United States, including areas in the vicinity of hazardous waste sites (EPA 1981; IARC 1993). Estimates of human intake from these media have been made (Elinder 1985a; Gartrell et al. 1986); however, most of the data are more than 3 years old. Continuing monitoring efforts would allow more precise estimation of current sources and levels of human exposure and would assist in identifying major sources contributing to current exposure.

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

Exposure Levels in Humans. Cadmium has been detected in human blood, urine, breast milk, liver, kidney, and other tissues, both in occupationally exposed individuals and in the general population (Elinder 1985b; Gochfeld et al. 1991; Jensen 1983; Sikorski et al. 1989). However, few detailed current surveys of levels in U.S. populations were located; such studies are needed to establish current exposures, especially in the vicinity of hazardous waste sites. Also, more information is needed on the specific exposure levels for different cadmium salts to determine if cadmium sulfides, for example, are associated with less harmful effects than cadmium oxides (Chettle and Ellis 1992).

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

Exposures of Children. Cadmium has been measured in maternal and neonatal (cord) blood and in placenta (Baranowska 1995; Galicia-Garcia et al. 1995; Kuhnert et al. 1982; Lauwerys et al. 1978; Roels et al. 1978; Truska et al. 1989), but the resulting data are sometimes conflicting with respect to the uptake of cadmium by the placenta. Research on the effects of timing and level of exposure on cadmium uptake by the placenta might help to explain these conflicting human studies. A study performed in Cincinnati, Ohio, investigated cadmium in human milk and found a mean concentration of 19 ppb (0.019 ppm) (Jensen 1983). More recent data would be useful, both from women living in unpolluted areas (for background levels) and in polluted areas such as those near existing or former lead smelters.

Some body burden data are available for children living near lead smelters (Brockhous et al. 1988; Carvalho et al. 1986; Carvalho et al. 1989; DHHS 1995; Maravelias et al. 1989). However, none of the studies took place in the United States. Body burden data from children living in polluted and unpolluted regions (for background levels) of the United States are needed.

Current information on whether children are different in their weight-adjusted intake of cadmium via oral, inhalation, and dermal exposures was not located. A study to determine this information would be useful. Also no information was found on childhood specific means to reduce cadmium exposure.

Child health data needs relating to susceptibility are discussed in Section 2.11.2, Identification of Data Needs: Children’s Susceptibility.

Exposure Registries. The State of New York has established the Heavy Metals Registry for surveillance of occupational heavy metals absorption (Baser and Marion 1990). Health facilities, clinical laboratories, and physicians are required to report state residents with elevated levels of heavy metals, including cadmium, in blood or urine. Cadmium levels greater than 10 μg/L in blood and 5 μg/24 hours in urine were reported. Over a 5-year period, twenty-six individuals occupationally exposed to cadmium were located by this registry. Similar registries have been established in New Jersey, California, Texas, and Maryland (Baser and Marion 1990).

No other exposure registries for cadmium were located. This substance is not currently one of the compounds for which a subregistry has been established in the National Exposure Registry. The substance will be considered in the future when chemical selection is made for subregistries to be established. The

information that is amassed in the National Exposure Registry facilitates the epidemiological research needed to assess adverse health outcomes that may be related to exposure to this substance.

5.8.2 Ongoing Studies

Table 5-3 lists information located concerning ongoing research into factors controlling the potential for human exposure to cadmium.

Table 5-3. Ongoing Studies on the Potential for Human Exposure to Cadmium

Investigator	Affiliation	Research description	Sponsor
V. Baligar, C. Clark, and R.B. Ritche	Virginia Polytechnic Institute and State University, Blacksburg, VA	Uptake, transport and accumulation of trace elements, including cadmium, by plants from soil treated with coal-fired power plant by-products	USDA
E.A. Brams	Prairie View A&M University, Prairie View, TX	A quality assessment of toxic trace metals in an agricultural food chain	USDA
R.L. Chaney and R.J. Wright	Beltsville Agricultural Research Center, Beltsville, MD	Soil and plant factors affecting concentration and bioavailability of cadmium in U.S. crops	USDA
A.C. Chang, A.L. Page, and C. Amrhein	University of California, Riverside, CA	Characterization of chemistry and bioavailability of waste constituents, including cadmium, in soils	USDA
M.H. Conklin	University of Arizona, Tucson, AZ	Humic-facilitated transport of metals, including cadmium, to groundwater through the vadose zone	NIEHS
S.J. Crafts-Brandner and G. Wagner	University of Kentucky, Lexington, KY	Mechanisms of cadmium transport and sequestration in tonoplast vesicles isolated from tobacco seedlings	USDA
D.M. Ditoro	New York University Medical Center, New York, NY	Development of a model for the flux of cadmium to and from sediment	NIEHS
M.J. Gartrell	Food and Drug Administration, Washington, DC	Monitoring to determine cadmium levels in food—Total Diet Study	FDA
D.L. Grunes and W.A. Norvell	Agricultural Research Service, Ithaca, NY	Determination of soil and plant factors affecting the plant availability and translocation of potentially harmful elements, principally cadmium	USDA
H.C. Harrison	University of Wisconsin, Madison, WI	Mechanism for differences in cadmium uptake of lettuce genotypes	USDA

Table 5-3. Ongoing Studies on the Potential for Human Exposure to Cadmium (continued)

Investigator	Affiliation	Research description	Sponsor
P.A. Helmke	University of Wisconsin, Madison, WI	Ion exchange and complex ion formation affecting the solubility and plant uptake of trace metals, including cadmium; chemistry and bioavailability of waste constituents in soil.	USDA
P.A. Helmke and P. Barak	University of Wisconsin, Madison, WI	Species-specific exchange reactions controlling solubility of elements in soil and their uptake by plants	USDA
R.L. Jones	University of Illinois, Urbana, IL	Determination of total concentrations of Cu, Zn, Cd, Pb, Cr, and Ni in Illinois surface soils	USDA
L.V. Kochian	Agricultural Research Service, Ithaca, NY	Investigation and characterization of basic transport processes used by plants to absorb and translocate heavy metals, including cadmium	USDA
L.V. Kochian	Agricultural Research Service, Ithaca, NY	Identification of plant species that can be used to remediate soils polluted with heavy metals, including cadmium	USDA
A.K. Koli	South Carolina State College, Orangeburg, SC	Measurements of selected trace elements, including cadmium, in fresh fish, meats and processed meats	USDA
S. Kuo	Washington State University Puyallup Research and Extension Center, Puyallup, WA	Chemistry and bioavailability of waste constituents, including cadmium, in soils	USDA
T.J. Logan	Ohio State University, Columbus, OH	Chemistry and bioavailability of waste constituents, including cadmium, in soils	USDA
M.B. McBride	Cornell University, Ithaca, NY	Reaction and availability of toxic metals, including cadmium, in soils over the long term	USDA
L.G. Morrill	Oklahoma State University, Stillwater, OK	Factors controlling cadmium leaching and plant uptake from fly ash/soil	USDA

Table 5-3. Ongoing Studies on the Potential for Human Exposure to Cadmium (continued)

Investigator	Affiliation	Research description	Sponsor
H. Motto and J. Walworth	Rutgers University, New Brunswick, NJ	Fate of metals, including cadmium, and nutrients from land application of wastes and manure	USDA
F.M. Morel and F. Morel	Massachusetts Institute of Technology, Cambridge, MA	Role of natural chelating agents in affecting the fate and biological effects of trace metals such as cadmium in natural waters	NSF
J.W. Odom	Auburn University, Auburn, AL USA	Occurrence, accumulation and plant availability of heavy metals, including cadmium, in acid ultisols	USDA
D.R. Parker and D.E. Crowley	University of California, Riverside, Riverside, CA	Plant uptake of cadmium complexed with organic and inorganic ligands	USDA
J.H. Peverly and J.L. Hutson	Cornell University, Ithaca, NY	Fate and movement of metals, including cadmium, in representative plant/soil systems amended with sewage sludge, composts and other wastes	USDA
P.N. Pintauro	Tulane University Medical Center, New Orleans, LA	Synthesis/application of chelating agents for removal of toxic heavy metals, including cadmium, from soils and clays at superfund waste sites	NIEHS
J.R. Preer	University of the District of Columbia, Washington, DC	Fate and transport of waste constituents, including cadmium, in soil plant systems	USDA
P.G. Reeves and R. Vanderpool	Agricultural Research Service, USDA	Health effects and bioavailability of cadmium from sunflower seed kernels	USDA
C.J. Schmitt	U.S. Fish and Wildlife Service, Columbia, MO	Analysis for cadmium and other contaminants in fish and wildlife—National Contaminant Biomonitoring Program	FWS
L.M. Shuman	University of Georgia, Athens, GA	Equilibrium of metals, including cadmium, in soils and effects on water quality	USDA

Table 5-3. Ongoing Studies on the Potential for Human Exposure to Cadmium (continued)

Investigator	Affiliation	Research description	Sponsor
R.N. Singh and R.F. Keefer	West Virginia University, Morgantown, WV	Factors affecting uptake of cadmium from soil treated with waste and manure	USDA
M. Sunthankar	IonEdge Corporation, Fort Collins, CO	Investigation of environmentally safer zinc-graphite dry plating as an alternative to cadmium electroplating	EPA
R.V. Thomann	New York University Medical Center, New York, NY	Predictive models of the fate and accumulation of metals, including cadmium, in benthic aquatic animals (crab, lobster and benthic fishes)	NIEHS
S. Toon	National Renewable Energy Laboratory	Remediation of toxic metals, including cadmium, using microorganisms	USDOE
G.J. Wagner	University of Kentucky, Lexington, KY	Genetic manipulation of cadmium uptake by tobacco leaves	USDA
R.M. Welch, W.A. Norvell, and D.L. Grunes	Agricultural Research Service, Ithaca, NY	Uptake, transportation, and interactions of essential and toxic mineral elements, including cadmium	USDA
L.Y. Young	New York University Medical Center, New York, NY	Microbial mediated transformations of cadmium in the environment	NIEHS

FDA = United States Food and Drug Administration; FWS = United States Fish and Wildlife Service; NIEHS = National Institute of Environmental Health Sciences; NSF = National Science Foundation; USDA = United States Department of Agriculture; USDOE = United States Department of Energy

Source: FEDRIP 1998