INORGANIC AND ORGANIC LEAD COMPOUNDS

Metallic lead and several inorganic and organic lead compounds have been considered by previous working groups convened by IARC (IARC, 1972, 1973, 1976, 1980, 1987). New data have since become available, and these are included in the present monograph and have been taken into consideration in the evaluation. The agents considered in this monograph are some inorganic and organic lead compounds.

1. Exposure Data

1.1 Chemical and physical data

1.1.1 *Nomenclature, synonyms, trade names, molecular formulae, chemical and physical properties*

Synonyms, trade names and molecular formulae for lead and some inorganic and organic lead compounds are presented in Table 1. The lead compounds shown are those for which data on carcinogenicity or mutagenicity are available or which are commercially most important. The list is not exhaustive.

Selected chemical and physical properties of the lead compounds listed in Table 1 are presented in Table 2.

Lead (atomic number, 82; relative atomic mass, 207.2) has a valence +2 or +4. The alchemists believed lead to be the oldest metal and associated it with the planet Saturn. Lead is a bluish-white metal of bright lustre, is very soft, highly malleable, ductile and a poor conductor of electricity. It is very resistant to corrosion; lead pipes bearing the insignia of Roman emperors, used as drains from the baths, are still in service (Lide, 2003). Natural lead is a mixture of four stable isotopes: ^{204}Pb (1.4%), ^{206}Pb (25.2%), ^{207}Pb (21.7%) and ^{208}Pb (51.7%) (O'Neil, 2003). Lead isotopes are the end-products of each of the three series of naturally occurring radioactive elements: ^{206}Pb for the uranium series, ^{207}Pb for the actinium series and ^{208}Pb for the thorium series. Forty-three other isotopes of lead, all of which are radioactive, are recognized (Lide, 2003).

Table 1. Synonyms and trade names, registry numbers, molecular formulae, and molecular weights for lead and lead compounds

Chemical name	Synonyms and trade names (Chemical Abstracts Service name in italics)	CAS registry number[a]	Molecular formula	Molecular weight[b]
Calcium plumbate	Pigment Brown 10	12013-69-3	Ca_2PbO_4	[351.4]
Lead, lead powder	C.I. 77575; C.I. Pigment Metal 4; Lead element; Lead Flake; Lead S 2; Pb-S 100; SSO 1	7439-92-1	Pb[c]	207.2[c]
Lead acetate	*Acetic acid, lead(2+) salt*; acetic acid lead salt (2:1); dibasic lead acetate; lead bis(acetate); lead diacetate; lead dibasic acetate; lead(2+) acetate; lead(II) acetate; neutral lead acetate; normal lead acetate; plumbous acetate; salt of Saturn; sugar of lead	301-04-2	$Pb(C_2H_3O_2)_2$	325.3
Lead acetate trihydrate	*Acetic acid, lead(2+) salt, trihydrate*; lead diacetate trihydrate; lead(II) acetate trihydrate; plumbous acetate trihydrate; sugar of lead	6080-56-4	$Pb(C_2H_3O_2)_2{\cdot}3H_2O$	379.3
Lead arsenate	*Arsenic acid (H_3AsO_4), lead(2+) salt (2:3)*; lead(2+) orthoarsenate ($Pb_3(AsO_4)_2$); Nu Rexform; trilead diarsenate	3687-31-8	$Pb_3(AsO_4)_2$	899.4
Lead azide	*Lead azide ($Pb(N_3)_2$)*; lead azide (PbN_6); lead diazide; lead(2+) azide; RD 1333	13424-46-9 [85941-57-7]	$Pb(N_3)_2$	291.2
Lead bromide	*Lead bromide ($PbBr_2$)*; lead dibromide	10031-22-8	$PbBr_2$	367.0
Lead carbonate	*Carbonic acid, lead(2+) salt (1:1)*; lead carbonate ($PbCO_3$); basic lead carbonate; dibasic lead carbonate; lead(2+) carbonate; plumbous carbonate; cerussite; white lead	598-63-0	$PbCO_3$	267.2
Lead chloride	*Lead chloride ($PbCl_2$)*; lead dichloride; lead(2+) chloride; lead(II) chloride; plumbous chloride; natural cotunite	7758-95-4	$PbCl_2$	278.1
Lead chromate	*Chromic acid (H_2CrO_4), lead(2+) salt (1:1)*; lead chromate(VI); lead chromate ($PbCrO_4$); lead chromium oxide ($PbCrO_4$); plumbous chromate; Royal Yellow 6000; chrome yellow	7758-97-6 [8049-64-7]	$PbCrO_4$	323.2
Lead fluoride	*Lead fluoride (PbF_2)*; lead difluoride; lead difluoride (PbF_2); lead(2+) fluoride; plumbous fluoride	7783-46-2 [106496-44-0]	PbF_2	245.2

Table 1 (contd)

Chemical name	Synonyms and trade names (Chemical Abstracts Service name in italics)	CAS registry number[a]	Molecular formula	Molecular weight[b]
Lead fluoroborate	Borate(1-), tetrafluoro-, lead(2+) salt (2:1); borate(1-), tetrafluoro-, lead(2+); lead fluoborate; lead tetrafluoroborate; lead boron fluoride; lead fluoroborate ($Pb(BF_4)_2$); lead(II) tetrafluoroborate	13814-96-5 [35254-34-3]	$Pb(BF_4)_2$	380.8
Lead hydrogen arsenate	*Arsenic acid (H_3AsO_4), lead(2+) salt (1:1)*; lead arsenate ($PbHAsO_4$); acid lead arsenate; arsenic acid lead salt; lead acid arsenate; lead arsenate; lead hydrogen arsenate ($PbHAsO_4$); lead(2+) monohydrogen arsenate	7784-40-9 [14034-76-5; 37196-28-4]	$PbHAsO_4$	347.1
Lead iodide	*Lead iodide (PbI_2)*; C.I. 77613; *lead diiodide*; lead(II) iodide; plumbous iodide	10101-63-0 [82669-93-0]	PbI_2	461.0
Lead naphthenate	*Naphthenic acids, lead salts*; lead naphthenates; naphthenic acid, lead salt; Naphthex Pb; Trokyd Lead	61790-14-5	Unspecified	
Lead nitrate	*Nitric acid, lead(2+) salt*; lead dinitrate; lead nitrate ($Pb(NO_3)_2$); lead(2+) bis(nitrate); lead(2+) nitrate; lead(II) nitrate; plumbous nitrate	10099-74-8 [18256-98-9]	$Pb(NO_3)_2$	331.2
Lead dioxide	*Lead oxide (PbO_2)*; C.I. 77580; lead brown; lead oxide brown; lead peroxide; lead superoxide; lead(IV) oxide; plumbic oxide; Thiolead A	1309-60-0 [60525-54-4]	PbO_2	239.2
Lead monoxide	*Lead oxide (PbO)*; C.I. 77577; C.I. Pigment Yellow 46; *lead monooxide*; lead oxide yellow; lead protoxide; lead(2+) oxide; lead(II) oxide; litharge; Litharge S; Litharge Yellow L-28; plumbous oxide; yellow lead ochre	1317-36-8 [1309-59-7; 12359-23-8]	PbO	223.2
Lead trioxide	*Lead trioxide (Pb_2O_3)*; C.I. 77579; *lead sesquioxide*; lead sesquioxide (Pb_2O_3); plumbous plumbate	1314-27-8	Pb_2O_3	462.4
Lead phosphate	*Phosphoric acid, lead(2+) salt (2:3)*; lead phosphate ($Pb_3P_2O_8$); C.I. 77622; C.I. Pigment White 30; lead diphosphate; *lead orthophosphate*; lead phosphate (3:2); lead(2+) phosphate ($Pb_3(PO_4)_2$); lead(II) phosphate (3:2); Perlex Paste 500; Perlex Paste 600A; Trilead phosphate; lead phosphate dibasic	7446-27-7	$Pb_3(PO_4)_2$	811.5

Table 1 (contd)

Chemical name	Synonyms and trade names (Chemical Abstracts Service name in italics)	CAS registry number[a]	Molecular formula	Molecular weight[b]
Lead phosphite, dibasic	Dibasic lead phosphite; lead dibasic phosphite; dibasic lead metaphosphate; C.I. 77620; lead oxide phosphonate, hemihydrate	1344-40-7	$2PbO{\cdot}PbHPO_3{\cdot}1/2H_2O$	[743]
Lead molybdate	Lead molybdate(VI); lead molybdate oxide ($PbMoO_4$)	10190-55-3	$PbMoO_4$	367.1
Lead stearate	*Octadecanoic acid, lead(2+) salt*; 5002G; lead distearate; lead(2+) octadecanoate; lead(2+) stearate; lead(II) octadecanoate; lead(II) stearate; Listab 28ND; Pbst; SL 1000 (stabilizer); SLG; Stabinex NC18; stearic acid, lead(2+) salt	1072-35-1 [11097-78-2; 37223-82-8]	$Pb(C_{18}H_{35}O_2)_2$	774.1
Lead stearate, dibasic	Dibasic lead stearate; Listab 51; lead, bis(octadecanoato)dioxodi-; stearic acid, lead salt, dibasic	56189-09-4	$2PbO{\cdot}Pb(C_{17}H_{35}COO)_2$	1220
Lead styphnate	*1,3-Benzenediol, 2,4,6-trinitro-, lead(2+) salt (1:1)*; 2,4-dioxa-3-plumbabicyclo[3.3.1]nona-1(9),5,7-triene, 3,3-didehydro-6,8,9-trinitro-; lead, [styphnato(2-)]-; lead tricinate; lead trinitroresorcinate; Tricinat; 2,4,6-trinitroresorcinol, lead(2+) salt (1:1)	15245-44-0 [4219-19-6; 6594-85-0; 59286-40-7; 63918-97-8]	$Pb(C_6H_3N_3O_8)$	[452.3]
Lead subacetate	*Lead, bis(acetato-êO)tetrahydroxytri-*; lead acetate ($Pb_3(AcO)_2(OH)_4$); lead, bis(acetato)-tetrahydroxytri-; lead, bis(acetato-O)tetra-hydroxytri-; bis(acetato)dihydroxytrilead; lead acetate hydroxide ($Pb_3(OAc)_2(OH)_4$); lead acetate, basic; monobasic lead acetate	1335-32-6	$Pb(CH_3COO)_2{\cdot}2Pb(OH)_2$	807.7
Lead sulfate	*Sulfuric acid, lead(2+) salt (1:1)*; Anglislite; C.I. 77630; C.I. Pigment White 3; Fast White; Freemans White Lead; HB 2000; Lead Bottoms; lead monosulfate; lead(II) sulfate (1:1); lead(2+) sulfate; lead(II) sulfate; Milk White; Mulhouse White; TS 100; TS 100 (sulfate); TS-E; sublimed white lead	7446-14-2 [37251-28-8]	$PbSO_4$	303.3
Lead sulfide	*Lead sulfide (PbS)*; C.I. 77640; lead monosulfide; lead sulfide (1:1); lead(2+) sulfide; lead(II) sulfide; natural lead sulfide; P 128; P 37; plumbous sulfide	1314-87-0 [51682-73-6]	PbS	239.3

Table 1 (contd)

Chemical name	Synonyms and trade names (Chemical Abstracts Service name in italics)	CAS registry number[a]	Molecular formula	Molecular weight[b]
Lead tetraoxide	*Lead oxide (Pb_3O_4)*; Azarcon; C.I. 77578; C.I. Pigment Red 105; Entan; Gold Satinobre; Heuconin 5; lead orthoplumbate; lead oxide (3:4); *lead oxide red*; lead tetroxide; Mennige; Mineral Orange; Mineral red; Minium; Minium Non-Setting RL 95; Minium red; Orange Lead; Paris Red; *red lead*; red lead oxide; Sandix; Saturn Red; trilead tetraoxide; trilead tetroxide; plumboplumbic oxide	1314-41-6 [12684-34-3]	Pb_3O_4	685.6
Lead thiocyanate	Thiocyanic acid, lead(2+) salt; lead bis(thiocyanate); lead dithiocyanate; lead(2+) thiocyanate; lead(II) thiocyanate	592-87-0 [10382-36-2]	$Pb(SCN)_2$	323.4
Tetraethyl lead	*Plumbane, tetraethyl-*; lead, tetraethyl-; TEL; tetraethyllead; tetraethylplumbane	78-00-2	$Pb(C_2H_5)_4$	323.5
Tetramethyl lead	*Plumbane, tetramethyl-*; lead, tetramethyl-; tetramethyllead; tetramethylplumbane; TML	75-74-1	$Pb(CH_3)_4$	267.3

From IARC (1980); Lide (2003); National Library of Medicine (2003); O'Neil (2003); STN International (2003)

[a] Deleted Chemical Abstracts Service numbers shown in square brackets

[b] Values in square brackets were calculated from the molecular formula.

[c] Atomic formula; atomic weight

Table 2. Physical and chemical properties of lead and lead compounds

Chemical name	Physical form	Melting-point (°C)	Boiling-point (°C)	Density (g/cm^3)	Solubility (per 100 g H_2O)
Lead, lead powder	Soft silvery-gray metal; cubic	327.5	1749	11.3	Insol. in water; sol. in conc. acid
Lead acetate	White crystal	280	Dec.	3.25	44.3 g at 20 °C; sl. sol. in ethanol
Lead acetate trihydrate	Colourless crystal	75 (dec)	–	2.55	45.6 g at 15 °C; sl. sol. in ethanol
Lead arsenate	White crystal	1042 (dec)	–	5.8	Insol. in water; sol. in nitric acid
Lead azide	Colourless orthorhombic needle	~350 (expl)	–	4.7	23 mg at 18 °C; v. sol. in acetic acid
Lead bromide	White orthorhombic crystal	371	892	6.69	975 mg at 25 °C; insol. in ethanol
Lead carbonate	Colourless orthorhombic crystal	~315 (dec)	–	6.6	Insol. in water; sol. in acid and alkaline solutions
Lead chloride	White orthorhombic needle or powder	501	951	5.98	1.08 g at 25 °C; sol. in alkaline solutions; insol. in ethanol
Lead chromate	Yellow-orange monoclinic crystals	844	–	6.12	17 µg at 20 °C; sol. in dilute acids
Lead fluoride	White orthorhombic crystal	830	1293	8.44	67 mg at 25 °C
Lead fluoroborate	Stable only in aqueous solution	–	–	–	Sol. in water
Lead hydrogen arsenate	White monoclinic crystal	280 (dec)		5.94	Insol. in water; sol. in nitric acid and alkaline solutions
Lead iodide	Yellow hexagonal crystal or powder	410	872 (dec)	6.16	76 mg at 25 °C; insol. in ethanol
Lead molybdate	Yellow tertiary crystal	~1060	–	6.7	Insol. in water; sol. in nitric acid and sodium hydroxide
Lead naphthenate	No data available				
Lead nitrate	Colourless cubic crystal	470	–	4.53	59.7 g at 25 °C; sl. sol. in ethanol

Table 2 (contd)

Chemical name	Physical form	Melting-point (°C)	Boiling-point (°C)	Density (g/cm^3)	Solubility (per 100 g H_2O)
Lead monoxide (PbO); litharge	Red tetrahedral crystal	Transforms to massicot at 489 °C	–	9.35	Insol. in water and ethanol; sol. in dilute nitric acid
Massicot	Yellow orthorhombic crystal	897	–	9.64	Insol. in water and ethanol; sol. in dilute nitric acid
Lead trioxide (Pb_2O_3)	Black monoclinic crystal or red amorphous powder	530 (dec)	–	10.05	Insol. in water; sol. in alkaline solutions
Lead phosphate	White hexagonal crystal	1014	–	7.01	Insol. in water and ethanol; sol. in alkali and nitric acid
Lead phosphite, dibasic	Pale yellow powder			6.1	
Lead stearate	White powder	~100	–	1.4	Insol. in water; sol. in hot ethanol
Lead styphnate	No data available				
Lead subacetate	White powder	Dec.	–	–	6.3 g at 0 °C; 25 g at 100 °C
Lead sulfate	Orthorhombic crystal	1087	–	6.29	4.4 mg at 25 °C; sl. sol. in alkaline solutions; insol. in acids
Lead sulfide	Black powder or silvery cubic crystal	1113	–	7.60	Insol. in water; sol. in acids
Lead tetraoxide	Red tetrahedral crystals	830	–	8.92	Insol. in water and ethanol; sol. in hot hydrochloric acid
Lead thiocyanate	White to yellowish powder	–	–	3.82	50 mg at 20 °C
Tetraethyl lead	Liquid	–136	200 (dec)	1.653 at 20 °C	Insol. in water; sol. in benzene; sl. sol. in ethanol and diethyl ether
Tetramethyl lead	Liquid	–30.2	110	1.995 at 20 °C	Insol. in water; sol. in benzene, ethanol and diethyl ether

From IARC (1980); Lide (2003); Physical and Theoretical Chemistry Laboratory (2004)
Abbreviations: conc., concentrated; insol., insoluble; sl. sol., slightly soluble; sol., soluble; v. sol., very soluble; dec, decomposes; expl., explodes

1.1.2 *Technical products and impurities*

Lead is produced in purity greater than 99.97% in many countries. Lead oxides and mixtures of lead and lead oxides are also widely available. Tables 3 and 4 show the specifications for metallic lead and some lead compounds, respectively, from selected countries.

Table 3. Specifications for metallic lead from selected countries

Country	% Pb (min.)	Contaminants with limits (% max.[a])	Reference
Argentina	99.97	Fe, 0.002; Sb, 0.004; Zn, 0.001; Cu, 0.002; Ag, 0.0095; Bi, 0.035; Cd, 0.001; Ni, 0.001	Industrias Deriplom SA (2003)
Australia	99.97–99.99	Ag, 0.001; As, 0.001; Bi, 0.005–0.029; Cu, 0.001; Sb, 0.001; Zn, 0.001; Cd, 0.001	Pasminco Metals (1998)
Belgium	99.9–99.95	(ppm) Bi, 90–250; Ag, 10–15; Cu, 5–10; As, 5; Sb, 3; Sn, 3; As+Sb+Sn, 8; Zn, 3–5; Fe, 3; Cd, 3–10; Ni, 2–3	Umicore Precious Metals (2002)
Bulgaria	99.97–99.99	Ag, 0.001–0.005; Cu, 0.0005–0.003; Zn, 0.0002–0.0015; Fe, 0.001; Cd, 0.0002–0.001; Ni, 0.0005–0.001; As, 0.0005–0.002; Sb, 0.0005–0.005; Sn, 0.0005–0.001; Bi, 0.005–0.03	KCM SA (2003)
Canada	99.97–99.99	NR	Noranda (2003); Teck Cominco (2003)
Kazakhstan	99.95–99.9996	NR	Southpolymetal (2003)
Mexico	99.97–99.99	Ag, 0.0015; Cu, 0.0005; Zn, 0.0005; Fe, 0.0010; Bi, 0.0250; Sb, 0.0005; As, 0.0005; Sn, 0.0005; Ni, 0.0002; Te, 0.0001	Penoles (2003)
Republic of Korea	99.995	Ag, 0.0003; Cu, 0.0003; As, 0.0003; Sb, 0.0003; Zn, 0.0003; Fe, 0.0003; Bi, 0.0015; Sn, 0.0003	Korea Zinc Co. (2003)
USA	99.995–99.9999	(ppm) Sb, 1; As, 1–5; Bi, 0.2–4; Cu, 1–4; Ag, < 0.1–2; Tl, 1–2; Sn, 0.3–1; Fe, < 0.1–0.3; Ca, 0.1–0.4; Mg, 0.1–0.3	ESPI Corp. (2002)

NR, not reported

[a] Unless otherwise specified

Table 4. Specifications for some lead compounds from selected countries

Country	Compound	Contaminants with limits (% max.)	Grade[a]	Reference
Argentina	Lead oxide	Fe, 0.003; Sb, 0.001–0.004; Zn, 0.0005–0.001; Cu, 0.0005–0.002; Ag, 0.001–0.0095; Bi, 0.003–0.035; Cd, 0.0008–0.001; Ni, 0.0008–0.001	5 grades of red lead ($Pb_3O_4 + PbO_2 + PbO$); 3 grades of yellow litharge (PbO, 99.65–99.96%; free Pb, 0.03–0.30%; Pb_3O_4, 0.0048–0.05%); 1 grade of green powder (PbO + Pb, 80%+20% or 62%+38%)	Industrias Deriplom SA (2003)
Australia	Lead oxide	Bi, 0.05–0.06; Ag, 0.001; Cu, 0.001; Sn, 0.0005–0.001; Sb, 0.0001–0.0002; As, 0.0001; Se, 0.0001; S, 0.0007; Cd, 0.0005; Ni, 0.0002–0.0003; Zn, 0.0005; Fe, 0.0002–0.0005; Mn, 0.0003–0.0005; Te, 0.00003–0.0001; Co, 0.0001–0.0002; Cr, 0.0002; Ba, 0.0005; V, 0.0004; Mo, 0.0003–0.0005	VRLA-refined™ and MF-refined™	Pasminco Metals (2000)
USA	Lead acetate	NR	5N	ESPI Corp. (2002)
	Lead bromide		3N and 5N	
	Lead chloride		3N and 5N	
	Lead fluoride		3N	
	Lead iodide		3N and 5N	
	Lead molybdate		3N	
	Lead monoxide		3N and 5N	
	Lead tetraoxide		3N	
	Lead sulfide		3N and 5N	

VRLA, valve-regulated lead acid; MF, maintenance-free; NR, not reported

[a] 3N, 99.9%; 5N, 99.999%

1.2 Production

Commercial lead metal is described as being either primary or secondary. Primary lead is produced directly from mined lead ore. Secondary lead is produced from scrap lead products which have been recycled.

1.2.1 *The ores and their preparation*

The most important lead ore is *galena* (lead sulfide). Other important ores such as *cerussite* (lead carbonate) and *anglesite* (lead sulfate) may be regarded as weathered products of *galena* and are usually found nearer to the surface of the earth's crust. Lead and zinc ores often occur together and, in most extraction methods, have to be separated. The most common separation technique is selective froth flotation. The ore is first processed to a fine suspension in water by grinding in ball or rod mills — preferably to a particle size of < 0.25 mm. Air is then bubbled through this pulp contained in a cell or tank and, following the addition of various chemicals and proper agitation, the required mineral particles become attached to the air bubbles and are carried to the surface to form a stable mineral-containing froth which is skimmed off. The unwanted or gangue particles are unaffected and remain in the pulp. For example, with lead–zinc sulfide ores, zinc sulfate, sodium cyanide or sodium sulfite can be used to depress the zinc sulfide, while the lead sulfide is floated off to form a concentrate. The zinc sulfide is then activated by copper sulfate and floated off as a second concentrate (Lead Development Association International, 2003a).

Around 3 million tonnes of lead are mined in the world each year. Lead is found all over the world but the countries with the largest mines are Australia, China and the United States of America, which together account for more than 50% of primary production. The most common lead ore is *galena* (lead sulfide). Other elements frequently associated with lead include zinc and silver. In fact, lead ores constitute the main sources of silver, contributing substantially towards the world's total silver output (Lead Development Association International, 2003b). Table 5 shows mine production of lead concentrate by country in the year 2000. Table 6 shows the trends in lead mine production by geographic region from 1960 to 2003.

1.2.2 *Smelting*

(*a*) *Two-stage processes*

The first stage in smelting consists of removing most of the sulfur from the lead concentrate. This is achieved by a continuous roasting process (sintering) in which the lead sulfide is largely converted to lead oxide and broken down to a size convenient for use in a blast furnace — the next stage in the process. The sinter plant gases containing sulfur are converted to sulfuric acid (Lead Development Association International, 2003a).

Table 5. Mine production of lead concentrate in 2000[a]

Country	Production (tonnes)	Country	Production (tonnes)
Algeria	818	Mexico	137 975
Argentina	14 115	Morocco	81 208[c]
Australia	739 000	Myanmar	1 200[b]
Bolivia	9 523	Namibia	11 114[c]
Bosnia and Herzegovina	200[b]	Peru	270 576
Brazil	8 832	Poland	51 200[c]
Bulgaria	10 500	Republic of Korea	2 724
Canada	152 765	Romania	18 750[c]
Chile	785[c]	Russian Federation	13 300
China	660 000[b]	Serbia and Montenegro	9 000
Colombia	226	South Africa	75 262
Democratic People's Republic of Korea	60 000[b,c]	Spain	40 300
		Sweden	106 584[c]
Ecuador	200[b]	Tajikistan	800[b]
Georgia	200[b]	Thailand	15 600
Greece	18 235[b]	The former Yugoslav Republic of Macedonia	25 000[b]
Honduras	4 805		
India	28 900	Tunisia	6 602
Iran	15 000[b]	Turkey	17 270
Ireland	57 825	United Kingdom	1 000[b]
Italy	2 000	USA	465 000
Japan	8 835	Viet Nam	1 000[b]
Kazakhstan	40 000	World total[d]	3 180 000[c]

From Smith (2002)

In addition to the countries listed, lead is also produced in Nigeria, but information is inadequate to estimate output.

[a] Data available at 1 July 2003

[b] Estimated

[c] Revised

[d] Data from the USA and estimated data are rounded to no more than three significant digits, so that values may not add to total shown.

The graded sinter (lead oxide) is mixed with coke and flux, such as limestone, and fed into the top of the blast furnace, where it is smelted using an air blast (sometimes preheated) introduced near the bottom. The chemical processes that take place in the furnace at about 1200 °C result in the production of lead bullion (lead containing only metallic impurities) which is tapped off from the bottom of the furnace and either cast into ingots or collected molten in ladles for transfer to the refining process. In the Imperial Smelting Furnace process, a very similar procedure is used for the simultaneous production of zinc and lead.

These traditional two-stage processes largely favour the release of hazardous dusts and fumes. They necessitate the use of extensive exhaust ventilation and result in large volumes

Table 6. Trends in lead mine production worldwide

Year	Production (thousand tonnes) by geographical region[a]						
	A[b]	B	C	D[b]	E	F[b]	Total
1960	370	207	822	84	306	583	2372
1965	366	250	984	99	361	724	2784
1970	476	210	1341	120	441	855	3443
1975	435	165	1340	140	395	1085	3560
1980	482	278	1298	112	382	1030	3582
1985	412	261	1197	155	474	1076	3575
1990	727	175	1184	545	556	NRS	3187
1995	382	186	1047	715	424	NRS	2753
2000	360	178	1053	805	650	NRS	3046
2003	218	123	1043	770	666	NRS	2821

From International Lead and Zinc Study Group (1990, 2004)
NRS, not reported separately
[a] Data from following countries:
A, Austria, Denmark, Finland, France, Germany (the Federal Republic of Germany before reunification), Greece, Ireland, Italy, Norway, Portugal, Spain, Sweden, United Kingdom and former Yugoslavia
B, Algeria, Congo, Morocco, Namibia, South Africa, Tunisia and Zambia
C, Argentina, Bolivia, Brazil, Canada, Chile, Colombia, Guatemala, Honduras, Mexico, Nicaragua, Peru and USA
D, Myanmar, India, Iran, Japan, Philippines, Republic of Korea, Thailand and Turkey
E, Australia
F, Bulgaria, China, former Czechoslovakia, Hungary, People's Democratic Republic of Korea, Poland, Romania and the former Soviet Union; values for the latter four countries are estimates.
[b] From 1990 onwards, data from region F are included in region A (for Belarus, Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, the Russian Federation, Slovakia and Ukraine) or region D (for all former Soviet Republics, China and People's Democratic Republic of Korea); lead mine production for 1991 in the former Soviet Union is split as follows: Europe, 19%; Asia, 81%.

of lead-laden exhaust gases which are usually cleaned before they are discharged into the atmosphere. The collected dusts are returned to the smelting process (Lead Development Association International, 2003a).

(*b*) *Direct smelting processes*

The environmental problems and inefficient use of energy associated with the sinter/blast furnace and Imperial Smelting Furnace processes have led to a considerable amount of research into more economical and less polluting methods for the production of lead. Most of this research has been aimed at devising processes in which lead is converted directly from the sulfide to the metal without producing lead oxide. As a result, a number of direct smelting processes now exist, although at varying stages of development (Lead Development Association International, 2003a).

Direct smelting processes offer several significant advantages over conventional methods. The first and most obvious advantage is that sintering is no longer necessary. As a result, the creation of dust, a major occupational and environmental problem, is avoided. Moreover, the heat evolved during sintering (for the oxidation of the ore) is no longer wasted but is used in the smelting operation, thus providing a considerable saving of fuel. The volumes of gas that require filtering are largely reduced and, at the same time, the sulfur dioxide concentration of the off-gases is greater and these are therefore more suitable for the manufacture of sulfuric acid. The major difficulty in all direct smelting processes lies in obtaining both a lead bullion with an acceptably low sulfur content and a slag with a sufficiently low lead content for it to be safely and economically discarded. In several cases, further treatment of the crude bullion or the slag or both is required in a separate operation. There are several direct smelting processes which come close to meeting the desired criteria — the Russian Kivcet, the QSL (Queneau–Schuhmann–Lurgi), the Isasmelt and the Outokumpu processes are examples. The use of these newer processes will probably increase.

At present, the relative importance of the different smelting methods in terms of amounts of metal produced is as follows: conventional blast furnace, 80%; Imperial Smelting Furnace process, 10%; and direct processes, 10% (Lead Development Association International, 2003a).

1.2.3 *Hydrometallurgical processes*

With the prospect of even tighter environmental controls, the possibilities of utilizing hydrometallurgical techniques for the treatment of primary and secondary sources of lead are being investigated. Several processes have been described in the literature, but most are still in the developmental stage and probably not yet economically viable in comparison with the pyrometallurgical (smelting) processes. The goal of the hydrometallurgical processes in most cases is to fix the sulfur as a harmless sulfate and to put the lead into a solution suitable for electrolytic recovery. Most of these processes recirculate leach solutions and produce lead of high purity. For example, the Ledchlor process can be used on primary materials; other methods such as Rameshni SO_2 Reduction (RSR) and the processes developed by Engitec (CX-EW) and Ginatta (Maja *et al.*, 1989) are more concerned with recovery of lead from secondary sources, in particular from battery scrap (Lead Development Association International, 2003a).

1.2.4 *Primary lead refining*

Apart from gold and silver, lead bullion contains many other metallic impurities including antimony, arsenic, copper, tin and zinc. Copper is the first of the impurities to be removed. The lead bullion is melted at about 300–600 °C and held just above its melting-point when solid copper rises to the surface and is skimmed off. Sulfur is stirred into the melt to facilitate the operation by producing a dry powdery dross which is more readily removed. Once copper has been removed, there are a number of processes available for the extraction of the other impurities from the bullion. These include pyrometallurgical techniques, in which elements are removed one or more at a time in several stages, and electrolytic processes that remove most of the impurities in one operation. Although electrolytic methods are used in large-scale production, pyrometallurgical techniques account for the larger portion of the world's refined lead production (Lead Development Association International, 2003c). Table 7 shows the trends in production of refined lead by geographic region from 1960 to 2003.

Table 7. Trends in refined lead production worldwide

Year	Production (thousand tonnes) by geographical region[a]						
	A[b]	B	C	D[b]	E	F[b]	Total
1960	950	70	1114	164	211	718	3227
1965	1046	124	1296	202	223	823	3714
1970	1412	147	1619	301	217	992	4688
1975	1354	124	1661	296	198	1195	4828
1980	1514	156	1776	397	241	1331	5415
1985	1613	159	1708	539	220	1416	5655
1990	2323	150	1900	924	229	NRS	5525
1995	1796	141	2102	1474	243	NRS	5756
2000	1882	125	2216	2163	263	NRS	6650
2003	1606	144	2043	2499	311	NRS	6603

From International Lead and Zinc Study Group (1990, 2004)

NRS, not reported separately

[a] Data from the following countries:

A, Austria, Belgium, Denmark, Finland, France, Germany (the Federal Republic of Germany before reunification), Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom and former Yugoslavia

B, Algeria, Morocco, Namibia, South Africa, Tunisia and Zambia

C, Argentina, Brazil, Canada, Mexico, Peru, USA and Venezuela

D, Myanmar, India, Indonesia, Japan, Malaysia, Philippines, Republic of Korea, China (Province of Taiwan), Thailand, and Turkey

E, Australia and New Zealand

F, Bulgaria, China, former Czechoslovakia, Germany (former Democratic Republic of), Hungary, People's Democratic Republic of Korea, Poland, Romania and former Soviet Union; values for Bulgaria, former German Democratic Republic, Romania, former Soviet Union, China and People's Democratic Republic of Korea are estimates.

[b] From 1990 onwards, data from region F are included in region A (Belarus, Bulgaria, Czech Republic, Estonia, Germany (former German Democratic Republic), Hungary, Latvia, Lithuania, Poland, Romania, Russian Federation and Ukraine) or in region D (China, all other former Soviet Republics and People's Democratic Republic of Korea); refined lead production in the former Soviet Union for 1991 is split as follows: Europe, 24%; Asia, 76%.

(*a*) *Pyrometallurgical processes*

(i) *Removal of antimony, arsenic and tin*

After the removal of copper, the next step is to remove antimony, arsenic and tin. There are two methods available — the softening process (so-called since these elements are standard hardeners for lead) and the Harris process. In the softening process, the lead bullion is melted and agitated with an air blast, causing preferential oxidation of the impurities which are then skimmed off as a molten slag. In the Harris process, the molten bullion is stirred with a flux of molten sodium hydroxide and sodium nitrate or another suitable oxidizing agent. The oxidized impurities are suspended in the alkali flux in the form of sodium antimonate, arsenate and stannate, and any zinc is removed in the form of zinc oxide (Lead Development Association International, 2003c).

(ii) *Removal of silver and gold*

After the removal of antimony, arsenic and tin, the softened lead may still contain silver and gold, and sometimes bismuth. The removal of the precious metals by the Parkes process is based on the fact that they are more soluble in zinc than in lead. In this process, the lead is melted and mixed with zinc at 480 °C. The temperature of the melt is gradually lowered to below 419.5 °C, at which point the zinc (now containing nearly all the silver and gold) begins to solidify as a crust on the surface of the lead and can be skimmed off. An alternative procedure, the Port Pirie process, used at the Port Pirie refinery in Australia, is based on similar metallurgical principles (Lead Development Association International, 2003c).

(iii) *Removal of zinc*

The removal of the precious metals leaves zinc as the main contaminant of the lead. It is removed either by oxidation with gaseous chlorine or by vacuum distillation. The latter process involves melting the lead in a large kettle covered with a water-cooled lid under vacuum. The zinc distils from the lead under the combined influence of temperature and reduced pressure and condenses on the underside of the cold lid (Lead Development Association International, 2003c).

(iv) *Removal of bismuth*

After removal of zinc, the only remaining impurity is bismuth, although it is not always present in lead ore. It is easily removed by electrolysis and this accounts for the favouring of electrolytic methods in Canada (see below), where bismuth is a frequent impurity. When pyrometallurgical methods of refining are used, bismuth is removed by adding a calcium–magnesium alloy to the molten lead, causing a quaternary alloy of lead–calcium–magnesium–bismuth to rise to the top of the melt where it can be skimmed off (Lead Development Association International, 2003c).

(*b*) *Electrolytic processes*

In the Betts process, massive cast anodes of lead bullion are used in a cell containing an electrolyte of acid lead fluorosilicate and thin cathode 'starter sheets' of high-purity lead. The lead deposited on the cathodes still contains tin and sometimes a small amount of antimony, and these impurities must be removed by melting and selective oxidation. For many years, the Betts process was the only process to remove bismuth efficiently. A more recent electrolytic process, first used in the 1950s in Italy, employs a sulfamate electrolyte. It is claimed to be an equally efficient refining method, with the advantage that the electrolyte is easier to prepare (Lead Development Association International, 2003c).

By combining the processes described above to build up a complete refining scheme, it is possible to produce lead of very high purity. Most major refiners will supply bulk quantities of lead of 99.99% purity and, for very specific purposes, it is possible to reach 99.9999% purity by additional processing (Lead Development Association International, 2003c).

1.2.5 *Secondary lead production*

Much of the secondary lead comes from lead batteries, with the remainder originating from other sources such as lead pipe and sheet. Lead scrap from pipes and sheet is 'clean' and can be melted and refined without the need for a smelting stage. With batteries, the lead can only be obtained by breaking the case open. This is commonly done using a battery breaking machine which, in addition to crushing the case, separates out the different components of the battery and collects them in hoppers. Thus, the pastes (oxide and sulfate), grids, separators and fragmented cases are all separated from one another. The battery acid is drained and neutralized, and the other components are either recycled or discarded (Lead Development Association International, 2003d).

Table 8 shows trends in recovery of secondary lead by geographic region from 1970 to 1988. Three million tonnes of lead are produced from secondary sources each year, by recycling scrap lead products. At least three-quarters of all lead is used in products which are suitable for recycling and hence lead has the highest recycling rate of all the common non-ferrous metals (Lead Development Association International, 2003a). Almost 50% of the 1.6 million tonnes of lead produced in Europe each year has been recycled. In the United Kingdom, the figure is nearer 60% (Lead Development Association International, 2003d).

(*a*) *Secondary lead smelting*

The workhorse of the secondary lead production industry used to be the blast furnace. Conversion from blast to rotary-furnace technology in Europe began in the 1960s and was largely complete by the 1990s, driven by the high price of metallurgical coke and the relative difficulty of preventing the escape of dust and fume. The blast furnace was used to provide a low-grade antimonial lead, which was softened. The high-antimony slags were accumulated for a subsequent blast furnace campaign to produce a high-antimony bullion

Table 8. Trends in recovery of secondary lead (refined lead and lead alloys produced from secondary materials)

Year	Recovery (thousand tonnes) by geographical region[a]					
	A	B	C	D	E	Total
1970	619	21	532	78	37	1287
1975	617	29	610	115	39	1410
1980	742	44	798	192	39	1815
1985	766	44	747	258	20	1835
1988	800	48	921	310	23	2102

From International Lead and Zinc Study Group (1990)

[a] Data from the following countries:

A, Austria, Belgium, Denmark, Finland, France, Germany (the Federal Republic of Germany before reunification), Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, Switzerland, United Kingdom and former Yugoslavia

B, Algeria, Morocco and South Africa

C, Argentina, Brazil, Canada, Mexico, USA and Venezuela

D, India, Japan and China (Province of Taiwan)

E, Australia and New Zealand

for blending into lead alloys. Although a few secondary smelters today still use furnaces based on blast furnace technology, most companies now use rotary furnaces in which the charge can be tailored to give a lead of approximately the desired composition. Alternatively, a two-stage smelting procedure can be employed, which yields crude soft lead and crude antimonial lead. In the latter process, for example, battery plates are first melted and crude soft lead is tapped off after a few hours while the antimonial slag and lead oxide and sulfate are retained in the furnace. Further plates are charged and more soft lead is withdrawn until sufficient slag has accumulated for the slag reduction stage. Then, coke or anthracite fines and soda ash are added, lead and antimony oxides and lead sulfate are reduced and the cycle ends with the furnace being emptied of antimonial lead and of slag for discarding. As with primary smelting, large volumes of gas are produced, carrying substantial quantities of dust. On leaving the smelter, the gases are cooled from about 900 °C to about 100 °C using air and/or water cooling, and pass into a baghouse where the dust is collected and eventually fed back into the smelter. The gases subsequently are released into the atmosphere. In the course of processing one tonne of lead, as much as 100 tonnes of air have to be cleaned in this way (Lead Development Association International, 2003d).

In the semi-continuous Isasmelt furnace process used for secondary lead production, the furnace is fed with a lead carbonate paste containing 1% sulfur. This is obtained as a result of the battery paste having gone through a desulfurizing process after battery breaking. Over the following 36 h, wet lead carbonate paste and coal as a reductant are continuously fed into the furnace. The soft lead that is produced is tapped every 3 h and contains 99.9% lead. After 36 h, the paste feed is stopped and the slag is reduced to produce antimonial lead alloy. As with the two-stage process described above, off-gases from the furnace are first cooled and then passed into a baghouse for fume and dust control (Lead Development Association International, 2003d).

(*b*) *Secondary lead refining*

The principal impurities that are removed in secondary lead refining are copper, tin, antimony and arsenic. Zinc, iron, nickel, bismuth, silver and other impurities may also be present. These impurities are generally removed using the same basic techniques as described above (Lead Development Association International, 2003d).

1.2.6 *Lead production by compound and country*

Table 9 summarizes the available information on the number of companies in various countries producing metallic lead and some lead compounds in 2002.

1.3 Use

Over the centuries the unique properties of lead have resulted in its use in many different applications. These properties are mainly its high resistance to corrosion, its softness and low melting-point, its high density and its relatively low conductivity (Lead Development Association International, 2003b).

Large quantities of lead, both as the metal and as the dioxide, are used in storage batteries. Lead is also used for cable covering, plumbing and ammunition. The metal is very effective as a sound absorber and as a radiation shield around X-ray equipment and nuclear reactors. It is also used to absorb vibration. Lead, alloyed with tin, is used in making organ pipes. Lead carbonate ($PbCO_3$), lead sulfate ($PbSO_4$), lead chromate ($PbCrO_4$), lead tetraoxide (Pb_3O_4) and other lead compounds (see Table 1 for synonyms) have been applied extensively in paints, although in recent years this use has been curtailed to reduce health hazards. Lead oxide (usually lead monoxide) is used in the production of fine ‘crystal glass’ and ‘flint glass’ with a high index of refraction for achromatic lenses. Lead nitrate and acetate are soluble salts that serve as intermediates and in specialty applications. Lead salts such as lead arsenate have been used as insecticides, but in recent years this use has been almost eliminated (Lide, 2003).

In most countries, lead is predominantly used as the metal and it may be alloyed with other materials depending on the application. Lead alloys are made by the controlled addition of other elements. The term ‘unalloyed lead’ implies that no alloying elements have been added intentionally; this may mean that the lead is of high purity, but the term also covers less pure lead containing incidental impurities (Lead Development Association International, 2003e).

Table 9. Lead production by compound and country

Compound	No. of companies	Countries
Metallic lead	10	Japan
	6	USA
	5	China, Mexico
	4	Belgium, Canada
	3	Brazil, Germany, Peru, Russian Federation
	2	Kazakhstan
	1	Argentina, Australia, Bolivia, Bulgaria, China (Province of Taiwan), Egypt, India, Ireland, Italy, Netherlands, Republic of Korea, Spain, Sweden, Turkey
Lead acetate	10	China
	8	India
	7	Mexico
	6	USA
	5	Brazil, Japan
	3	Spain
	2	Germany, Italy
	1	Australia, China (Province of Taiwan), France, Romania, Russian Federation
Lead arsenate	3	Japan
	1	Peru
Lead azide	2	Brazil
	1	Japan
Lead bromide	1	Germany, India, Japan, United Kingdom, USA
Lead carbonate	6	India
	2	China, China (Province of Taiwan), Germany, USA
	1	Argentina, Australia, Italy, Japan, Mexico, Republic of Korea, Romania, Ukraine and United Kingdom
Lead chloride	5	India
	4	USA
	1	Australia, Belgium, China, China (Province of Taiwan), Germany, Japan, Mexico, Romania, Spain
Lead chromate (Pigment Yellow 34)	22	China
	8	India
	6	USA
	5	China (Province of Taiwan), Japan, Spain
	3	Germany, Italy
	2	Brazil, Republic of Korea, Netherlands, United Kingdom
	1	Argentina, Austria, Belgium, Canada, Colombia, France, Mexico, Peru, Romania, Russian Federation, Turkey, Venezuela
Lead fluoride	4	China
	3	India, Japan, USA
	1	Argentina, Canada, France, Germany

Table 9 (contd)

Compound	No. of companies	Countries
Lead fluoroborate	7	China, India
	5	USA
	3	Japan
	2	Australia, China (Province of Taiwan), France, Germany
	1	Argentina, Brazil, Russian Federation, Spain
Lead iodide	2	Japan, United Kingdom
	1	China, India, USA
Lead naphthenate	6	China
	5	Japan, Mexico
	3	Argentina, USA
	2	France, India, Peru, Spain
	1	Australia, Belgium, Brazil, Canada, China (Province of Taiwan), Germany, Italy, Romania, Thailand, Turkey
Lead nitrate	12	India
	8	China
	7	USA
	6	Japan
	4	Brazil, Mexico
	3	Spain
	2	Belgium, Germany
	1	Australia, Italy, Russian Federation, Tajikistan
Lead monoxide	24	China
	7	Japan
	6	India
	4	China (Province of Taiwan), Germany, Mexico, USA
	3	France, Spain
	2	Brazil, Italy, Peru, Republic of Korea, Russian Federation
	1	Argentina, Australia, Canada, Kazakhstan, Malaysia, Portugal, South Africa, Tajikistan, Turkey, United Kingdom
Lead dioxide	6	India
	4	Japan
	3	USA
	2	Germany
	1	Australia, Italy, South Africa, Spain, United Kingdom
Lead phosphate	6	China
	2	India
	1	Japan, Russian Federation
Lead stearate	25	China
	17	India
	9	China (Province of Taiwan)
	4	Japan
	3	Germany, Spain, Thailand
	2	Mexico, Peru, Philippines, Republic of Korea, USA
	1	Albania, Argentina, Belgium, Brazil, Indonesia, Italy, Portugal, Romania, South Africa, Turkey

Table 9 (contd)

Compound	No. of companies	Countries
Lead stearate, dibasic	15	India
	8	China
	5	China (Province of Taiwan)
	2	Japan, Philippines, Spain, Thailand, USA
	1	Belgium, Germany, Indonesia, Peru, Republic of Korea, South Africa, Turkey, United Kingdom
Lead styphnate	2	Brazil
	1	Japan
Lead subacetate	4	India
	3	Mexico
	2	China
	1	Australia, Brazil, China (Province of Taiwan), Romania, Spain, USA
Lead sulfate	6	India
	4	Mexico
	3	Germany
	2	Spain
	1	China, Japan, Romania, USA
Lead sulfide	4	India
	2	France, Japan
	1	Austria, China, Germany, USA
Lead tetraoxide	22	China
	5	India, Japan
	4	China (Province of Taiwan)
	3	Mexico, Spain
	2	Brazil, France, Germany, Italy, Russian Federation, USA
	1	Argentina, Kazakhstan, Peru, Poland, Portugal, Republic of Korea, South Africa, Tajikistan, Turkey, United Kingdom
Lead thiocyanate	2	USA
Lead trioxide	1	China
Tetraethyl lead	1	Germany, Italy
Tetramethyl lead	2	Russian Federation
	1	Italy

From Chemical Information Services (2003)

Trends in the reported consumption of lead by geographical region between 1960 and 2003 are shown in Table 10. Tables 11 and 12 show the trends in total lead consumption by country and by major use category, respectively, in selected countries between 1985 and 2001.

For six of the major lead-consuming countries (France, Germany, Italy, Japan, the United Kingdom, USA), detailed historical data are available from 1960 to 1990 (Tables 13–19). In this period, total consumption of lead reported by these countries rose from 2.06 to 2.94 million tonnes, an overall increase of 43% and an average annual increase of 1.2%. During those three decades, however, there were marked changes in the rates of lead consumption. These included: (1) the rapid expansion of consumption during the 1960s and early 1970s leading to peak levels in 1973 prior to the onset of the first world energy crisis; (2) the steep reduction in 1974–75 and the subsequent revival in 1977–79, with lead consumption recovering to its 1973 level; (3) the decrease in 1980–82 during the second energy crisis; and (4) the sustained growth from 1983 until 1990 in the industrialized world as a whole, supported by rapid advances in some of the newly-industrializing countries, but with much more restricted progress in the fully-industrialized countries where the rates of economic expansion and industrial activity slowed down compared with those previously achieved (International Lead and Zinc Study Group, 1992).

1.3.1 *Lead–acid batteries*

By far the largest single application of lead worldwide is in lead–acid batteries. The most common type of lead–acid battery consists of a heavy duty plastic box (normally polypropylene) containing grids made from a lead–antimony alloy (commonly containing 0.75–5% antimony) with minor additions of elements such as copper, arsenic, tin and selenium to improve grid properties. For the new generation of sealed, maintenance-free batteries, a range of lead–calcium–tin alloys is used. These contain up to 0.1% calcium and 0–0.5% tin. The tin-containing alloys are used in the positive grids to protect against corrosion. Grids are still manufactured in pairs on special casting machines, but production of grids in strip form by continuous casting or expansion of rolled sheet is becoming increasingly popular as it facilitates automation and minimizes the handling of plates. The spaces in the grids are filled with a paste consisting largely of lead dioxide. When immersed in sulfuric acid, these pasted grids (plates) form an electric cell that generates electricity from the chemical reactions that take place. The reactions require the presence of lead dioxide and lead metal and each cell produces a voltage of 2V. These reactions are reversible and the battery can therefore be recharged. A rechargeable cell is known as a secondary cell and provides a means of storing electricity. Lead is well suited for this application because of its specific conductivity and its resistance to corrosion. The addition of antimony or calcium gives the lead an increased hardness to resist the mechanical stresses within the battery caused, for example, by the natural vibration of road vehicles and by the chemical reactions taking place (Lead Development Association International, 2003e).

Table 10. Trends in total industrial consumption of refined lead

Year	Consumption (thousand tonnes) by geographical region[a]						
	A[b]	B	C	D[b]	E	F[b]	Total
1960	1152	19	986	204	65	654	3080
1965	1306	33	1229	270	70	762	3670
1970	1517	46	1488	360	72	1019	4502
1975	1403	76	1454	413	86	1310	4742
1980	1652	102	1476	600	85	1446	5361
1985	1614	98	1510	735	69	1470	5496
1990	2439	114	1648	1193	59	NRS	5454
1995	1948	112	2017	1718	84	NRS	5879
2000	2022	130	2332	1989	46	NRS	6519
2003	2030	154	2012	2471	45	NRS	6712

From International Lead and Zinc Study Group (1990, 2004)

NRS, not reported separately

[a] Data from the following countries:

A, Austria, Belgium, Denmark, Finland, France, Germany (the Federal Republic of Germany before reunification), Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom and former Yugoslavia

B, Algeria, Egypt, Morocco, South Africa, Tunisia and Zambia

C, Argentina, Brazil, Canada, Mexico, Peru, USA and Venezuela

D, India, Iran, Japan, Malaysia, Philippines, Republic of Korea, China (Province of Taiwan), Thailand and Turkey

E, Australia and New Zealand

F, Albania, Bulgaria, China, Cuba, former Czechoslovakia, Germany (the former German Democratic Republic), Hungary, People's Democratic Republic of Korea; Poland, Romania, former Soviet Union; values for Albania, Cuba, China, Germany (the former German Democratic Republic), Peoples' Democratic Republic of Korea, Romania and former Soviet Union are estimates.

[b] From 1990 onwards, data from countries in region F are included in region A (Albania, Bulgaria, Czech Republic, Hungary, Poland, the former German Democratic Republic, Poland, Romania, Estonia, Latvia, Lithuania, Belarus, Russian Federation and Ukraine) or in region D (all other former Soviet Republics, China, Cuba and People's Democratic Republic of Korea). Lead metal consumption for 1991 in the former Soviet Union was split as follows: Europe, 86%, Asia, 14%.

The most common form of lead–acid battery is the so-called SLI battery (starting, lighting and ignition) used in road vehicles such as cars and trucks. Another form, the traction battery, is used to power vehicles such as golf carts and airport support vehicles. Other uses of lead power include larger stationary batteries for stand-by emergency power storage in hospitals and other critical facilities, and for some electricity utilities to help meet peak power demands and to maintain a stable electricity supply (Lead Development Association International, 2003e).

Table 11. Total industrial lead consumption

Country or region	Consumption (thousand tonnes) in year			
	1985	1990	1996	2001
Australia	49.5	45.9	67.0	41.0
Austria	58.0	65.5	58.0	59.0
Belgium	66.8	67.7	50.6	40.3
Brazil	79.6	75.0	110.0	112.0
Canada	104.5	71.7	93.4	71.8
China	NA	NA	470.1	700.0
Czech Republic	NA	NA	25.0	80.0
Finland	22.0	13.4	3.5	2.0
France[a]	234.3	261.6	273.8	282.5
Germany[a]	348.2	375.3	331.0	392.6
India	51.3	51.8	85.0	127.0
Italy[a]	235.0	259.0	268.0	283.0
Japan	397.4	417.0	329.9	284.7
Mexico	90.6	66.8	141.0	205.0
Netherlands	45.1	65.0	57.0	30.0
New Zealand	8.6	8.0	7.0	5.0
Republic of Korea	81.0	150.0	289.8	314.7
Romania	NA	NA	22.0	20.0
Scandinavia[b]	55.6	36.3	49.0	13.0
South Africa	48.2	65.9	63.1	59.1
South-East Asia[c]	125.2	185.0	413.0	427.0
Spain	125.3	126.7	144.0	246.0
Switzerland	10.5	8.7	10.5	12.6
United Kingdom[a]	303.2	334.0	309.2	266.5
USA[a]	1148.3	1288.4	1554.4	1587.3
Total	3688.2	4038.7	5225.3	5662.1

From International Lead and Zinc Study Group (1992, 2003)
NA, not available
[a] Data for these countries include total metal usage in all forms, i.e. refined lead and alloys (lead content), plus re-melted lead recovered from secondary materials. Data for other countries include refined lead and alloys only.
[b] Denmark, Norway and Sweden
[c] China, Hong Kong Special Administrative Region, China (Province of Taiwan), Indonesia, Malaysia, Philippines and Singapore

Since 1960 the manufacture of lead–acid batteries has remained the largest single use of lead in nearly all countries, accounting for an ever-increasing percentage of total lead consumption (see Tables 12, 14 and 15) (International Lead and Zinc Study Group, 1992).

Table 12. Trends in uses of lead in selected countries[a]

Use	Percentage of total usage in year			
	1985	1990	1996	2001
Batteries	57.7	63.0	72.5	76.7
Cable sheathing	5.6	4.5	2.1	1.4
Rolled and extruded products[b]	7.6	7.7	5.9	6.0
Shot/ammunition	2.8	2.8	2.3	2.1
Alloys	4.2	3.3	3.2	2.5
Pigments and other compounds	14.2	12.8	10.0	8.1
Gasoline additives	3.7	2.1	0.9	0.4
Miscellaneous	4.2	3.8	3.3	2.8
Total	100.0	100.0	100.0	100.0

From International Lead and Zinc Study Group (1992, 2003)

[a] Countries include: Australia, Austria, Belgium, Brazil, Canada, China (Hong Kong Special Administrative Region), China (Province of Taiwan), Denmark, Finland, France, Germany, India, Indonesia, Italy, Japan, Malaysia, Mexico, Netherlands, New Zealand, Norway, Philippines, Republic of Korea, Singapore, South Africa, Spain, Sweden, Switzerland, United Kingdom and USA.

[b] Including lead sheet

Table 13. Trends in total lead consumption in six major consuming countries

Country	Consumption (thousand tonnes) in year			
	1960	1973	1979	1990
France	196	240	233	262
Germany	281	342	342	375
Italy	108	259	280	259
Japan	162	347	368	417
United Kingdom	385	364	336	334
USA	926	1398	1358	1288
Total	2058	2950	2917	2935

From International Lead and Zinc Study Group (1992)

The data include refined metal and direct use of lead in scrap form.

Table 14. Trends in principal uses of lead in six major consuming countries[a]

Use	Percentage of total use in year		
	1960	1979	1990
Batteries	27.7	50.8	64.4
Cable sheathing	17.9	5.9	3.8
Rolled/extruded products	18.0	7.7	7.8
Shot/ammunition	3.2	3.2	3.8
Alloys	10.5	6.7	3.5
Pigment/compounds	9.9	12.3	10.9
Gasoline additives	9.1	9.8	2.7
Miscellaneous	3.7	3.6	3.1
Total	100.0	100.0	100.0

From International Lead and Zinc Study Group (1992)

[a] France, Germany, Italy, Japan, United Kingdom and USA

Table 15. Trends in consumption of lead for batteries in six major consuming countries

Country	Consumption (thousand tonnes) in year			
	1960	1973	1979	1990
France	45.0	90.0	110.7	163.5
Germany[a]	73.2	132.9	158.3	195.2
Italy	25.5	68.0	93.0	113.2
Japan	30.0	163.1	191.8	294.6
United Kingdom	76.2	106.5	113.9	103.7
USA	320.4	698.0	814.4	1019.6
Total	570.3	1258.5	1481.2	1889.8

From International Lead and Zinc Study Group (1992)

[a] Excludes consumption by some independent producers of lead oxides for batteries.

Table 16. Trends in consumption of lead for rolled/ extruded products in six major consuming countries

Country	Consumption (thousand tonnes) in year			
	1960	1973	1979	1990
France	43.7	31.0	27.2	22.4
Germany	44.3	31.1	32.7	39.1
Italy	29.1	50.3	40.8	21.5
Japan	35.9	39.6	26.7	10.9
United Kingdom	88.0	57.7	48.9	98.6
USA	130.1	90.2	47.7	35.8
Total	371.1	299.9	224.0	228.3

From International Lead and Zinc Study Group (1992)

Table 17. Trend in consumption of lead for cable sheathing in six major consuming countries

Country	Consumption (thousand tonnes) in year			
	1960	1973	1979	1990
France	60.8	41.1	21.4	16.3
Germany	83.9	54.6	31.5	12.2
Italy	24.0	44.8	40.0	48.7
Japan	47.0	28.7	36.8	4.9
United Kingdom	97.0	45.8	26.6	10.4
USA	54.7	39.0	16.4	18.3
Total	367.4	254.0	172.7	110.8

From International Lead and Zinc Study Group (1992)

Table 18. Trends in consumption of lead for alloys in six major consuming countries

Country	Consumption (thousand tonnes) in year			
	1960	1973	1979	1990
France	17.3	14.8	9.3	3.2
Germany	22.7	22.8	16.5	9.0
Italy	6.0	6.0	5.7	3.5
Japan	7.1	24.2	18.3	18.7
United Kingdom	37.0	35.0	24.5	22.0
USA	125.3	128.8	120.0	46.4
Total	215.4	231.6	194.3	102.8

From International Lead and Zinc Study Group (1992)

Table 19. Trends in consumption of lead for pigments and compounds in six major consuming countries

Country	Consumption (thousand tonnes) in year			
	1960	1973	1979	1990
France	11.9	34.5	33.0	29.4
Germany	38.4	69.6	76.8	100.3
Italy	10.1	45.2	60.4	40.0
Japan	17.2	64.2	62.4	64.0
United Kingdom	35.9	38.8	34.1	28.6
USA	89.3	98.7	90.8	56.5
Total	202.8	351.0	357.5	318.8

From International Lead and Zinc Study Group (1992)

1.3.2 *Lead sheet*

The use of lead sheet has increased dramatically over recent years, particularly for the building industry. Lead sheet has been produced for decades by traditional wide lead mills in which lead slabs are fed through large drum-like rollers, sometimes several times, to produce lead sheets of the desired thickness. The traditional wide lead mill is being replaced by more sophisticated rolling mills producing coils of lead 1.2–1.5 m wide. Most lead sheets in building applications are between 1.3 and 2.2 mm thick, but sheets of 2.6–3.6 mm are used for roofing prestige buildings. Thick sheet alloys are rolled for applications such as anodes for electrowinning and thin foils are used for sound attenuation. A manufacturing technique other than milling is continuous casting in which a rotating, water-cooled drum is partly immersed in a bath of molten lead. The drum picks up a solid layer of lead, which is removed over a knife edge adjacent to the drum as it rotates. The thickness is controlled by varying the speed of rotation and the temperature of the drum (Lead Development Association International, 2003e).

In the building industry, most of the lead sheet (or strip) is used as flashings or weatherings to prevent water from penetrating, the remainder being used for roofing and cladding. By virtue of its resistance to chemical corrosion, lead sheet is also used for the lining of chemical treatment baths, acid plants and storage vessels. The high density of lead sheet and its ‘limpness’ make it a very effective material for reducing the transmission of sound through partitions and doors of comparatively lightweight construction. Often the lead sheet is bonded adhesively to plywood or to other building boards for convenience of handling. A particular advantage of the high density of lead is that only relatively thin layers are needed to suppress the transmission of sound (Lead Development Association International, 2003e).

Lead sheet is the principal element in the product category ‘rolled and extruded products’. In many countries, the demand for rolled and extruded lead products declined in the 1960s and 1970s, due in part to a rapid decline in the use of lead pipe (see Tables 14 and 16). Nevertheless, in a number of countries (see Table 12), lead sheet remains the third largest use of lead at about 6% of the total reported consumption (International Lead and Zinc Study Group, 1992, 2003).

1.3.3 *Lead pipes*

Lead piping, once a substantial use in the ‘rolled and extruded products’ category, has been replaced progressively by copper tubes for the transport of domestic water and the supply of gas and by plastic tubing for disposal of wastewater. Lead pipes have not been used in new supplies of domestic water for about 30 years. However, due to their corrosion-resistant properties, they are still used for transport of corrosive chemicals at chemical plants. Also, lead pipe of appropriate composition is extruded for cutting into short-length ‘sleeves’ used in the jointing of lead-sheathed cables (see below) (International Lead and Zinc Study, 1992; Lead Development Association International, 2003e).

1.3.4 *Cable sheathing*

Because of its corrosion resistance when in contact with a wide range of industrial and marine environments, soils and chemicals, lead was one of the first materials to be used to provide an impervious sheath on electric cables. Lead can be applied to the cable core in unlimited lengths by extrusion at temperatures that do not damage the most sensitive conductors (optical fibres) or insulating materials (paper or plastics). Lead is pliable and withstands the coiling, uncoiling, handling and bending operations involved in the manufacturing and installation of the cable. A lead sheath can be readily soldered at low temperatures when cables need to be jointed or new cables installed. With modern screw-type continuous extruders, unjointed submarine power cables as long as 100 km have been produced (Lead Development Association International, 2003e).

Until 1960 sheathing of electrical cables was the largest single use of lead in many countries including France, Germany, Japan and the United Kingdom, representing 25–30% of total lead consumption in these four countries. It was used much less extensively in the USA where, during the late 1950s, lead was replaced by alternative materials, generally plastics, as the sheathing material for telephone cables. Since the mid-1960s, however, there has been a gradual decline in the use of lead for cable sheathing in most countries (Table 17). By 1990, lead consumption for cable sheathing had fallen to 4.5% of total consumption and, by 2001, to 1.4% (Table 12) (International Lead and Zinc Study Group, 1992, 2003).

1.3.5 *Lead alloys*

(*a*) *Lead–antimony alloys*

By far the largest use of lead–antimony alloys is in batteries. At one time, antimony contents of ~10% were common, but the current generation of lead–acid batteries has a much lower antimony content. Alloys with 1–12% antimony are used widely in the chemical industry for pumps and valves, and in radiation shielding both for lining the walls of X-ray rooms and for bricks to house radioactive sources in the nuclear industry. The addition of antimony to lead increases the hardness of the lead, and therefore its resistance to physical damage, without greatly reducing its corrosion resistance (Lead Development Association International, 2003e).

(*b*) *Solders*

Soldering is a method of joining materials, in which a special metal (solder) is applied in the molten state to wet two solid surfaces and join them on solidification. Solders are classified according to their working temperatures. Soft solders, which have the lowest melting-points, are largely lead–tin alloys with or without antimony, while fusible alloys contain various combinations of lead, tin, bismuth, cadmium and other low melting-point metals. Depending on the application, lead–tin solders may contain from a few per cent to more than 60% tin.

A substantial proportion of solder is used in electrical or electronic assemblies. The advances made in the electronics industry have required the development of fast and highly-automated methods of soldering. Printed circuit assemblies can be soldered by passing them across a standing wave of continuously-circulating molten solder (Lead Development Association International, 2003e).

The use of lead solder in plumbing has declined with the replacement of lead piping by copper tubing and, more recently, as a result of concerns of potential leaching of lead into water supplies. Similarly, concerns of possible danger to health have restricted the use of lead solders in the canning industry, formerly an important market.

(*c*) *Lead for radiation shielding*

Lead and its alloys in metallic form, and lead compounds, are used in various forms of radiation shielding. The shielding of containers for radioactive materials is usually metallic lead (see above). Radioactive materials in laboratories and hospitals are usually handled by remote control from a position of safety behind a wall of lead bricks. X-ray machines are normally installed in rooms lined with lead sheet; lead compounds are constituents of the glass used in shielding partitions to permit safe viewing; and lead powder is incorporated into plastic and rubber sheeting materials used for protective clothing (Lead Development Association International, 2003e).

(*d*) *Other uses of lead alloys*

A variety of lead alloys are produced for a wide range of applications in various industries. In the 1990s, these alloys accounted for 130–150 000 tonnes of lead used in industrialized countries (Table 18). However, the trend in this sector had been one of steady decline during the previous three decades (Table 14), as some uses have been overtaken by technological changes or have been restricted by health and environmental regulations. The use of terne metal (a thin tin–lead alloy coating) for corrosion protection, and the addition of lead to brass and bronze to assist in free machining, and in bearing metals to reduce friction and wear in machinery, have declined slowly due to competition from alternative materials such as aluminum and plastics. The market for type metal in the printing industry has largely disappeared as hot metal printing has been replaced by new technology. In the USA, this use peaked at 30 000 tonnes in 1965 but had fallen to 1–2000 tonnes by the mid-1980s and is similarly low in other developed countries (International Lead and Zinc Study Group, 1992).

1.3.6 *Lead pigments and compounds*

The market for lead pigments and compounds constitutes the second largest use of lead after lead–acid batteries. The market peaked in the mid-1980s, when over 500 000 tonnes of lead were used in lead pigments and compounds, mainly by the plastics, glass and ceramics industries, and accounting for 14% of total lead consumption (Table 14). Since then these uses have been restricted by health and environmental concerns while still remaining the second largest use of lead (8% of total lead consumption) (Table 12).

Besides the six major consuming countries (Table 19), pigments and compounds are also the second most important use of lead in other countries including Brazil, Canada, the Republic of Korea, South Africa, Spain and countries of South-East Asia (International Lead and Zinc Study Group, 1992, 2003).

(*a*) *Lead pigments*

The use of lead in paints for domestic purposes and in some commercial and industrial applications is now severely restricted or banned in view of the potential health risks caused by exposure to weathered or flaking paint. However, lead tetraoxide (Pb_3O_4) still retains some of its traditional importance for rust-inhibiting priming paints applied directly to iron and steel in view of its anti-corrosion properties, but faces growing competition from zinc-rich paints containing zinc dust and zinc chromate. The use of lead carbonate (white lead) in decorative paints has been phased out. Calcium plumbate-based paints are effective on galvanized steel. Lead chromate (yellow) and lead molybdate (red orange) are still used in plastics and to a lesser extent in paints. Lead chromate is used extensively as the yellow pigment in road markings and signs, which are now commonplace in most European countries and in North America (Lead Development Association International, 2003e).

(*b*) *Lead stabilizers for polyvinyl chloride (PVC)*

Lead compounds are used in both rigid and plasticized PVC to extend the temperature range at which PVC can be processed without degradation. In the building industry, the widespread adoption of PVC materials for corrosion-resistant piping and guttering in industrial facilities, for potable water piping (lead content, < 1%), and for windows and door frames provides a major market for lead sulfate and lead carbonate as stabilizers to prevent degrading of PVC during processing and when exposed to ultraviolet light. However, concerns over potential health hazards are limiting the use of lead in PVC water piping in some countries. Dibasic lead phosphite also has the property of protecting materials from degradation by ultraviolet light. Normal and dibasic lead stearates are incorporated as lubricants. All these compounds are white pigments that cannot be used when clear or translucent articles are required (International Lead and Zinc Study Group, 1992; Lead Development Association International, 2003e). The levels of lead in 16 different PVC pipes used for water supplies in Bangladesh were found to be in the range of 1.1–6.5 mg/g (Hadi *et al.*, 1996).

(*c*) *Lead in glass*

Decorative lead crystal glass was developed in England in the seventeenth century. Normally added in the form of lead monoxide (PbO) at 24–36%, lead adds lustre, density and brilliance to the glass. Its attractiveness is further enhanced by decorative patterns that can be cut on the surface and by the characteristic ring associated with lead crystal. There is now a substantial market for a cheaper form of 'semi-crystal' containing 14–24% lead oxide, and such glasses are usually moulded with the decorative pattern rather than being hand-cut later. Lead is also used in optical glass (e.g. telescopes, binoculars), ophthalmic glass (e.g. spectacles), electrical glass (e.g. lamp tubing, cathode ray tubes) and radiation protection glass (e.g. for windows in remote-handling boxes, television tubes) (Lead Development Association International, 2003e).

(*d*) *Lead for ceramics*

Lead is used in a wide range of glaze formulations for items such as tableware (earthenware and china), wall and floor tiles, porcelain and sanitary-ware and electrical transistors and transducers. The lead compounds used are mainly lead monoxide (litharge, PbO), lead tetraoxide and lead silicates. The properties offered by lead compounds are low melting-points and wide softening ranges, low surface tension, good electrical properties and a hard-wearing and impervious finish. Lead compounds are also used in the formulation of enamels used on metals and glass.

Another important application for lead compounds is in a range of ceramics (other than the glazes) used in the electronics industry. Typical of these are piezoelectric materials such as the lead zirconate/lead titanate range of compositions known generally as PZI. These materials have a wide range of applications, such as spark generators, sensors, electrical filters, gramophone pick-ups and sound generators (International Lead and Zinc Study Group, 1992; Lead Development Association International, 2003e).

1.3.7 *Gasoline additives*

Tetraethyl and tetramethyl lead have been used as anti-knock additives in gasoline, at concentrations up to 0.84 g/L, as an economic method of raising the 'octane rating' to provide the grade of gasoline needed for the efficient operation of internal combustion engines of high compression ratio (Thomas *et al.*, 1999). However, increasing recognition of the potential health effects from exposure to lead has led to the reformulation of gasoline and the removal of lead additives. In addition, lead in gasoline is incompatible with the catalytic converters used in modern cars to control nitrogen oxides, hydrocarbons and other 'smog'-producing agents. The use of lead in gasoline in the USA has been phased out gradually since the mid-1970s, and moves to phase it out in the European Community began in the early 1980s. Since 1977 in the USA and 1991 in Europe, all new cars are required to run on unleaded gasoline. By the end of 1999, forty countries or regions had banned the use of lead in gasoline (Table 20), although it is still permitted in some of these countries for certain off-road and marine vehicles and for general aviation aircraft (Smith, 2002). Numerous other countries are planning the phase-out of lead in gasoline in the near future. About 79% of all gasoline sold in the world in the late 1990s was unleaded (International Lead Management Center, 1999). The market for tetraethyl and tetramethyl lead has declined considerably (Table 21) and will continue to do so (Lead Development

Table 20. Countries or regions that had phased out the use of lead in gasoline[a] by the end of 1999

Argentina
Austria
Bahamas
Bangladesh
Belize
Bermuda
Bolivia
Brazil
Canada
Colombia
Costa Rica
Denmark
Dominican Republic
El Salvador
Finland
Germany
Guam
Guatemala
Haiti
Honduras
Hong Kong SAR
Hungary
Iceland
Japan
Luxembourg
Malaysia
Mexico
Netherlands
New Zealand
Nicaragua
Norway
Portugal
Puerto Rico
Republic of Korea
Singapore
Slovakia
Sweden
Thailand
USA
US Virgin Islands

From International Lead Management Center (1999)

[a] See Section 1.3.7 for permitted uses of leaded gasoline.

Table 21. Trends in consumption of lead for gasoline additives in five major consuming countries

Country	Consumption (thousand tonnes) in year			
	1960	1973	1979	1990
France	6.1	13.5	15.1	9.8
Germany	NA	9.4	10.8	NA
Italy	4.8	11.8	13.0	3.7
United Kingdom	27.1	54.4	58.9	45.1
USA	148.6	248.9	186.9	20.7
Total	186.6	338.0	284.7	79.3

From International Lead and Zinc Study Group (1992)
NA, not available

Association International, 2003e). In 2001, less than 0.5% of lead consumption was for gasoline additives (Table 12) (International Lead and Zinc Study Group, 2003).

1.3.8 *Miscellaneous uses*

About 150 000 tonnes of lead are employed each year in a variety of other uses, of which about 100 000 tonnes are consumed in the production of lead shot and ammunition in the major consuming countries (excluding Japan where this use is not reported separately). Globally, this use has remained relatively stable since the 1960s, at around 3–4% of total lead consumption (Tables 12 and 14).

Lead cames have long been a feature of stained-glass windows in churches and cathedrals. They consist of H-shaped sections of lead which hold together the individual pieces of glass. They are now being used more widely in modern homes both in the traditional way and in the form of self-adhesive strips stuck on to a larger piece of glass to simulate an integral came.

Lead weights for fishing have been largely phased out but lead stampings, pressings and castings are widely used for many weighting applications, for example curtain weights, wheel balance weights, weights for analytical instruments and yacht keels.

Lead wool is made by scratching fine strands from the surface of a lead disc. It is used for the caulking of joints in large pipes like gas mains and in some specialty batteries.

Lead-clad steel is a composite material manufactured by cold rolling lead sheet onto sheet steel that has been pretreated with a terne plate. A strong metallurgical bond is formed between the lead and the steel, which provides a material that combines the physical and chemical properties of lead with the mechanical properties of steel. Although primarily aimed at the sound-insulation market, lead-clad steel has also found use in radiation shielding and in the cladding of buildings.

Lead powder is incorporated into a plasticizer to form sheets of lead-loaded plastic. This material is used to make radiation-protective clothing and aprons for the medical, scientific and nuclear industries (see Section 1.4.5.c). It also has sound-insulating properties. Lead powder is also used as the basis for some corrosion-resistant paints (see Section 1.4.6).

Smaller amounts of lead are used in galvanizing, annealing and plating (International Lead and Zinc Study Group, 1992; Lead Development Association International, 2003e).

1.4 Occurrence

1.4.1 *Environmental occurrence*

Lead was one of the first metals used by man; there is evidence that it has been used for approximately 6000 years (Hunter, 1978). As a result, although both natural and anthropogenic processes are responsible for the distribution of lead throughout the environment, anthropogenic releases of lead are predominant. Industrial releases to soil from nonferrous smelters, battery plants, chemical plants, and disturbance of older structures containing lead-based paints are major contributors to total lead releases. Lead is transferred continuously between air, water, and soil by natural chemical and physical processes such as weathering, run-off, precipitation, dry deposition of dust, and stream/river flow; however, soil and sediments appear to be important sinks for lead. Lead is extremely persistent in both water and soil. Direct application of lead-contaminated sludge as fertilizers, and residues of lead arsenate used in agriculture, can also lead to the contamination of soil, sediments, surface water and ground water. In countries where leaded gasoline is still used, the major air emission of lead is from mobile and stationary sources of combustion. Besides environmental exposures, exposure to lead may arise from sources such as foods or beverages stored, cooked or served in lead-containing containers, food growing on contaminated soils, and traditional remedies, cosmetics and other lead-containing products.

The ubiquity of lead in the environment has resulted in present-day body burdens that are estimated to be 1000 times those found in humans uncontaminated by anthropogenic lead uses (Patterson *et al.*, 1991), but exposures have decreased substantially over the past 10–30 years in countries where control measures have been implemented.

The estimated contributions of the common sources and routes of lead exposure to total lead intake vary from country to country and over time. In 1990, the estimated daily intake of lead from consumption of food, water and beverages in the USA ranged from 2 to 9 µg/day for various age groups and was approximately 4 µg/day for children 2 years of age and younger (ATSDR, 1999). For many young children, the most important source of lead exposure is through ingestion of paint chips and leaded dusts and soils released from ageing painted surfaces or during renovation and remodeling (CDC, 1997a; Lanphear *et al.*, 1998). Compared with nonsmokers, smokers have an additional lead intake of approximately 6 µg/day, based on an estimated exposure of 14 µg/day and absorption of 30–50% of the inhaled lead into the bloodstream (IARC, 2004a).

Lead is absorbed into the body via inhalation and ingestion and, to a limited extent, through the skin. The uptake of inhaled or ingested lead is dependent on the type of lead compound involved, particle size, site of contact within the body, acidity of the body fluid at that site, and physiological status of the individual (see Section 4.1).

(*a*) *Natural occurrence*

Lead occurs naturally in the earth's crust in trace quantities at a concentration of approximately 8–20 mg/kg (Rudnick & Fountain, 1995; Taylor & McLennan, 1995). Metallic lead occurs in nature, but it is rare. The most important lead ore is *galena* (PbS). *Anglesite* ($PbSO_4$), *cerussite* ($PbCO_3$) and *minium* (Pb_3O_4) are other common lead minerals. Small amounts of lead reach the surface environment through natural weathering processes and volcanic emissions, thus giving a baseline environmental exposure. However, the abundant and widespread presence of lead in our current environment is largely a result of anthropogenic activity.

(*b*) *Air and dust*

Lead is released into the air by natural processes such as volcanic activity, forest fires, weathering of the earth's crust and radioactive decay from radon (WHO, 1995). However, these natural contributions are of relatively minor consequence. The vast majority of lead in the atmosphere results from human activity. Globally, the main source of lead in air has been exhaust from motor vehicles using leaded gasoline (see also Section 1.4.1(*f*)). Release of lead also occurs during lead smelting and refining, the manufacture of goods, and the incineration of municipal and medical wastes (ATSDR, 1999). Almost all lead in air is bound to fine particles of less than 1 µm diameter, although some may be solubilized in acid aerosol droplets. The size of these particles varies with the source and with the age of the particle from the time of emission (US EPA, 1986a; WHO, 1995).

Concentrations of lead in ambient air range from 76×10^{-6} µg/m^3 in remote areas such as Antarctica (Maenhaut *et al.*, 1979), to 0.2 µg/m^3 in rural areas in Chile (Frenz *et al.*, 1997) and to > 120 µg/m^3 near stationary sources such as smelters (Nambi *et al.*, 1997). Tables 22–27 show examples of lead concentrations in air and dust worldwide by geographic region. A few studies are detailed below according to the main source of airborne lead.

Trends in emissions of lead in air in the USA have continued to fall since the late 1970s from both point sources (from 2.9 µg/m^3 in 1979 to 0.4 µg/m^3 in 1988) and urban sites (from 0.8 µg/m^3 in 1979 to 0.1 µg/m^3 in 1988). The large decrease in emissions from point sources resulted from the use of emission controls in industrial processes as well as automotive controls; the decrease in emissions from urban sites was primarily the result of the decreased use of leaded gasoline (ATSDR, 1999). Between 1976 and 1995, overall ambient air concentrations of lead in the USA declined by 97% (US EPA, 1996a). Lead concentrations in urban and suburban air in the USA (maximum quarterly mean concentrations) decreased between 1986 and 1995 from 0.18 µg/m^3 to 0.04 µg/m^3; rural air concentrations of lead during the same period were typically 3- to 5-fold lower (US EPA, 1996a). In remote sites, air lead concentrations as low as 0.001 µg/m^3 have been reported (Eldred & Cahill, 1994).

Urban air lead concentrations are typically between 0.15 and 0.5 µg/m^3 in most European cities (WHO, 2000a). In Bulgaria, the Czech Republic, Hungary, Poland, Romania, Slovakia and Slovenia, exposure to lead is primarily through airborne lead. It is estimated that in congested urban areas 90% of this is due to leaded gasoline. In 1998, there was a wide range in use of unleaded gasoline for automobiles, from 100% in Slovakia to 5–7% in Bulgaria and Romania. Table 22 illustrates improvements in air quality during the 1990s through a concerted effort by the countries to phase out the use of leaded gasoline (Regional Environmental Center for Central and Eastern Europe, 1998).

Lead concentration in the thoracic fraction of atmospheric particulate matter (PM_{10}) — that part of the inspirable fraction that penetrates into the respiratory tract below the larynx — in the ambient air of Delhi, India, in 1998, was reported to range from 0.1 to 2 µg/m^3 (Table 26). Principal component analysis identified three major sources, namely vehicle emissions, industrial emissions and soil resuspension (Balachandran *et al.*, 2000). Samples collected from high-exposure areas of Mumbai, India, had higher lead concentrations than those collected in other high-exposure areas of the world including Beijing (China), Stockholm (Sweden) and Zagreb (Serbia and Montenegro) (Parikh *et al.*, 1999). A recent report of the Central Pollution Control Board (2001–2002) found concentrations of lead in air in Mumbai, India, to be on the decline. In fact, the introduction of unleaded petrol reduced lead concentrations in ambient air by about half in seven sites throughout India (Central Pollution Control Board, 1998–99).

In Semarang, Indonesia, mean urban airborne lead concentrations were found to be 0.35 µg/m^3 in a highway zone, 0.95 µg/m^3 in a residential zone (mainly due to solid-waste

Table 22. Lead concentrations in ambient air in central and eastern Europe

Country	Location	Mean concentration ($\mu g/m^3$)[a] by year						
		1990	1991	1992	1993	1994	1995	1996
Bulgaria	Sofia	0.3	0.3	0.3	0.3	0.2	0.2	
	Pernik	0.5	0.4	0.4	0.2	0.2	0.4	
	Plovdiv	0.6	0.5	0.4	0.3	0.2	0.3	
	Kardjali	1.2	1.2	1.2	0.9	0.9	0.7	
Czech Republic[b]	Prague				0.06	0.04	0.01	
	Pribram				0.08	0.06	0.02	
	Usti n. Labem				0.06	0.04	0.03	
	Brno				0.07	0.08	0.05	
	Ostrava				0.05	0.08	0.05	
Hungary	Budapest				*0.20*	*0.22*	*0.22*	*0.19*
	Pecs				*0.42*	*0.44*	*0.25*	*0.21*
	Miskolc						*0.18*	*0.12*
	Debrecen				*0.56*	*0.30*	*0.27*	*0.28*
Poland[c]	Katowice	*0.73*	*0.90*	*1.16*	*0.68*	*0.68*	*0.78*	*0.58*
	Chorzuw	*2.69*	*0.85*	*0.76*	*0.44*	*0.44*	*0.81*	*1.00*
	Pszczyna	*0.64*	*0.55*	*0.45*	*0.49*	*0.49*	*0.62*	*0.16*
	Lodz		*1.16*	*1.48*	*0.87*	*0.87*	*1.85*	*0.55*
Romania	Copsa Mica	*30.30*	*21.30*	*16.07*	*42.20*	*18.91*	*12.70*	
	Bucuresti	*60.58*	*60.58*	*70.65*			*7.63*	
	Bala Mare	*5.45*	*8.20*	*97.50*	*15.07*	*16.12*	*13.34*	
	Medias	*10.15*	*21.80*	*7.20*	*4.18*	*9.99*	*14.70*	
	Zlatna	*22.72*	*27.10*	*10.00*	*14.00*	*9.44*	*11.46*	
Slovakia	Bratislava	0.11	0.09	0.11	0.10	0.05	0.06	
	B. Bystrica	0.11	0.09	0.08	0.05	0.03	0.03	
	Ruzomberok	0.14	0.05	0.06	0.03	0.04	0.02	
	Richnava	0.50	0.53	0.46	0.14	0.14	0.21	
Slovenia	Trbovlje		*0.90*	*0.70*	*0.30*			
	Zagorje		*1.50*	*0.70*	*0.30*			
	Hrastnik		*0.25*	*0.45*	*0.10*			

From Regional Environmental Center for Central and Eastern Europe (1998)

[a] Italicized text denotes short-term maximal concentration.

[b] Annual geometric means

[c] Maximum average daily concentration

Table 23. Lead concentration in outdoor air in Latin America and the Caribbean

Country	Location	Year of study	Period covered	Concentration (μg/m^3) mean or range of means	Reference
Bolivia	La Paz	NR	NR	1.1	Romieu *et al*. (1997)
Brazil	S. Paulo	1985	Annual average	0.39	Romieu *et al.* (1997)
	Osasco	1985	Annual average	0.16	
	S. Caetano do Sul	1985	Annual average	0.31	
	Santo Amaro, Bahia, near smelter	1989	4-day		Tavares (1990)
	at 526 m			2.8	
	at 955 m			0.13	
	S. Francisco Conde, Bahia (downwind of oil refinery)	July 1994[a]	5-day	0.029	Tavares (1996a)
		Jan. 1995		0.0051	
	Lamarao de Passé, Bahia (downwind of petrochemical complex)	July 1994	5-day	0.0162	
		Jan. 1995		0.0054	
	Itacimirim/Praia do Forte, Bahia (Atlantic air masses)	July 1994	5-day	0.0015	
		Jan. 1995		0.00025	
Chile	San Felipe	1996	NR	0.19	Frenz *et al.* (1997)
	NS	1990	Annual average	1.1	Romieu *et al*. (1997)
Colombia	Bogota	1990	3-month average	3.0	Romieu *et al*. (1997)
Guatemala	Tegucigalpa	NR	NR	0.18	Romieu *et al*. (1997)
	NS	1994	Annual average	0.17	
Honduras	NS	1994	Annual average	1.11	Romieu *et al*. (1997)
	NS	1994	3-month average	1.83	
Mexico	Mexico City	1988	3-month average	0.34–0.24	Romieu *et al*. (1997)
		1990		1.08–1.47	
		1994		0.24–0.37	
		1988	Annual average	1.95	
		1990		1.23	
		1994		0.28	
		1995	24-h average	0.54	

Table 23 (contd)

Country	Location	Year of study	Period covered	Concentration (μg/m^3) mean or range of means	Reference
Peru	NS	1980	3-month average	1.8	Romieu *et al*. (1997)
		1985		1.9	
		1990		2.2	
		1994		2.1	
		1980	Annual average	1.7	
		1985		1.5	
		1990		1.6	
		1994		1.7	
Venezuela	Caracas	1982	Annual average	4.5	Romieu *et al*. (1997)
		1986		2.6	
		1990		1.9	
		1994		1.6	

NR, not reported; NS, not stated

[a] July is in wet season whereas January is during the dry season.

Table 24. Lead concentration in indoor dust in Latin America and the Caribbean

Country	Location	Year(s) of study	Source of contamination	Concentration (μg/g) mean ± SD or range of means	Reference
Mexico	Cd. Juarez, Chihuahua	1974	Lead smelter		Ordóñez *et al*. (2003)
			< 1.6 km	1322 ± 930	
			1.6–4 km	220	
	Villa de la Paz	NR	Mining	955 (range, 220–5190)	Yáñez *et al*. (2003)
	Mexico City	1983	Multiple urban	587 ± 303	Bruaux & Svartengren (1985)
Venezuela	Caracas (day-care centre)	1997–98	Urban	999–1707	Fernández *et al*. (2003)

NR, not reported; SD, standard deviation

Table 25. Lead concentrations in outdoor air and dust in Africa

Country	Location	Year(s) of study	Source of contamination	Concentration (μg/m^3)[a] mean or range of means (range)	Reference
Egypt	Cairo	1983–84	Town centre Residential/industrial Residential district Suburban district Commercial	3.0 1.3 1.4 0.6 2.2	Ali *et al.* (1986)
	Cairo	NR	Industrial district	2	Hindy *et al.* (1987); Nriagu (1992)
Nigeria	Lagos	1981	Urban setting	770–1820 μg/g[b,c]	Ajayi & Kamson (1983)
		1991	Urban traffic	51–1180 μg/g[b]	Ogunsola *et al.* (1994a)
South Africa	Cape Town	NR	High traffic Low traffic High traffic Low traffic	1.5 (1.3–2.1) 0.8 (0.4–0.9) 2900–3620[b] 410–2580[b]	von Schirnding *et al.* (1991a)
	KwaZulu/ Natal	1995	Industrial/highway Commercial Park/beach Residential Rural	1.84 0.86 0.56 0.44 < 0.03	Nriagu *et al.* (1996a)
	8 cities	1993–95	Urban setting	0.36–1.1	Nriagu *et al.* (1996b)
Zambia	Kasanda	1973–74	NR	10 (5–145)	Nriagu (1992)

Adapted from Nriagu (1992)
NR, not reported
[a] Unless specified otherwise
[b] Lead concentrations in dust
[c] Median values

Table 26. Lead concentrations in outdoor air and dust in Asia

Country	Location	Year(s) of study	Concentration (ng/m^3) mean or range of means (range)	Reference
China	Beijing and Shanghai	1984–97	60–980	Zhang, Z.-W. *et al.* (1998)[b]
	Provincial capitals		30–13 700	
	Other regions		8–2800	
	Beijing		21–318	Parikh *et al.* (1999)
	Taiyuan			Yang & Ma (1997)
	Winter		490–1125	
	Summer		115–504	
China (Province of Taiwan)	Tainan		180	[Environment Protection Administration ROC (1991)]
India	Delhi	1998	100–2000	Balachandran *et al.* (2000)
	Delhi	2000	590	Central Pollution Control Board (2001–2002)
		2001	550	
	Kolkata (road dust)[c]		536 μg/g	Chatterjee & Banerjee (1999)
	Mumbai		82–605 (31–1040)	Khandekar *et al.* (1984)
	Mumbai		30–440	Raghunath *et al.* (1997)
	Mumbai			Nambi *et al.* (1997)
	Industrial		500–120 000	
	Rural		110	
	Mumbai			Parikh *et al.* (1999)
	High-exposure area		432.4 (131–864)	
	Low-exposure area		268.2 (147–476)	
	Mumbai	1984–96		Tripathi *et al.* (2001)
	Urban		100–1120	
	Industrial		1180–4120	
	Nagpur	1996	42–65	Patel *et al.* (2001)
	7 cities	1980	60–310	Sadasivan *et al.* (1987)
	Whole country	1994	11 000	Gupta & Dogra (2002)
Indonesia	Semarang			Browne *et al.* (1999)
	Urban		350–990	
	Industrial		8410	
Japan	Tokyo and Kyoto	1996–97	15–81	Environment Agency, Japan (1997)

Table 26 (contd)

Country	Location	Year(s) of study	Concentration (ng/m^3) mean or range of means (range)	Reference
Korea	Pusan		902–1596	[Moon & Lee (1992)]
	Seoul	1984–93	100–1500[d]	Lee *et al.* (1994)
	Seoul	1986–94	22–1070	Reviewed by Moon & Ikeda (1996)
	Pusan	1990	1310 (210–2870)	Cho *et al.* (1992)
Malaysia	Kuala Lumpur		30–462	[Hisham & Pertanika (1995)]
	Kuala Lumpur (urban)		95	Hashim *et al.* (2000)
	Kemaman (semiurban)		27	
	Setiu (rural)		15	
Pakistan[c]	Karachi		7.9–101.8 µg/g	Rahbar *et al.* (2002)
Philippines	Whole country	1993	600–1300	Environmental Management Bureau (1996)
		1994	300–500	
	Manila	1994	300–1200[d]	
		1995	200–800[d]	
Saudi Arabia	Riyadh			Al-Saleh (1998)
	High traffic		3200	
	Residential		720	
Thailand	Bangkok		210–390	[Pollution Control Department (1996)]

Updated from Ikeda *et al.* (2000a)
[a] Unless specified otherwise
[b] Review of 15 reports published primarily in China between 1984 and 1997
[c] Lead concentration in dust
[d] Values read from graphs
References in square brackets could not be retrieved as original papers.

Table 27. Lead concentrations in outdoor air in Japan, 1996–97, as monitored in 16 monitoring stations

Statistical parameter	Monthly average concentration (ng/m^3)												
	1996									1997			
	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	Average[b]
AM[a]	54.9	56.3	51.1	40.3	34.9	44.2	52.4	62.2	73.5	56.5	49.5	55.3	51.3
ASD[a]	28.0	23.6	24.3	21.1	13.9	24.9	28.0	31.5	34.2	26.6	23.0	21.3	23.1
Min	16	< 10	< 10	< 10	< 10	11	12	16	20	14	15	19	13
Max	110	100	84	81	59	85	99	120	130	100	77	87	81
GM[a]													45.0
GSD[a]													1.78

From Environment Agency, Japan (1997)

AM, arithmetic mean; ASD, arithmetic standard deviation; min, minimum; max, maximum; GM, geometric mean; GSD, geometric standard deviation

[a] Values calculated by the Working Group; values < 10 were not included in the calculations.

[b] Mean, standard deviation, min. and max. of local annual arithmetic means among the 16 stations

burning) and 0.99 µg/m^3 in a commercial zone. Airborne lead concentrations of 8.41 µg/m^3 were recorded in an industrial area; values of this magnitude had not been reported previously in Indonesia (Browne *et al.*, 1999).

After leaded gasoline, lead mining and the smelting and refining of both primary and secondary lead are the next highest sources of lead emissions that can cause contamination of the nearby environment. The nature and extent of contamination depend on many factors, including the level of production, the effectiveness of emission controls, climate, topography and other local factors. Concentrations are usually highest within 3 km of the point source (US EPA, 1989, cited by WHO, 1995). For example, near a smelter in Santo Amaro, Bahia, Brazil, 4-day average values in 1989 of 2.8 ± 1.0 µg/m^3 (range, 1.8–3.9 µg/m^3) were reported 526 m from the smelter chimney in one direction and 0.13 ± 0.06 µg/m^3 (range, 0.08–0.22 µg/m^3) 955 m in the opposite direction (see Table 23; Tavares, 1990). A report from China found that lead concentrations in ambient air, plants and soil increased proportionally with proximity to a large primary smelter; air lead concentrations were 1.3 µg/m^3 at 1000 m from the source and 60 µg/m^3 at 50 m from the source (Wang, 1984). Some earlier studies have shown air pollution and soil contamination as far as 10 km from lead smelters (Djuric *et al.*, 1971; Landrigan *et al.*, 1975a).

A survey conducted in the vicinity of three lead industries in Maharashtra, India, showed the highest measured concentration of lead in air of 120 µg/m^3 in a residential area 200 m from one of the industries (see Table 26; Nambi *et al.,* 1997).

High concentrations of lead in household dust in the vicinity of lead smelters or mining activity, or from vehicles using leaded gasoline, have been reported (see Tables 24, 25 and 26). Lead concentrations in dust inside houses located in the vicinity of a lead smelter at Cd. Juarez, Chihuahua, Mexico, increased from 220 µg/g at 4 km to 1322 µg/g at less than 1.6 km from the smelter (Ordóñez *et al.*, 2003). An international study coordinated by WHO found a mean lead concentration (± standard deviation) in indoor dust in Mexico City of 587 ± 303 µg/g, compared with 440 ± 263 µg/g and 281 ± 500 µg/g in Sweden and Belgium, respectively (Bruaux & Svartengren, 1985). In 1997–98 lead concentrations of floor dust in day-care centres in Caracas, Venezuela, ranged from 999 to 1707 µg/g (Fernández *et al.*, 2003).

Data on lead in air in South America are scarce, and refer only to total lead in suspended particles. One study of lead concentrations in incoming Atlantic air masses reaching the north-eastern Brazilian coast in 1994–95 showed concentrations of 1.5 ng/m^3 during the rainy season (April–August) and of 0.25 ng/m^3 during the dry season (September–March) (see Table 23; Tavares, 1996a).

Biomass burning, which takes place during the dry season both for forest clearance and for agricultural purposes, can be an important source of lead in rural environments with otherwise low concentrations. Measurements in the Amazon forest during the wet season (September–March) showed lead concentrations of 0.33–0.61 ng/m^3 in particles smaller than 2.5 µm and 0.26–0.50 ng/m^3 in particles 2.5–10 µm in size; corresponding values during the dry season (June–September) were 0.73 ng/m^3 and 0.46 ng/m^3, respectively (Artaxo *et al.*, 1990).

Coal contains small amounts of lead, and fly ash from coal combustion and refuse incineration can leach substantial amounts of lead into ambient air (Wadge & Hutton, 1987). In an urban area of Taiwan, China, where the winter is cold, lead concentrations in air were reported to be about three times higher in winter (0.49–1.13 μg/m^3) than in summer (0.12–0.50 μg/m^3), due to use of lead-containing coal for heating (Yang & Ma, 1997). Surveys of lead in air in seven cities in India indicated concentrations ranging from 0.06 ± 0.02 μg/m^3 in Coimbatore to 0.31 ± 0.10 μg/m^3 in Kanpur (Sadasivan *et al.,* 1987). In addition to automobile exhaust, increased fuel burning in the winter and open burning of refuse were identified as sources of lead contamination (Table 26). In contrast, lead air concentrations in Japan in 1996–97 averaged 50 ng/m^3 and little seasonal variation was observed (Table 27).

Lead concentrations in indoor air are affected by the presence of smokers, air conditioning and lead-painted surfaces. Two studies conducted in the Netherlands and the United Kingdom showed that air lead concentrations inside dwellings where there is no major internal lead source were highly correlated with those outside and averaged approximately 60% of those in the external air immediately outside the house (Diemel *et al.*, 1981; Davies *et al.*, 1987).

(*c*) *Water*

Lead enters groundwater from natural weathering of rocks and soil, indirectly from atmospheric fallout and directly from industrial sources. Lead can enter freshwater bodies from municipal sewage, from harbour activities and from lead storage sites and production plants, particularly mining and smelting. In local aquatic environments, pollution can also result from leaching of lead from lead shot, shotgun cartridges and fishing weights (WHO, 1995). The concentration of lead in surface water is highly variable depending upon the sources of pollution, the lead content of sediments and the characteristics of the system (pH, temperature). An additional and distinct hazard to the water supply is the use of lead piping or lead solder in plumbing systems. Water with low pH and low concentrations of dissolved salts (referred to as aggressive or corrosive water) can leach substantial quantities of lead from pipes, solder and fixtures (ASTDR, 1999). Lead-lined reservoirs, cisterns and water tanks can be a major source of lead contamination of drinking-water.

Lead concentrations in surface water, groundwater and tap-water in different geographical regions of the world are presented in Tables 28–31. A few examples are detailed below, according to the type of water analysed.

Seawater generally contains low levels of lead. It was estimated that lead concentrations in the ocean were 0.0005 μg/L in the pre-industrial era and around 0.005 μg/L in the late 1970s (US EPA, 1982).

Concentrations of lead in surface water and groundwater throughout the USA typically range between 5 and 30 μg/L and between 1 and 100 μg/L, respectively, although concentrations as high as 890 μg/L have been measured (US EPA, 1986a). The mean concentration of lead measured at nearly 40 000 surface-water stations throughout the

Table 28. Lead concentrations in water in Latin America and the Caribbean

Country	Location	Year of study	Source of contamination	Concentration (µg/L) mean (range)	Reference
Argentina	La Plata river, Buenos Aires		Industry, sewage, harbour activities		Verrengia Guerrero & Kesten (1994)
	Port	1989		28.1 (2.4–58.6)	
	Fishing Club	1989		11.3 (9.9–16.4)	
Bolivia	Pilcomayo river (at Potosi)	1999	Mine tailings	1399 (911–2111)	Smolders *et al.* (2003)
	Tarapaya river	1999	Mine tailings	2291 (1101–3980)	
	Cachi Mayu	1999	No specific source	1.0 (0.6–1.7)	
Brazil	Ribeira do Iguape river	1994	NR	< 20–70	Romieu *et al.* (1997)
	Sao Paulo State	1994	NR	2.8	
Chile	Antofagasta (household)	1998	Lead storage site	Max. 170	Sepúlveda *et al.* (2000)
Mexico	Drinking-water	1983	No specific source	2 ± 1 (1–3)	Bruaux & Svartengren (1985)
Uruguay	Tap-water	1992	Lead pipes	15 (0.2–230)	Schütz *et al.* (1997)

NR, not reported; max., maximum concentration (µg/L)

Table 29. Lead concentrations in fresh water, seawater and sediment in the Canary Islands, Egypt and Nigeria

Country	Location	Type of water/ sediment	Concentration mean or range of means (range)	Reference
Canary Islands (Spain)	Santa Cruz	Seawater	1.4–11.3 µg/L (0.42–116.9)	Díaz *et al.* (1990)
Egypt	Lake Nubia	Sediment	79 µg/g	Lasheen (1987)[a]
	Alexandria	Seawater	0.05–0.7 µg/L	Abdel-Moati & Atta (1991)
		Sediment	2–49 µg/g	
Nigeria	Agunpa river	River water	1.3–46 µg/L	Mombeshora *et al.* (1983)
		Sediment	62–75 µg/g	
	Ona river	River water	0.2–17 µg/L	
		Sediment	25–58 µg/g	

Adapted from Nriagu (1992)
[a] Original paper was not available.

USA was 3.9 µg/L (Eckel & Jacob, 1988). Lead concentrations in surface water are typically higher in urban areas than in rural areas (US EPA, 1982).

Lead concentrations in the La Plata river at two sites in Buenos Aires, Argentina, ranged from 2.4 to 58.6 µg/L at the port area and from 9.9 to 16.4 µg/L at the Fishing Club (Table 28; Verrengia Guerrero & Kesten, 1994). The Ribeira do Iguape river, in South Brazil, receiving urban and industrial effluents, showed lead concentrations between < 20 and 70 µg/L in 1994 (Romieu *et al.*, 1997). Intensive mining and tailing releases to the Pilcomayo and Tarapaya rivers resulted in mean lead concentrations in the water of 1399 and 2291 µg/L, respectively, against 1.0 µg/L in Cachi Mayu, which had not been contaminated by specific lead sources (Smolders *et al.*, 2003).

Lead contamination of groundwater around the Hussain Sagar lake, Hyderabad, India, indicated that the source of pollution was the contaminated lake. Lead was detected at concentrations in the range of 1–28 µg/L in groundwater and 38.4–62.5 µg/L in the lake (Table 30). The concentrations were appreciably higher than those for uncontaminated fresh waters which are generally below 1 µg/L (Srikanth *et al.*, 1993). During a 2-year study of the Nainital lake, India, the average lead contamination levels in water and sediment were 600 µg/mL and 50.0 µg/g, respectively (Ali *et al.,* 1999). The lead content in various bodies of water in India ranged from 35 to 70 µg/L in the Eastern Ghats (Rai *et al.,* 1996), from 350 to 720 µg/L in various lakes in Lucknow, and from 510 to 1510 µg/L in Unnao (Chandra *et al.,* 1993). In the Gomti river, lead concentrations of 13–26 µg/L were reported (Singh, 1996) and in the Ganga river from 0.98 to 6.5 µg/L (Israili, 1991). The waters of Vasai Creek (Maharashtra, India) had concentrations of 10.5–29.5 µg/L, which was the result of contamination from 18 major industries that

Table 30. Lead concentrations in water and sediment in Asia

Country	Location	Type of water/ sediment	Concentration (µg/L)^a mean or range of means (range)	Reference	Comments
India	Pilani	Tube well	88 (21–354)	Kaphalia *et al*. (1981)	pH of water, 7.5–9.1
	Lucknow	Tap-water	33 (0–67)		
		River	35 (8–58)		
	Cambay	Tank	6 (0–16)		
	Kanpur villages	Tube well	20 (0–40)		
	Company	Tube well	24 (0–80)		
	Mumbai	Drinking-water	12 ± 3	Khandekar *et al*. (1984)	
	Various cities along Ganga river	River	0.98–6.5	Israili (1991)	Highest concentration in water and sediment at Garsh Mukteshwara
		Sediment	1.2–16.0 µg/g		
	5 cities along Yamuna river	River (10 samples)	0.76–8.51	Israili & Khurshid (1991)	
	Koraput (Orissa)	Water stations	15 ± 1	Chandra *et al*. (1993)	
	Unnao (Uttar Pradesh)		510 ± 50 (summer) 1510 ± 150 (winter)		
	Various sites along Gomti river	River		Singh (1996)	Highest concentrations at Mohan Meakin, Sultampur and Pipraghat
		unfiltered	13–25		
		filtered	9–21		
	Hussain Sagar lake, Hyderabad	Lake	38.4–62.5	Srikanth *et al*. (1993)	
		Ground water			
		200–1000 m from lake	7–28		
		1000–2000 m from lake	1–9		

Table 30 (contd)

Country	Location	Type of water/ sediment	Concentration (µg/L)[a] mean or range of means (range)	Reference	Comments
India (contd)	Eastern Ghats (Koraput Orrisa)	Drinking-water facilities		Rai *et al*. (1996)	
		adequate	54 ± 5		
		primitive	35 ± 5		
		absent	70 ± 37		
	Nainital	Lake water	150–480	Ali *et al*. (1999)	
		Sediment	50.0 µg/g		
	Vasai Creek, Maharashtra	River/sea	10.5–29.5	Lokhande & Kelkar (1999)	
	Mumbai	Drinking-water		Parikh *et al.* (1999)	
	High exposure area		2.8 ± 0.8		
	Low exposure area		4.5 ± 1.7		
	Nagpur	Tap-water	2.82	Patel *et al*. (2001)	
		Well	3.30		
	Lucknow	Lake and ponds	350–720	Rai & Sinha (2001)	
	Darbhanga District, North-Bihar	9 ponds	[147–1056]	Rai *et al.* (2002)	Data for 1996–97; highest values for water and sediment in same pond
		Sediment	[72.21–240.95 µg/g]		
Indonesia	Central Kalimantan	6 rivers	0.41–5.23	Kurasaki *et al*. (2000)	Motor boats are an important mode of transport.
		3 channels	0.1–1.28		
		3 lakes	0.28–11.48		
		1 fish pond	0.51		
Malaysia	Klang river	1992[b]	28	APEC (1997)	
		1993	21		
		1994	18.6		
		1995	25.9		
		1996	8		
Pakistan	Karachi	Drinking-water from household	3.1–4.3	Rahbar *et al*. (2002)	

[a] Unless specified otherwise
[b] Year of sample collection

Table 31. Lead concentration in drinking-water, Japan, 2001

	Number [%] of samples with lead concentration (µg/L)				
	Total	< 5	5–< 10	10–< 15	≥ 15
Source water	5178	5110 [98.69]	53 [1.02]	5 [0.10]	10 [0.19]
Treated water[a]	5647	5536 [98.03]	84 [1.49]	14 [0.25]	13 [0.23]

From Ministry of Health, Labour and Welfare, Japan (2001)

[a] Concentrations measured at drinking-water treatment plants

Note: A drinking-water standard of < 10 µg/L lead was established in Japan as of 1 April, 2004 (Ministry of Health, Labour and Welfare, Japan, 2003).

collectively released about seven tonnes of lead per year into the creek (Lokhande & Kelkar, 1999).

Among six locations along four rivers in central Kalimantan, Indonesia, the highest lead concentrations were found in the Kahayan river (5.23 and 2.09 µg/L at two sampling sites), followed by Murung river (1.71 µg/L). Of various channel, lake and pond waters (7 locations), lake Tundai was found to be by far the most contaminated with lead (11.48 µg/L), followed by channel Dablabup (1.28 µg/L) (Kurasaki *et al.,* 2000).

Surveys in Canada and the USA showed that drinking-water supplies leaving treatment plants contain 2–8 µg/L lead (US EPA, 1986a; Dabeka *et al.*, 1987). EPA estimated that less than 1% of the public water systems in the USA have water entering the distribution system with lead concentrations above 5 µg/L. However, most lead contamination comes from corrosion by-products of lead pipes and lead-soldered joints (US EPA, 1991). A survey of 1245 drinking-water samples taken from various districts in the USA showed that average lead concentrations in water in copper, galvanized and plastic pipes were 9, 4.2 and 4.5 µg/L, respectively. These data show that even plumbing that did not use lead solder (e.g. plastic pipes) contained significant amounts of lead, primarily from the brass faucet fixtures which are used in almost all plumbing. The brass fixtures may account for approximately one-third of the lead in the first-draw water (Lee *et al.*, 1989).

Following an increased volcanic activity that resulted in the release of acid aerosols, Wiebe *et al.* (1991) analysed over 2000 water samples in Hawaii, USA, and found lead concentrations in drinking-water collected in catchment systems ranging from < 20 to 7000 µg/L.

The use of lead pipes in Uruguay resulted in tap-water concentrations of lead ranging between 0.2 and 230 µg/L (Schütz *et al.*, 1997). In 1983, lead concentrations in drinking-water from an underground source in Mexico City, Mexico, ranged between 1 and 3 µg/L, in spite of the past intensive use of lead in petrol (Bruaux & Svartengren, 1985). Storage of minerals near urban areas in Antofagasta, Chile, resulted in concentrations of lead in household water of up to 170 µg/L in 1998 (Sepúlveda *et al.*, 2000).

Water samples collected from tube wells, tanks and taps in India showed lead concentrations that varied between 0 and 354 µg/L (Kaphalia *et al.*, 1981). The lead concentration in drinking-water in Karachi, Pakistan, was found to be in the range of 3.08–4.32 µg/L as an arithmetic mean for each of five monitored areas (Rahbar *et al.*, 2002). Throughout Japan, more than 98% of the drinking-water samples had concentrations below 5 µg/L (Table 31; Ministry of Health, Labour & Welfare, 2001).

Gulson *et al.* (1997a) measured lead in household water throughout the day in an unoccupied test house in Australia. Lead concentrations in water ranged from 119 µg/L for the initial (first-draw) sample to 35–52 µg/L for hourly samples (125 mL) to 1.7 µg/L for a fully flushed sample.

(*d*) *Sediments*

Lead reaching surface waters is readily bound to suspended solids and sediments, and sediments from both freshwater and marine environments have been studied for their lead content. Sediments contain considerably higher concentrations of lead than corresponding surface waters, and provide a unique record of the history of global lead fluxes (WHO, 1995).

Concentrations of lead in sediments in Africa, Asia and Latin America are summarized in Tables 29, 30 and 32, respectively.

Average concentrations of lead in river sediments in the USA have been reported to be about 23 mg/kg (Fitchko & Hutchinson, 1975; US EPA, 1982). In coastal sediments a mean value of 87 mg/kg was measured (range, 1–912 mg/kg) (Nriagu, 1978; US EPA, 1982). Surface sediment concentrations of lead in Puget Sound, near Seattle, were found to range from 15 to 53 mg/kg (Bloom & Crecelius, 1987). An analysis of sediments taken from 10 lakes in Pennsylvania indicated that the lead does not principally originate from parent materials in the watershed (from the native rocks as a result of acid deposition), but rather from transport of anthropogenic lead through the atmosphere onto the soil surface and subsequent run-off of soil particulates into the lake (Case *et al.*, 1989).

The main reported sources of lead entering surface-water bodies in Latin America have been metallurgy, smelter and mining effluents, oil refineries and port activities. In Brazil, the All Saints bay showed values of 119 mg/kg in sediments at the river mouth downstream from a smelter; 176 mg/kg at the river mouth downstream from an oil refinery; and 618 mg/kg in the vicinity of metallurgical industries and an industrial port, compared with 35.7 mg/kg in an area with no specific source of lead, away from industries (Tavares, 1996a,b).

Mine tailings in Bolivia were responsible for an increase in lead concentrations from 7.4 mg/kg in Cachi mayu, where no specific source of lead contamination exists, to average values of 603 mg/kg (range, 292–991 mg/kg) and 902 mg/kg (range, 761–1236 mg/kg), in sediments from the Pilcomayo river at Potosi and from the Tarapaya river,

Table 32. Lead in sediments in Latin America and the Caribbean

Country	Location	Year(s) of study	Source of contamination	Concentration (µg/g) mean (range)	Reference
Brazil	All Saints bay, São Brás	1994	Downstream from lead smelter	119	Tavares (1996b)
	All Saints bay, Mataripe river mouth	1994	Oil refinery	176	
	All Saints bay, Aratu Port	1994	Metallurgies, industrial port	618	
	All Saints bay, Cabuçu	1994	No specific source	35.7	
	Ribeira do Iguape river	1994	NR	(3–240)	Romieu *et al.* (1997)
	Jacareí, São Paulo	1994	NR	(10–9100)	
Bolivia	Pilcomayo river, Potosi	1997–98	Mine tailings	603 (292–991)	Smolders *et al.* (2003)
	Tarapaya river	1997–98	Mine tailings	902 (761–1236)	
	Cachi mayu	1997–98	No specific source	7.4 (3.3–9.9)	
Honduras	Yojoa lake	NR	NR	371	Romieu *et al.* (1997)
Mexico	Gulf of Mexico coast	1983–87	NR	(0.29–90.15)	Albert & Badillo[a] (1991)
Uruguay	Montevideo	NR	NR	(20–160)	Romieu *et al.* (1997)

NR, not reported
[a] Review of 7 studies at 8 sites

respectively (Smolders *et al.*, 2003). Mean concentrations of lead in sediments from the Gulf of Mexico were found to range from 0.29 to 90.15 mg/kg (Albert & Badillo, 1991).

(*e*) *Soil*

Most of the lead released into the environment from emissions or as industrial waste is deposited in soil. Lead-containing wastes result from the processing of ores, the production of iron and steel, the various end-products and uses of lead, and the removal and remediation of lead paint (ATSDR, 1999). Lead in soil may be relatively insoluble (as a sulfate, carbonate or oxide), soluble, adsorbed onto clays, adsorbed and coprecipitated with sesquioxides, adsorbed onto colloidal organic matter or complexed with organic moieties present in soil (WHO, 1995). The soil pH, the content of humic and fulvic acids and the amount of organic matter influence the content and mobility of lead in soils. Since acidic conditions favour the solubilization and leaching of lead from the solid phase, acidic soils tend to have lower lead concentrations when analysed as dry soil. Acid rain promotes the release of lead into groundwater. Humic and fulvic acids can also mobilize lead, and certain complex organic molecules can act as chelators of lead (WHO, 1995).

Table 33 shows some sources and amounts of lead released in soils worldwide. Tables 34, 35 and 36 summarize data on lead concentration in soils in Latin America, Africa and Asia, respectively.

Background concentrations of lead in soil measured across the USA in the 1970s were estimated to be in the range of < 10–70 mg/kg (Boerngen & Shacklette, 1981). Soil samples taken at distances of 50–100 m from highways, outside the range of immediate impact from traffic emissions, usually show concentrations of lead below 40 mg/kg (WHO, 1995).

Studies carried out in Maryland and Minnesota indicate that within large light-industrial urban settings such as Baltimore, soil lead concentrations are generally highest in inner-city areas, especially where high traffic flows have long prevailed (Mielke *et al.*, 1983, 1989); the amount of lead in the soil is correlated with the size of the city, which in turn is related to traffic density (Mielke *et al.*, 1989; Mielke, 1991). It has been suggested that the higher lead concentrations in soil samples taken around houses in the inner city are the result of greater atmospheric lead content from the burning of leaded gasoline in cars and the washdown by rain of building surfaces to which the small lead particles adhere (Mielke *et al.*, 1989).

Table 33. Discharge of lead in soil worldwide

Source of lead	Amount released (tonnes/year)
Agricultural and food wastes	1500–27 000
Animal wastes, manure	3200–20 000
Logging and other wood wastes	6600–8200
Urban refuse	18 000–62 000
Municipal sewage sludge	2800–9700
Miscellaneous organic wastes, including excreta	20–1600
Solid wastes, metal manufacturing	4100–11 000
Coal fly ash, bottom fly ash	45 000–242 000
Fertilizer	420–2300
Peat (agricultural and fuel use)	450–2600
Wastage of commercial products	195 000–390 000
Atmospheric fallout	202 000–263 000
Mine tailings	130 000–390 000
Smelter slags and wastes	195 000–390 000
Total yearly discharge on land	803 090–1 818 800

From Nriagu and Pacyna (1988)
Many of these discharges remain localized due to the nature of the particulate matter.

Table 34. Lead concentrations in soils in Latin America and the Caribbean

Country	Location	Year(s) of study	Source of contamination	Concentration (mg/kg) mean ± SD (range)	Reference
Argentina	Buenos Aires	1975	NR	6–12	Romieu *et al.* (1997)
Brazil	Santo Amaro, Bahia[a]	1980	900 m from smelter, 12 m high chimney	10 601 ± 14 611 (32–107 268) 4415 ± 4.4[b]	Tavares (1990)
		1985	90 m high chimney	4812 ± 8523 (236–83 532) 2529 ± 2.9[b]	
	Jacareí, São Paolo	1994	NR	(51–338)	Romieu *et al.* (1997)
Chile	Antofagasta	1998	Storage of minerals	(81–3159)	Sepúlveda *et al.* (2000)
		1998	Upwind from storage site	(51–321)	
Ecuador	Andean village La Victoria	NR	Glazing of ceramics		Counter *et al.* (2000)
			At 1 m	29 213 ± 9458[a]	
			At 5 m	172 ± 26	
			At 10 m	81 ± 13	
			At 1 km	55 ± 2	
			At 2 km	19 ± 1	
			At 6 km	1.4 ± 0.1	
	Mambija, San Carlos and Esmeraldas		Control area	(2.3–21)	

Table 34 (contd)

Country	Location	Year(s) of study	Source of contamination	Concentration (mg/kg) mean ± SD (range)	Reference
Mexico	N and NE Mexico city irrigation districts	1980–81	Traffic fallout	5.3 ± 1.5	Albert & Badillo (1991)
	Mexico city airport	1979	Traffic fallout	(739–890)	
	Mexico city centre	1979	Traffic fallout	(6–107)	
	Mexico city Viaducto Piedad	1979	Traffic fallout	(43–578)	
	Mexico city Estadio Azteca	1979	Traffic fallout	(2.1–2.7)	
Venezuela	Caracas, Day-care centres	1997–98	Traffic (high flow)	Particle size, 44–62.5 µm: 113–375 Particle size, < 44 µm: 190–465	Fernández *et al.* (2003)
			Traffic (low flow)	Particle size, 44–62.5 µm: 106 ± 3 Particle size, < 44 µm: 142 ± 3	

NR, not reported; SD, standard deviation

[a] Leachable lead

[b] Geometric mean and standard deviation

Table 35. Lead concentrations in soil in Saudi Arabia and Africa

Country	Location	Source of contamination	Concentration (mg/kg) mean or range of means (range)	Reference
Saudi Arabia	NR	Heavy traffic	95.3	Al-Saleh
		Residential	34.5	(1998)
Kenya	Nairobi	City traffic	137–2196	Onyari *et al.*
		Industrial area	148–4088	(1991)
Zambia	Kasanda	2 km from lead smelter	100–> 2400	Nriagu (1992)
	Kabwe	5 km from lead smelter	(9862–2580)	Nwankwo &
	Lusaka	No specific	16 (11–40)	Elinder (1979)

NR, not reported

Lead-based paint can also be a major source of lead in soil. In the state of Maine, USA, 37% of soil samples taken within 1–2 feet (30–60 cm) of the foundation of a building more than 30 years of age had lead concentrations > 1000 mg/kg (Krueger & Duguay, 1989).

In a study of the association between the concentrations of lead in soil and in blood samples taken from children in urban and rural areas in Louisiana, USA, blood lead concentrations in children appeared to be closely associated with soil lead concentration (Mielke *et al.*, 1997a).

Three prospective studies were conducted in Boston, Baltimore and Cincinnati, USA, to determine whether abatement of lead in soil could reduce blood lead concentrations of children. No significant evidence was found that lead reduction had any direct impact on children's blood lead concentrations in either Baltimore or Cincinnati (US EPA, 1996b). In the Boston study, however, a median soil lead reduction from 2075 mg/kg to 50 mg/kg resulted in a mean decline of 2.47 µg/dL blood lead concentration 10 months after soil remediation (Weitzman *et al.*, 1993; Aschengrau *et al.*, 1994). A number of factors appear to be important in determining the influence of soil abatement on blood lead concentrations in children, including the site-specific exposure scenario, the extent of the remediation, and the magnitude of additional sources of lead exposure.

Children with pica — a serious eating disorder characterized by repetitive consumption of nonfood items — may be at increased risk for adverse effects through ingestion of large amounts of soil contaminated with lead. It has been estimated that an average child may ingest on average between 20 and 50 mg of soil per day through normal hand-to-mouth activity, whereas a child with pica may ingest up to 5000 mg of soil per day (LaGoy, 1987). This source can contribute an additional lead intake of 5 µg/day for a toddler engaging in normal hand-to-mouth activity, and significantly more for a child demonstrating pica behaviour (ATSDR, 1999).

Davis *et al.* (1992, 1994), using electron microprobe analysis of soil and waste rock from the mining district of Butte, Montana, USA, showed that the lead bioavailability of

Table 36. Lead concentrations in soil and plants in Asia

Country	Location	Source of contamination	Lead concentration in:		Reference	Comments
			Soil (mg/kg)	Plant (mg/kg)		
China	NR	Smelter			Wang (1984)	
		50 m	170	29.1		
		500 m	28	1.7		
India	Mumbai	Lead industries	200–3454	145–1048 (grass)	Nambi *et al.* (1997)	
		Control	8.6	1.42		
	Residential area of greater Kolkata	Lead factory	200–46 700	214 ± 17 (leaf)	Chatterjee & Banerjee (1999)	Soil contaminated at least up to 0.5 km
	Coimbatore	Sewage	Surface: 13.3–22.2 Subsurface: 10.26–19.3		Duraisamy *et al.* (2003)	The highest values were found in Nov.–Dec. and the lowest in March.
	Coimbatore	Fertilization with superphosphate and zinc sulfate	1992: 24–47.2 2000: 32.4–63.2		Kamaraj *et al.* (2003)	Fertilizer used during entire period
Mongolia		Urban	92		Burmaa *et al.* (2002)	
		Residential	44			
Philippines	Manila	Playground			Sharma & Reutergardh (2000)	
		contaminated	34.5–281.5			
		control	15			
Thailand	Grazing-land site	Highway	5.25–14.59	0.76–6.62 (grass)	Parkpian *et al.* (2003)	

these samples is constrained by alteration and encapsulation of the lead-bearing minerals (*galena*, *anglesite*, *cerussite* and *plumbojarosite*), which would limit the available lead-bearing surface area. The inherent chemical properties of soil-lead adsorption sites may reduce the bioavailability of soil lead compared with that of soluble lead salts and lead compounds ingested without soil and may explain the low blood lead concentrations observed in children in this mining community.

Davies (1983) calculated that uncontaminated soils in the United Kingdom have a (geometric) mean lead concentration of 42 mg/kg, with a maximum of 106 mg/kg.

A study conducted in Wales, United Kingdom, in an area where lead mining began 2000 years ago and ended in the middle of the 20th century, reported concentrations of lead in garden soils 14 times higher than in uncontaminated areas (Davies *et al.*, 1985).

In Port Pirie, Australia, a community with one of the world's largest and oldest primary lead smelters, lead concentrations in soils were found to be grossly elevated, ranging up to over 2000 mg/kg (McMichael *et al.*, 1985). The frequency of elevated lead concentrations in the blood of pregnant women and young children in this community was also increased above that found in other communities in Australia (Wilson *et al.*, 1986; McMichael *et al.*, 1988).

The main reported sources of lead in soil in Latin America have been from smelter activities, storage of minerals, glazing of ceramics, and leaded gasoline (Table 34). In Santo Amaro, Brazil, in 1980, lead concentrations as high as 107 268 mg/kg in soil have been found in orchards and homes around a smelter (arithmetic mean value for the area within 900 m from the smelter, 10 601 mg/kg), as a result of the use of dross as paving material around houses. At that time, the smelter had a 12-m high chimney. Five years later, after a 90-m high chimney was built, these values dropped to mean values of 4812 mg/kg (Tavares, 1990). In Antofagasta, in the north of Chile, storage of minerals resulted in lead concentrations up to 3159 mg/kg in soil around the site compared with values of 51–321 mg/kg upwind from the site (Sepúlveda *et al.*, 2000). Analysis of soil around ceramic glazing facilities in an Andean Equadorian village showed a significant fall in lead soil concentration with distance from the baking kilns; concentrations were 29 213 mg/kg at 1 m, 55 mg/kg at 1 km and 1.4 mg/kg at 6 km from the kilns (Counter *et al.*, 2000). In 1979, when tetraethyl lead was still added to gasoline, soil lead concentrations in Mexico City, Mexico, were determined near avenues in different parts of the city. Higher concentrations of lead were found in the north and north-west of the city, with the highest values found at the airport, ranging from 739 to 890 mg/kg. The centre of the city showed values between 6 and 107 mg/kg (Albert & Badillo, 1991). In 1980–81, agricultural soils north and north-east of the city, irrigated either directly from wastewaters or with clean water, were analysed for lead; there was no influence of irrigation on soil lead concentrations (Albert & Badillo, 1991). Soil lead concentrations in day-care centres near areas of high traffic flow in Caracas, Venezuela, ranged between 113 and 465 mg/kg, with higher values in soil particles < 44 µm (Fernández *et al.*, 2003). In Argentina, a study of phosphate fertilizers imported from different parts of the world showed lead concentrations between 5.1 and 30.7 mg/kg, which could potentially increase lead concentrations in soils undergoing continuous fertilization (Giuffré de López Camelo *et al.*, 1997).

A number of studies have reported soil lead concentrations in the proximity of smelters and mining areas. A report from China found that lead concentrations in ambient air, plants and soil increased proportionally with proximity to a primary smelter: lead concentration in soil was 28.0 mg/kg at 500 m and 170 mg/kg at 50 m distance from the smelter (Wang, 1984).

Concentrations of lead in soil have been found elevated in many locations in Asia (Table 36), such as in the vicinity of a lead refinery in Kolkata, India (Chatterjee & Banerjee, 1999), in sewage-affected soils (Duraisamy *et al.*, 2003), or on a playground in Manila, Philippines (Sharma & Reutergardh, 2000).

(*f*) *Lead in gasoline*

Globally, by far the largest source of lead emissions into air has been exhaust from motor vehicles using organic lead as an anti-knock agent in gasoline (see Section 1.3.7). In motor-vehicle exhaust from leaded gasoline, > 90% of the lead emission is inorganic lead (e.g. lead bromochloride) and < 10% is alkyl lead vapour. Furthermore, alkyl lead compounds decompose in the atmosphere to lead oxides through a combination of photolysis and oxidation reactions, over a period ranging from a few hours to a few days (ATSDR, 1999). Vehicle emissions increase lead concentrations in the surrounding air, and lead compounds adhere to dust particles that settle and increase the lead content of dusts and soils, thus constituting a major source of exposure of the general population. By comparing ratios of stable lead isotopes in remote areas with those characteristic of lead from industrial sources in various regions, investigators have shown that the lead found in pristine areas such as Greenland and Antarctica originated from motor vehicle exhaust from North America (Rosman *et al.*, 1994a) and South America (Rosman *et al.*, 1994b), respectively.

Nriagu and Pacyna (1988) estimated that in 1983 mobile sources worldwide contributed 248 000 tonnes of lead to the atmosphere. This compares with total estimated emissions to the atmosphere from all sources of 288 700–376 000 tonnes. By 1997, global emissions from leaded gasoline had been reduced to 40 000 tonnes and are still declining, as permissible lead contents of gasoline have been lowered and unleaded gasoline has replaced, or is replacing, leaded fuel in many countries (see Table 20). However, in a number of countries, leaded gasoline is still in use (see Section 1.3.7). Table 37 shows lead concentrations in gasoline over time in a number of countries worldwide.

In Japan, the use of lead in gasoline had been phased out since 1974 and reached almost zero in 1983 (Friberg & Vahter, 1983). The Central Pollution Control Board in India (1998–1999) reported a 50% reduction of lead concentration in air as unleaded gasoline came into use. Leaded gasoline has been banned in India with effect from February 2000. In Pakistan, the addition of lead to gasoline was reduced in 1998–99 from 0.42 to 0.34 g/L in regular gasoline and from 0.84 to 0.42 g/L in high-octane gasoline. In 2001, a directive

Table 37. Lead concentrations in gasoline, air and blood in adults and children worldwide

Country	Location	Population	Year(s) of study	Lead concentration in			Reference
				Gasoline (g/L)	Air[a] (µg/m^3)	Blood[a] (µg/dL)	
Belgium	NR	≥ 20 years	1979	0.45	1.05	17.0[b]	Ducoffre *et al*. (1990)
			1983	0.40	0.66	14.7[b]	
			1987	0.15	0.49	9.0[b]	
Canada	Ontario	3–6 years	1984	0.30	NR	11.9[c] (11.3–12.6)[d]	Loranger & Zayed (1994); Langlois *et al*. (1996)
			1988	0.09	NR	5.1[c] (4.8–5.4)[d]	
			1990	0.04	NR	3.6[c] (3.3–3.9)[d]	
			1992	0.00	NR	3.5[c] (3.1–3.8)[d]	
Finland	Helsinki	Children	1983	0.35	0.33	4.8 (2.1–8.3)	Pönkä *et al*. (1993); Pönkä (1998)
			1988	0.14	0.095	3.0 (2.1–4.1)	
			1996	0.00	0.007	2.6 (1.7–3.7)	
Greece	Athens	Adults	1979	0.80	3.2	NR	Chartsias *et al*. (1986); Kapaki *et al*. (1998)
			1982	0.40	1.76	16.0	
			1984	0.22	0.91	11.8	
			1988	0.15	0.7	8	
			1993	0.14	0.43	5.5	
Italy	Turin	≥ 18 years	1974	0.6	4.7	NR	Facchetti (1989); Bono *et al*. (1995)
			1980	0.6	3.1	21	
			1985	0.4	2.8	15.1 (± 3.9)[e]	
			1989	0.3	1.4	NR	
			1993	0.11	0.53	6.4 (± 1.7)[e]	
Japan	Rural	≥ 20 years	1977–80	0.00	NR	4.9[c] (± 0.15)[e] (men) 3.2[c] (± 0.15)[e] (women)	Watanabe *et al*. (1985)
Mexico	Mexico City	0.5–3 years	1988	0.2	NR	12.2	Octel Ltd (1982, 1988, 1990); Driscoll *et al*. (1992); Mexico City Commission for Prevention and Control of Pollution (1993); Rothenberg *et al*. (1998)
			1989	0.2	NR	14.6	
			1990	0.18	NR	9.8	
			1991	0.08	NR	8.6	
			1992	0.07	NR	9	
			1993	0.06	NR	7	

Table 37 (contd)

Country	Location	Population	Year(s) of study	Lead concentration in			Reference
				Gasoline (g/L)	Air[a] (µg/m^3)	Blood[a] (µg/dL)	
Nepal	Himalayas	Adults and children	NR	0.00	< 0.004[g]	3.4[c]	Piomelli *et al.* (1980)
New Zealand	Christchurch	Adults and children	1978–81	0.84	NR	15.2	Hinton *et al.* (1986); Walmsley *et al.* (1988, 1995)
			1982–83	0.84	NR	11.8	
			1984–85	0.84	NR	8.1	
			1989	0.45	NR	7.3	
			1994	0.2	NR	4.9	
South Africa	Cape Town	Adults	1984	0.84	NR	9.7 (3.0–16.0)	Maresky & Grobler (1993)
			1990	0.40	NR	7.2 (0.62–14.1)	
Spain	Barcelona	20–60 years	1984	0.60	1.03	18.6 (6.8–38.9)	Rodamilans *et al.* (1996)
		19–63 years	1994	0.15	0.24 (0.18–0.3)	8.8 (0.9–31.8)	
	Tarragona	16–65 years	1990	0.40	2.0 (0.97–3.26)	12.0[c] (± 1.8)[e]	Schuhmacher *et al.* (1996a)
			1995	0.13	0.23 (0.02–0.43)	6.3[c] (± 1.8)[e]	
Sweden	Trelleborg	3–19 years	1979	0.40	NA	5.6[c] (2.7–10.4)	[Stockholm Municipal Environment and Health Administration (1983)]; Strömberg *et al.* (1995)
			1983	0.15	NA	4.2[c] (1.9–8.1)	
			1993	0.00	NA	2.3[c] (1.0–6.7)	
	Stockholm	Adults	1980	0.40	1.20	7.7 (± 3.3)[e]	Elinder *et al.* (1986)
			1983	0.15	0.50	5.4 (± 3.3)[e]	
	Landskrona	3–19 years	1978	0.40	0.12–0.42	6.0[c] (1.8–25.0)	Skerfving *et al.* (1986); Schütz *et al.* (1989); Strömberg *et al.* (1995)
			1982	0.15	0.17	4.8[c] (1.5–10.0)	
			1984	0.15	NA	4.2[c] (1.4–12.9)	
			1988	0.00	NA	3.3[c] (1.5–7.1)	
			1994	0.00	NA	2.5[c] (1.2–12.3)	
Switzerland	Vaud, Fribourg	25–74 years	1984–85	0.15	NR	10.3[c] (8.0–17.2)[f]	Wietlisbach *et al.* (1995)
			1988–89	0.10	NR	7.3[c] (5.6–12.7)[f]	
			1992–93	0.05	NR	5.9[c] (4.4–10.2)[f]	

Table 37 (contd)

Country	Location	Population	Year(s) of study	Lead concentration in			Reference
				Gasoline (g/L)	Air[a] ($\mu g/m^3$)	Blood[a] ($\mu g/dL$)	
United Kingdom	England	≥ 11 years	1979	0.42	NR	12.9[c]	Quinn (1985); Quinn & Delves, 1987, 1988, 1989; Delves *et al*. (1996)
			1981	0.38	NR	11.4[c]	
			1984	0.38	NR	8.0–10.9[c]	
			1985	0.38	0.48	9.5[c]	
			1986	0.14	0.24	8.4[c]	
			1995	0.055	NR	3.1[c]	
USA	Countrywide	1–74 years	1976	0.465	0.97	15.9	Annest *et al*. (1983); [US EPA (1985; 1992)]; Brody *et al*. (1994); Pirkle *et al*. (1994)
			1977	0.394		14.0	
			1978	0.349		14.6	
			1979	0.306	0.71	12.1	
			1980	0.30	0.49	9.5	
			1988–91	0.00	0.07 (0.05–0.12)[d]	2.8[c] (2.7–3.0)[d]	
Venezuela	Caracas	≥ 15 years	1986	0.62	1.9	17.4	Cedeño *et al*. (1990); Romero (1996)
			1989	0.45	1.3	15.2	
			1991	0.39	1.3	15.6	

From Thomas *et al*. (1999) with minor modifications

NR, not reported

References in square brackets could not be retrieved as original papers.

[a] Arithmetic mean (range), unless stated otherwise

[b] Median value

[c] Geometric mean

[d] 95% confidence interval

[e] Standard deviation

[f] 90% confidence interval

[g] Detection limit

by the Government of Pakistan established a permissible limit of 0.02 g/L; most of the petrol produced in Pakistan is now lead-free (Paul *et al.*, 2003).

By 1995, six countries in Latin America and the Caribbean (Antigua and Barbuda, Bermuda, Bolivia, Brazil, Columbia, and Guatemala) had removed all lead from gasoline (Pan American Health Organization, 1997). Brazil introduced the national alcohol programme [hydrated alcohol used as fuel in a mixture with gasoline] in 1975, leading to 100% of cars running on unleaded fuel by the beginning of the 1980s. This resulted in a decrease of annual atmospheric lead concentrations from an average of 1.11 μg/m^3 in 1980 to 0.27 μg/m^3 in 1990 in São Paulo. Similarly, by 1994, 80% of the cars in Guatemala and 46% in Mexico ran on unleaded gasoline, reducing the annual average concentration of lead in air to 0.17 and 0.28 μg/m^3, respectively. In Mexico City, the concentration was 1.95 μg/m^3 in 1988 and had decreased by 86% in 1994. Between 1982 and 1990, the city of Caracas, Venezuela, showed a decrease in the annual average atmospheric lead concentrations from 4.5 μg/m^3 to 1.9 μg/m^3 (57.8% decrease). However, this is still higher than the value of 1.5 μg/m^3 recommended by WHO and established as an air quality standard by US EPA. According to a survey carried out by the Pan American Center for Human Ecology and Health in Mexico in 1994, lead concentrations in gasoline in participating Latin American and Caribbean countries ranged from 1.32 g/L in Suriname to 0.03 g/L in Uruguay (Romieu & Lacasana, 1996; Romieu *et al.*, 1997).

Data on lead in gasoline, lead in air and blood lead concentrations of the local population in a number of countries worldwide are summarized in Table 37. An analysis of 17 published studies from five continents (Thomas *et al.*, 1999) found a strong linear correlation between blood lead concentrations in the population and the consumption-weighted average concentration of lead in gasoline, with a median correlation coefficient of 0.94. As the use of lead in gasoline was phased out, blood lead concentrations across study locations converged to a median of 3.1 ± 2.3 μg/dL, and air lead concentrations were reduced to $\leq$ 0.2 μg/m^3.

(*g*) *Lead in paint*

In the past, the use of lead pigments in paints was widespread, but it is now restricted in many countries. Dusting, flaking or peeling of paint from surfaces are major sources of lead contamination of surface dust and soil near houses, and contribute to the amount of lead in household dust. Exposure occurs not only through the direct ingestion of flaking and chalking paint but also through the inhalation of dust and soil contaminated with paint. Renovation and remodelling activities that disturb lead-based paints in homes can produce significant amounts of lead dust which can be inhaled or ingested. Removal of lead-based paint from surfaces by burning (gas torch or hot air gun), scraping or sanding can result, at least temporarily, in high levels of exposure for residents in these homes (ATSDR, 1999). Lead from paint can constitute the major source of lead exposure, in particular for young children, and can even make a significant contribution to blood lead concentrations in children living in areas that are highly contaminated with lead, e.g. around one of the largest lead mines in the world (Gulson *et al.*, 1994). Consumption of a single chip of paint with a lead concentration of 1–5 mg/cm^2 would provide greater short-term exposure than any other source of lead (US EPA, 1986a).

An estimated 40–50% of occupied housing in the USA in 1986 was thought to have lead-based paint on exposed surfaces (Chisolm, 1986). Intervention programmes to reduce exposures to lead in house dust have been reported (Lanphear *et al.*, 2000a; Galke *et al.*, 2001; Leighton *et al.*, 2003).

In a study by Schmitt *et al.* (1988) in the USA, soil samples taken from around the foundations of homes with wooden exteriors were found to have the highest lead concentrations (mean, 522 mg/kg) while concentrations around homes composed of brick were significantly lower (mean, 158 mg/kg). Lead concentrations up to 20 136 mg/kg were found in soil samples taken near house foundations adjacent to private dwellings with exterior lead-based paint. A state-wide study in Minnesota, USA, found that exterior lead-based paint was the major source of contamination in severely contaminated soils located near the foundations of private residences, while lead aerosols accounted for virtually all of the contamination of soils at some distance from the houses. Contamination due to lead-based paint was found to be highly concentrated over a limited area, while lead aerosols were less concentrated but more widespread (Minnesota Pollution Control Agency, 1987). (See also Section 1.4.1(*e*)).

Many countries have restricted the use of lead in paint. Leroyer *et al.* (2001) mention that lead in paint was banned in France in 1948. A lead concentration greater than 0.06% is not permitted in indoor paints sold in the USA (US DHUD, 1987). However, the lead content of paint remains unregulated in some countries (Nriagu *et al.*, 1996b). Ten per cent of lead metal used in India was reported to be used in the manufacture of paint, and wherever such paint is used there will be the potential for human exposure to lead (van Alphen, 1999). Results of a study of lead content of paint used in India are shown in Table 38. Of the 24 samples analysed, 17 had lead concentrations ≥ 0.5%, 13 had concentrations ≥ 1% and five had concentrations ≥ 10%. The lead in these paints was predominantly in the form of lead chromates (van Alphen, 1999).

(*h*) *Food*

A major source of lead for non-occupationally exposed adults is food and drink. The amount of lead intake from food is dependent on the concentration of lead in soil, air, water and other sources. Lead present in soils is taken up by food crops. Roots usually contain more lead than stems and leaves, while seeds and fruits have the lowest concentrations. In contrast, particulate lead present in air may adhere tenaciously to leafy vegetables. Leaves collected in or near urban areas have been shown to contain substantially elevated concentrations of lead. The use of leaded gasoline or the proximity of industries producing ambient emissions of lead can greatly influence lead concentrations in foodstuff. Therefore, caution is required with regard to concentrations of foodborne lead when extrapolating between regions and countries (WHO, 1995).

Typical lead concentrations in foodstuffs from some 30 countries are given in Table 39 (Galal-Gorchev, 1991a). Concentrations of lead in a variety of foodstuffs in the

Table 38. Lead content in some paints used in India

Paint colour[a]	Lead concentration (mg/kg)
Ultra white	< 1
White primer	< 1
White	< 1
Brown red	1
White	2
Phiroza	3
Oxford blue	3–6
Phorozi	5
Brown red	5
Brilliant white	6
Signal red	16
Bus green	32
New bus green	40
Deep green	50
Post office red	60–62
Mint green	61
Singal red	78
Tractor orange	114–130
Golden yellow	168–202

Adapted from van Alphen (1999)

[a] Paint samples from six companies in Bangalore and Chennai, India

USA, Canada, Latin America and the Caribbean, Africa, South Asia and Japan are shown in Tables 40–45, respectively. Lead concentrations of specific food items available in various countries are given in Tables 46–49. Studies from various countries on dietary lead intake by children and adults are listed in Tables 50–51. The section below presents a variety of specific sources of lead contamination in food.

(i) *Contamination of livestock*

Elevated concentrations of lead in the blood of cattle grazing near a lead smelter have been reported, although no inferences regarding lead in beef were made. Mean lead concentrations were highest in animals grazing near the smelter and decreased with increasing distance. Ingestion of soil along with the forage was thought to be the major source of lead (Neuman & Dollhopf, 1992).

Evidence has been shown for transfer of lead to milk and edible tissue in cattle poisoned by licking the remains of storage batteries which had been burned and left in a pasture (Oskarsson *et al.*, 1992). Concentrations of lead in muscle of eight acutely-sick cows that were slaughtered ranged from 0.14 to 0.50 mg/kg (wet weight basis). Normal lead concentrations in bovine meat from Sweden are < 0.005 mg/kg. Eight cows showing

Table 39. Representative concentrations of lead in foods[a]

Food category	Typical lead concentration (µg/kg)
Cereals	60
Roots and tubers	50
Fruit	50
Vegetables	50
Meat	50
Vegetable oils and fats	20
Fish	100
Pulses	40
Eggs	20
Nuts and oilseeds	40
Shellfish	200
Offal	200
Spices and herbs	300
Drinking-water	20
Canned beverages (lead-soldered cans)	200
Canned food (lead-soldered cans)	200

From Galal-Gorchev (1991a)

[a] Data collected from 30 countries in the Global Environmental Monitoring System/Food network

Table 40. Concentrations of lead in various foods in the USA

Food category	Concentration (µg/kg) range of mean
Dairy products	3–83
Meat, fish and poultry	2–83
Grain and cereal products	2–84
Vegetables	5–74
Fruit and fruit juices	5–53
Oils, fats and shortenings	2–28
Sugar and sweets, desserts	6–73
Canned food	16–649
Beverages	2–41

From US Environmental Protection Agency (1986a) Appendix 7D

Table 41. Concentrations of lead in various foods in Canada

Food category	Concentration (µg/kg) median (range)
Cereals, bread and toast (as prepared)	32.4 (11.5–78.3)
Water consumed directly	2.0 (0.25–71.2)
Coffee, tea, beer, liquor, sodas, etc. (as prepared)	8.8 (< 0.05–28.9)
Fruit juices, fruits (canned and fresh)	7.9 (1.5–109)
Dairy products and eggs	3.3 (1.21–81.9)
Starch vegetables, e.g. potatoes, rice	16.9 (5.5–83.7)
Other vegetables, vegetable juices and soups	31.7 (0.62–254)
Meat, fish, poultry, meat-based soups	31.3 (11–121)
Miscellaneous (pies, puddings, nuts, snack foods)	33.1 (13.6–1381)
Cheese (other than cottage cheese)	33.8 (27.7–6775)

From Dabeka *et al*. (1987)

no acute symptoms of poisoning were followed for 18 weeks. The mean lead concentration in milk 2 weeks after exposure was 0.08 ± 0.04 mg/kg; the highest concentration was 0.22 mg/kg. There was an initial rapid decrease in lead concentrations in milk during the first 6 weeks after exposure, after which the concentrations remained constant or increased slightly. Lead concentration in most milk samples was < 0.03 mg/kg 6 weeks after exposure. Two cows calved at 35 and 38 weeks post-exposure. The lead concentration in the blood of the cows at the time of delivery was high, which suggests mobilization of lead during the later stages of gestation and delivery. Lead concentrations in colostrum were increased compared to those in mature milk samples taken 18 weeks after exposure (i.e. during pregnancy), but decreased rapidly after delivery in mature milk to near the limit of detection.

Lead poisoning was observed in cattle and buffalo grazing near a primary lead–zinc smelter in India. Affected animals had a history of clinical signs characterized by head pressing, violent movement, blindness and salivation, and had high lead concentrations in blood (143 ± 1 µg/dL) and milk (0.75 ± 0.19 mg/L). Animals from the same pasture but without any history of clinical signs suggestive of lead poisoning had lower blood lead concentrations than the affected animals, but nonetheless higher than those reported for cattle in rural and urban areas of India (Dwivedi *et al*., 2001).

Analysis of animal feed and meat from cattle, horse (an important food animal) and sheep in a metal-processing region (Oskemen) of eastern Kazakhstan revealed high lead concentrations in many feed and meat samples (horse > cattle > sheep). The highest concentrations of lead were found in the liver and kidney, and lower concentrations in muscle and lung. A lead concentration of 2.2 mg/kg was found in horse liver (Farmer & Farmer, 2000).

Recreational and subsistence hunters consume a wide range of species including birds and mammals, some of which represent significant exposure to toxic agents, including

Table 42. Lead concentrations in foods in Latin America and the Caribbean

Country	Location	Food item	Main source of lead	Concentration mean ± SD or range of means (range)	Year(s) of study	Reference
Argentina	Buenos Aires	Cultivated vegetables (leaves)	Traffic	2 mg/kg	1975	Romieu *et al.* (1997)
	Mixed	White wine Red wine	NR NR	55 ± 36 µg/L 85 ± 55 µg/L	NR	Roses *et al.* (1997)
Brazil	Santo Amaro, Bahia	Vegetables	Smelter	(0.01–215 mg/kg)[a]	1980	Tavares (1991)
	All Saints Bay	Mussels			1994	Tavares (1996b)
	Mataripe (N)		Oil refinery	(12.0–57.9 mg/kg)[a]		
	Såo Bras (NW)		Downstream smelter	(1.36–22.5 mg/kg)[a]		
	Baiacu (SW)		No specific source	5.30 mg/kg[a]		
	Paraiba valley, S. Paulo	Cow's milk	Smelter	0.05 (0.01–0.20 mg/L)	1994	Okada *et al.* (1997)
	Ribeira do Iguape	Fish	NR	0.03–12 mg/kg	1994	Romieu *et al.* (1997)
Chile	Antofagasta (pre-Andean region)	Vegetables Potato skin	Rural areas, vulcanos	0.6–39.2 µg/kg[b] 94 µg/kg[b]	NR	Queirolo *et al.* (2000)
	Temucho Bay	Vegetables	NR	20 mg/kg	NR	Romieu *et al.* (1997)
Ecuador	Andean village:		Glazing of ceramic		NR	Counter *et al.* (2000)
	La Victoria	Cherries		6.3 ± 2.0 mg/kg		
		Tomatoes		119 ± 1.2 mg/kg		
		Corn		61.7 mg/kg (9.86–118.68 mg/kg)		
		Wheat grain		23.9 mg/kg		
		Kernels of wheat		0.75 mg/kg		
Honduras	Lago Yojoa	Fish	NR	0.30 mg/kg	NR	Romieu *et al.* (1997)
Mexico	Vera Cruz, Campeche and Tabasco	4 crustaceae and 7 freshwater fish	Industrial region	0.03–5.62 mg/kg	1972	Albert & Badillo (1991)[c]

Table 42 (contd)

Country	Location	Food item	Main source of lead	Concentration mean ± SD or range of means (range)	Year(s) of study	Reference
	Gulf of Mexico	Oyster	NR	ND–3.0 mg/kg	1976–87	
	Coatzacoalcos river	Fish	NR	0.1–2.84 mg/kg	1983	
	Laguna de Terminos	Oyster	March–May	2.4 (0.7–4.1)^{a} mg/kg	1985–86	
			June–October	5.5 (5.1–5.9)^{a} mg/kg		
			Dec–Feb	9.5 (8.5–10.5)^{a} mg/kg		
	N and NE Mexico districts	Alfalfa	NR	(0.4–2.5 mg/kg)	1980–81	
		Beans	NR	(0.3–3.5 mg/kg)		
	Commercially available	Milk in different forms	NR	5–88 µg/L	1982	
	Commercially available	Canned products (fish, fruits and vegetables)	NR	(ND–2.35 mg/kg)	1988	
	Commercially available	Canned fruits	NR	0.6–1.6 mg/kg	NR	Tamayo *et al.* (1984)
Trinidad and Tobago	Imported	Iodized salt	NR	6.4 mg/kg	NR	Romieu *et al.* (1997)
Uruguay	Seashore	Bivalve shell fish	NR	6–32 mg/kg	1992	Romieu *et al.* (1997)
Venezuela	States of Guarico and Portuguesa	Rice (commercially available)	NR	0.024–0.21 mg/kg	NR	Buscema *et al.* (1997)

SD, standard deviation; NR, not reported; ND, not detectable

[a] Dry weight

[b] Fresh weight

[c] Review including mainly reports and literature not easily accessible

Table 43. Lead concentrations in food in Africa (Nigeria)

Food item	Lead concentration (mg/kg)
Condensed or powdered milk	0.25–0.83
Beef	1.3
Plantains	0.2
Melon seeds	0.43
Water and bitter leaf	0.25–0.3
Gari flour	0.11
Yam tubers	0.35

From Ukhun *et al.* (1990)

Table 44. Lead concentrations in foods in some Asian countries

Country	Place/location	Food item	Concentration (mg/kg)[a] mean or range of means (range)	Reference
India	Nine localities of Greater Mumbai (high to negligible vehicle traffic)	Cereals	0.23–0.56	Khandekar *et al.* (1984)
		Pulses	0.54–0.88	
		Leafy vegetables	0.47–1.12	
		Other vegetables	0.042–0.16	
		Meat	0.40–0.46	
		Fruit	0.032–0.044	
		Milk	0.16	
	Commercially available	Five brands of beer	10.4–15.7 µg/L (8.0–18.0)	Srikanth *et al.* (1995a)
	Commercially available	Rice and other cereal products	0.189–0.332 (0.128–0.371)	Srikanth *et al.* (1995b)
	Rajasthan	Milk from cattle and buffalo	0.21–1.47 µg/L	Dwivedi *et al.* (2001)
	Nagpur	Milk		Patel *et al*. (2001)
		Infant formula	4.13 µg/L	
		Dairy	4.75 µg/L	
		Human	2.73 µg/L	
Kazakhstan	4 districts around a metal production center	Muscle, liver, kidney, lung	0.49–1.03 (horse) 0.86–2.22 (cattle) 0.06–1.16 (sheep)	Farmer & Farmer (2000)
Pakistan	Karachi	Cooked food	1.25–3.90	Rahbar *et al*. (2002)
South Asia	14 regions of south Asia	181 rice samples	0.0048–0.090[b] (ND–0.269)	Watanabe *et al.* (1989)
Thailand	Grazing land site near highway	Milk	14 µg/L	Parkpian *et al.* (2003)

ND, not detectable

[a] Unless specified otherwise

[b] Dry weight

Table 45. Estimated lead concentrations in foods and dietary lead intake in Japan, 2001

Food category	Lead intake (µg/day)	Lead intake (%)	Food intake[a] (g/day)	Estimated lead concentration[b] (µg/kg)
Rice	6.63	[28.4]	356.3	[18.6]
Other cereals and potatoes	3.42	[14.7]	162.6	[21.0]
Sugar and confectionary	0.55	[2.4]	90.7	[6.1]
Fat and oil	0.25	[1.1]	11.3	[22.1]
Pulses and pulse products	1.06	[4.5]	57.2	[18.5]
Fruits	1.64	[7.0]	132	[12.4]
Green yellow vegetables	1.23	[5.3]	93.6	[13.1]
Other vegetables and algae	2.09	[9.0]	175.7	[11.9]
Beverages	2.39	[10.3]	509.3	[4.7]
Fish and shellfish	1.62	[6.9]	94.0	[17.2]
Meats and eggs	1.25	[5.4]	113.1	[11.1]
Milk and dairy products	0.73	[3.1]	170.0	[4.3]
Prepared foods	0.34	[1.5]		
Drinking-water	0.11	[0.5]		
Total	23.31	[100.0]	2042	

From National Institute of Health Sciences, Japan (2000)
[a] From Ministry of Health, Labour and Welfare, Japan (2002)
[b] Lead intake divided by food intake

Table 46. Lead concentrations in cow's milk and infant formula

Product	Canada[a] 1986 median (range) (µg/kg)	Mexico[b] 1982 average (µg/kg)	USA[c] late 1980s average (µg/kg)
Fluid milk	1.19 (0.01–2.5)	5	
Evaporated milk			
Can	71.9 (27–106)	88	10
Cardboard container	–	9	
Infant formula		13	
Ready to use, lead-solder can	30.1 (1.1–122)		10
Ready to use, lead-free can	1.6 (1.5–2)		1
Powder formula	6.6 (3.7–19)		
Powdered milk[d]	–	21	

Table adapted from WHO (1995)
[a] From Dabeka & McKenzie (1987)
[b] From Olguín *et al.* (1982) cited by WHO (1995)
[c] From Bolger *et al.* (1991)
[d] The concentration of lead in milk consumed by the infant will be highly dependent on the concentration of lead in water used to dilute the powdered milk.

Table 47. Distribution of lead concentrations in table wines produced worldwide[a]

Range of lead concentrations (µg/L)	Number of samples ($n = 432$)	Percentage of total samples analysed
0–10	36	8.3
11–25	62	14.4
26–50	105	24.3
51–100	144	33.3
101–250	64	14.8
251–500	12	2.8
501–673	9	2.1

From US Department of the Treasury (1991)

[a] Wines produced in 28 different countries and commercially available in the USA

Table 48. Lead concentrations in rice consumed in various countries

Country/area	Lead content (µg/kg fresh weight)		
	N	GM	GSD
China	215	22.17	2.31
China (Province of Taiwan)	104	10.84	3.18
Colombia	22	8.09	2.80
Indonesia	24	39.07	2.26
Italy	15	6.97	3.28
Japan	788	5.06	2.64
Malaysia	97	9.31	2.61
Philippines	26	37.60	2.71
Republic of Korea	172	7.95	1.79
Saudi Arabia[a]	27	[57.5][b]	[2.34][b]
Thailand	13	8.75	2.28
USA	29	7.42	2.11

From Zhang *et al.* (1996), Al-Saleh & Shinwari (2001)

GM, geometric mean; GSD, geometric standard deviation; N, no. of samples

[a] Samples of rice imported from Australia ($n = 2$), Egypt ($n = 2$), India ($n = 17$), Thailand ($n = 4$) and USA ($n = 2$)

[b] Estimated from arithmetic mean and ± arithmetic SD of 134.8 ± 285.9 mg/kg by the moment method

Table 49. Lead concentrations in a variety of food items

Location	Source	Lead concentration	Reference
Canada	Apple juice stored in glazed earthenware	65/117 samples > 7 mg/L 19/147 samples 500–1000 mg/L	Klein *et al.* (1970)
Ontario, Canada	Water boiled in lead-soldered electric kettle	0.75–1.2 mg/L	Ng & Martin (1977)
New York, USA	Alcoholic beverages stored in crystal containers	0.01–21.5 mg/L	Graziano & Blum (1991)
South Carolina, USA	Mourning dove	Feathers, 465.7–2011.6 μg/kg dry wt Muscle, 81.7–142.9 μg/kg wet wt Liver, 188.3–806.1 μg/kg wet wt	Burger *et al.* (1997)
Kuwait	Seafood (fish, shrimp)	0.06–0.16 mg/kg wet wt	Bu-Olayan & Al-Yakoob (1998)
Iowa, USA	Mexican candy wrappers	810–16 000 mg/kg	Fuortes & Bauer (2000)

lead. Wild game may be contaminated through the environment or from lead bullets ingested by or embedded in the animal (Burger *et al.*, 1997, 1998).

(ii) *Contamination from food preparation, storage and tableware*

Lead present in food storage and serving vessels such as lead-soldered cans, ceramic dishes, cooking vessels, crystal glassware, and labels on food wrap and/or dishes can contaminate food. Acidic foods tend to leach more lead, but certain foods such as corn and beans are associated with greater release of lead than would be predicted from their acidity alone. Also, oxygen appears to accelerate the release of lead from food containers (WHO, 1995).

If food is stored in ceramic or pottery-ware that is lead-glazed and fired in a low-temperature kiln, lead can migrate from the glaze into the food. The glazing process uses a flux, a material that, at high temperatures, reacts with and helps dissolve the components of the glaze. Lead oxide is commonly used as flux. Factors determining whether, and to what extent, lead will migrate include the temperature and extent of firing of the pottery during the manufacturing process, the temperature and duration of food storage, the age of the pottery and the acidity of the food. It is extremely difficult to quantify the extent of such exposures in view of variations in manufacturing processes and quality control practised in the country of origin; however, exposure can be quite significant, particularly to infants (WHO, 1995). Gersberg *et al.* (1997) estimated that dietary exposure to lead from beans prepared in Mexican ceramic pottery may account for the major fraction of the blood lead in children whose families use such ceramic-ware.

Table 50. Estimated dietary lead intake in adults and children

Country	Population studied	Daily intake (µg/day)[a]		Reference
Adults				
Belgium[b]	Men and women	230	M	Fouassin & Fondu (1980)
Belgium[b]	Men and women	96[c]	D	Buchet *et al.* (1983)
Canada	Men and women	43[c]	D	Dabeka *et al.* (1987)
China	Women	46	D	Vahter *et al.* (1991a)
	Women	24.6		Ikeda *et al.* (2000a)
China (Province of Taiwan)	Women	19.5		Ikeda *et al.* (2000a)
Croatia	Women	15	D	Vahter *et al.* (1991a)
Finland	Men and women	66	M	Varo & Koivistoinen (1983)
Germany	Men and women	54–61		Kampe (1983)
India	Men and women	6.4–76.9		Parikh *et al.* (1999)
Italy	Men and women	140		[IAEA (1987)]
Japan	Women	31	D	Vahter *et al.* (1991a)
	Women	9.3		Ikeda *et al.* (2000a)
Malaysia	Women	7.0		Ikeda *et al.* (2000a)
New Zealand	Men and women	213	M	Pickston *et al.* (1985)
Philippines	Women	11.3		Ikeda *et al.* (2000a)
Republic of Korea	Women	21.5		Ikeda *et al.* (2000a)
Sweden	Men and women	27	M	Slorach *et al.* (1983)
	Women	26	D	Vahter *et al.* (1991a,b)
Thailand	Women	15.1		Ikeda *et al.* (2000a)
Turkey	Men and women	70		[IAEA (1987)]
United Kingdom	Men and women	110	M	Sherlock *et al.* (1983)
		71	D	Sherlock *et al.* (1983)
USA	Men and women	83	M	Gartrell *et al.* (1985a)
Children				
India	6–10 years	15.2–23.3		Raghunath *et al.* (1997)
	6–10 years	14.4–19.1		Raghunath *et al.* (1999)
Poland	0–1 year	225		Olejnik *et al.* (1985)
	1–3 years	259		
	7–18 years	316		
UK	Infant	1–2	breast milk or formula	Kovar *et al.* (1984)
USA	< 6 months	16–17	infant formula	Ryu *et al.* (1983)
	Infant	34	M	Gartrell *et al.* (1985b)
	Toddler	43	M	

Adapted from WHO (1995); Ikeda *et al.* (2000a)
References in square brackets could not be retrieved as original papers.
[a] M, market basket survey; D, duplicate diet study
[b] Populations studied from the same region
[c] Median value

Table 51. Estimated respiratory and dietary intakes of lead in various cities in Asia

Country, city	Route	Lead in air (ng/m^3)	Intake[a] (µg/day)	Uptake[b] (µg/day)	Total (µg/day)	Dietary/ total (%)
China, Beijing + Shanghai	Respiratory Dietary	60–540	2.70 23.1	1.35 1.16	2.50	46
Japan, Tokyo + Kyoto	Respiratory Dietary	70–81	1.13 9.0	0.57 0.68	1.24	54
Malaysia, Kuala Lumpur	Respiratory Dietary	30–462	3.69 7.0	1.85 0.53	2.37	22
Philippines, Manila	Respiratory Dietary	648	9.72 11.1	4.86 0.63	5.69	15
Thailand, Bangkok	Respiratory Dietary	210–390	4.29 15.1	2.15 1.13	3.28	34

From Ikeda *et al*. (2000a,b); data are on adult women and were based on studies in 1990s.
[a] Respiration volume was assumed to be 15 m^3/day.
[b] Uptake rates are assumed to be 50% in the lungs and 5–10% in the gastrointestinal tract.

Several studies have shown contamination of foods and beverages from lead used in the manufacture or repair of metal vessels. Coating the inner surface of brass utensils with a mixture of lead and tin, described as ‘tinning’, is widely practised by artisans in India. The tin–lead alloy contains 55–70% lead. Water boiled with tamarind in a tinned brass vessel for 5 min was found to contain 400–500 µg/L lead (Vatsala & Ramakrishna, 1985). Zhu *et al.* (1984) described 344 cases of chronic lead poisoning in Jiansu Province, China, in people who had drunk rainwater boiled in tin kettles. After boiling, the water contained 0.79–5.34 mg/L lead. Lead concentrations have also been shown to increase when water is boiled in kettles that contain lead in their heating elements. A study in India showed that although lead leaching from pressure cookers occurs during cooking, especially from the rubber gasket and safety valve, it is only a minor source of lead in cooked food (Raghunath & Nambi, 1998).

Lead-contaminated water may also contribute to foodborne lead where large volumes of water are used in food preparation and cooking, e.g. in foods prepared in boiling water. Experiments have shown that vegetables and rice cooked in water containing lead may absorb up to 80% of the lead in the water (Little *et al.*, 1981).

Trace metals, including lead, have been detected in human breast milk, thus breastfeeding could deliver lead to an infant. The reader is referred to Section 4.1.1(*a*)(v) for information on lead mobilisation in bones and transfer to breast milk during pregnancy and lactation. In a study in Australia, the mean lead concentration (± standard deviation) in breast milk from 21 lactating mothers was 0.73 ± 0.70 µg/kg (Gulson *et al.*, 1998a). Analysis of 210 human milk samples taken across Canada showed a mean lead concentration of 1.04 μg/kg (range, < 0.05–15.8 μg/kg) (Dabeka *et al.*, 1988). The median lead concentration in breast milk from 41 volunteers in Sweden was 2 μg/kg (range, 0.5–9.0 μg/kg) (Larsson *et al.*, 1981), whereas the mean value for breast milk 5 days postpartum from urban residents in Germany in 1983 was 13.3 μg/L (Sternowsky & Wessolowski, 1985). The concentration in 3-day postpartum milk samples from 114 women in Malaysia averaged 47.8 μg/L (Ong *et al.*, 1985).

Concentrations of lead in human milk vary considerably depending on the mother's exposure and occupation. Lead concentrations in the milk of a mother who had worked in a battery factory until 7 weeks before delivery decreased gradually from 19–63 to 4–14 μg/L in samples taken soon after delivery and those taken up to 32 weeks later, respectively (Ryu *et al.*, 1978). Lead concentrations in breast milk of 96 mothers in three districts (urban, mining area and rural) of Hubei, China averaged 76, 101 and 90 μg/L (geometric mean; $n = 21$, 11 and 32, respectively). The concentrations were very similar in colostrum and mature milk, and correlated well with blood lead concentrations (Wang *et al.*, 2000).

Gulson *et al.* (1998a) measured lead isotope ratios ($^{207}Pb/^{206}Pb$ and $^{206}Pb/^{204}Pb$) in mothers' breast milk and in infants' blood and established that, for the first 60–90 days postpartum, the contribution from breast milk to blood lead in the infants varied from 36% to 80%. Maternal bone and diet appeared to be the major sources of lead in breast milk.

Lead has also been reported in home-prepared reconstituted infant formula (breast-milk substitute). Lead concentrations in cows' milk and infant formula analysed in Canada, Mexico and the USA are shown in Table 46. Two of forty samples of infant formula collected in a study in the Boston area of the USA had lead concentrations > 15 μg/L. In both cases, the reconstituted formula had been prepared using cold tap-water run for 5–30 sec, drawn from the plumbing of houses > 20 years old. It was concluded that three preparation practices for infant formula should be avoided: (1) excessive water boiling, (2) use of lead-containing vessels and (3) use of morning (first-draw) water (Baum & Shannon, 1997).

Canning foods in lead-soldered cans may increase concentrations of lead in foods 8–10-fold. In 1974, for example, the lead concentration in evaporated milk in lead-soldered cans was 0.12 μg/g; in 1986, after these cans had been phased out, the concentration dropped to 0.006 μg/g (Capar & Rigsby, 1989). The lead content in canned foods in the USA dropped from an overall mean of 0.31 μg/g in 1980 to 0.04 μg/g in 1988 (National Food Processors Association, 1992). The production and use of three-piece lead-soldered cans ceased in 1991 in the USA. However, older lead-soldered cans may still be present in some households (ATSDR, 1999). Dabeka and McKenzie (1987, 1988) found that the intake of lead by 0–1 year-old infants fed infant formula, evaporated milk and concentrated liquid formula stored in lead-soldered cans exceeded the provisional tolerable weekly intake (PTWI) of 25 μg/kg body weight (bw) lead set by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) in 1993 (FAO/WHO, 1993). This value does not include lead in water used to prepare infant formula. Mean intakes far in excess of the PTWI were obtained in studies carried out in areas with high lead content in tap-water (Galal-Gorchev, 1991b).

Lozeena, a bright orange powder from Iraq used to colour rice and meat, can contain 7.8–8.9% lead (CDC, 1998).

Lead may leach from lead crystal decanters into the liquids they contain. Three samples of port wine with an initial concentration of 89 µg/L lead were found to have lead concentrations of 5331, 3061 and 2162 µg/L after storage for four months in crystal decanters containing 32%, 32% and 24% lead monoxide, respectively (Graziano & Blum, 1991). Lead was also found to elute from lead crystal wine glasses within minutes. Mean lead concentrations in wine contained in 12 glasses increased from 33 µg/L initially to 68, 81, 92 and 99 µg/L after 1, 2, 3 and 4 h, respectively (Graziano & Blum, 1991). [See comments on this article in de Leacy, 1991; Zuckerman, 1991].

(iii) *Alcoholic beverages*

In addition to contamination from lead crystal glass, contamination of alcoholic beverages with lead may occur in several ways. For example, from lead solder used to repair casks or kegs and tap lines, from lead capsules used as seals on wine bottles, or from residues of lead arsenate pesticides in soils. Alcoholic beverages tend to be acidic and there is the possibility for large amounts of lead to dissolve during preparation, storage or serving (WHO, 1995). Wai *et al.* (1979) showed that wine can react with the lead capsule to form lead carbonate, which may dissolve in the wine during storage and pouring. In one study, lead concentrations in wine on the Swedish market ranged between 16 and 170 µg/L (Jorhem *et al.*, 1988). The analysis of 432 table wines originating from many countries and sold in the USA is summarized in Table 47. In a study of the lead content of Argentinian wines, red wine was found to have 50% higher lead concentrations than white wine, average values being 85 and 55 µg/L, respectively (Roses *et al.*, 1997).

Sherlock *et al.* (1986) found that in the UK the majority of canned and bottled beer (90 and 86% respectively) contained less than 10 µg/L lead. Draught beers typically contained higher lead concentrations, with 45% having concentrations > 10 µg/L, 16% having concentrations > 20 µg/L and 4% having concentrations > 100 µg/L. The higher lead concentrations in draught beers are thought to be due to the draught-dispensing equipment which may contain brass or gunmetal, both of which contain low but significant amounts of lead.

The analysis of lead concentration in five different beer brands in India showed that all brands had a mean lead concentration > 10 µg/L, with an overall mean of 13.2 µg/L. Assuming the lead concentration in beer to be 13 µg/L, the uptake of lead from beer to be 20% and consumption by three types of consumer to be 1, 5 or 10 L/week, this would result in a lead uptake of 2.6, 13 and 25 µg/week, respectively (Srikanth *et al.,* 1995a).

Illicit ‘moonshine’ whiskey made in stills composed of lead-soldered parts (e.g. truck radiators) may contain high concentrations of lead. Lead was detected in 7/12 samples of Georgia (USA) moonshine whiskey, with a maximum concentration of 5300 µg/L (Gerhardt *et al.*, 1980). In a more recent study, regular consumers of moonshine whiskey (15/49 subjects) had blood lead concentrations > 50 µg/dL (Morgan *et al.*, 2001).

In general, alcoholic beverages do not appear to be a significant source of lead intake for the average person.

(iv) *Fish and seafood*

The uptake and accumulation of lead by aquatic organisms from water and sediment are influenced by various environmental factors such as temperature, salinity and pH, as well as humic and alginic acid content of the sediment. In contaminated aquatic systems, only a minor fraction of lead is dissolved in the water. Lead in fish is accumulated mostly in gill, liver, kidney and bone. In contrast to inorganic lead compounds, tetraalkyllead is rapidly taken up by fish and rapidly eliminated after the end of exposure (WHO, 1989).

The Fish and Wildlife Service in the USA reported on the concentration of selected metals in 315 composite samples of whole fish collected at 109 stations nationwide in 1984–85. For lead, the geometric mean was 0.11 mg/kg (wet weight), with a maximum of 4.88 mg/kg. Lead concentrations in fish declined steadily from 1976 to 1984, suggesting that reduction in use of leaded gasoline and controls on mining and industrial discharges have reduced lead concentrations in the aquatic environment (Schmitt & Brumbaugh, 1990).

Recreational and subsistence fishers consume larger quantities of fish and shellfish than the general population and frequently fish the same waterbodies routinely. Thus, these populations are at greater risk of exposure to lead and other chemical contaminants if the waters they fish are contaminated. Ingestion of lead is also a matter of concern in regular consumers of seafood produced near industrial areas such as in All Saints Bay and Ribeira do Iguape in Brazil (Tavares, 1996a,b), as well as in Uruguay (Romieu *et al.*, 1997).

(v) *Rice and cereals*

Rice is an important source of lead intake, particularly in east and south-east Asia where rice is a staple component of the diet. Lead concentrations in rice consumed in some areas in Asia, Australia, Europe and North America are summarized in Table 48. The data show a substantial variation from < 10 to about 40 µg/kg fresh weight (Zhang *et al.*, 1996; Al-Saleh & Shinwari, 2001a). In a study performed by Watanabe *et al.* (1989), rice samples were collected in 15 areas of Asia and Australia (192 samples), and in four areas in other parts of the world (15 samples). Lead concentrations were distributed log-normally, with a geometric mean ± geometric standard deviation of 15.7 ± 3.5 µg/kg and concentrations ranging from 5 µg/kg in Japan to 90 µg/kg in India.

Lead in rice has been estimated to represent 28% (National Institute of Health Sciences, Japan, 2000; see Table 45), 14% (Zhang *et al.*, 2000), 12% (Moon *et al.*, 1995) and < 5% (Zhang *et al.*, 1997a) of dietary lead intake in a series of studies in China, Japan and the Republic of Korea. In Japan, dietary lead intake has decreased on average from 33 µg/day in 1980 to 7 µg/day in 1990, partly as a result of a decrease in rice consumption (Watanabe *et al.*, 1996).

Cereals other than rice, e.g. millet and maize, may also be important sources of dietary lead. The lead concentration in these cereals (43–47 μg/kg) is higher than that in rice (20–21 μg/kg) or wheat (26–30 μg/kg) (Zhang *et al*., 1997b). In one study in China, lead from all cereals accounted for 26% of total dietary lead intake (Watanabe *et al*., 2000). Lead intake from rice in Japan was found to be 1.5 times that from wheat in 1998–2000 (Shimbo *et al*., 2001).

The contribution of lead in rice and cereal products to the total dietary intake of lead in southern India varies among different socioeconomic groups, based on occupation and choice of consumption. It has been suggested that rice is the major source of lead among the rural and economically-deprived populations, but sources of dietary lead appeared to be more diverse in the urban middle-class and the economically-privileged (Srikanth *et al.,* 1995b).

(vi) *Daily intake through food*

Estimates of daily dietary intakes of lead by adults and children worldwide are presented in Table 50. The available data indicate a general decrease in those areas where the concentration of lead in gasoline has decreased and those where a concerted effort has been made to avoid lead-soldered cans for food storage (Bolger *et al*., 1991; OECD, 1993). Similar decreases in other countries are expected to occur when similar actions to eliminate these sources of lead exposure are taken.

Dietary lead intake by adult women in several Asian cities, in comparison with amounts of lead inhaled, is presented in Table 51. The ratio of dietary to total lead intake varied primarily as a reverse function of the lead concentration in atmospheric air (Ikeda *et al*., 2000a). In Mumbai, India, where atmospheric lead concentrations in different zones of the city varied between 82 and 605 ng/m^3, the daily lead uptake by a nonsmoker living in the city area was estimated to be 33 μg, of which 75% come from food. For a suburban resident, 85% of the lead intake was estimated to come from food (Khandekar *et al.,* 1984).

(*i*) *Plants and fertilizers*

Lead occurs naturally in plants both from deposition and uptake; there is a positive linear relationship between lead concentrations in soil and in plants. As with other environmental compartments, measurement of ‘background’ concentrations of lead in plants is complicated by the general contamination of the environment from centuries of lead use, which has included direct application of lead-containing chemicals in agriculture and contamination of fertilizers with lead (WHO, 1995).

Lead has been detected in a superphosphate fertilizer at concentrations as high as 92 mg/kg (WHO, 1995). Sewage sludge, used as a source of nutrients in agriculture, may contain concentrations of lead > 1000 mg/kg; concentrations as high as 26 g/kg have been measured in the USA (WHO, 1995). In a study of soil that had received heavy sludge applications over years in the United Kingdom, the lead concentration was found to be 425 mg/kg, compared with 47 mg/kg in untreated soil (Beckett *et al*., 1979).

Lead concentrations in grass and water plants in Asia are shown in Table 52.

Table 52. Lead concentrations in terrestrial and aquatic plants in Asia

Country	Location	Year(s) of study	Source of contamination	Plant[a]	Concentration (mg/kg) mean ± SD or range of means	Reference
India	Koraput	NR	NR	*Ipomea aquatic*	83.3 ± 4.2	Chandra *et al*. (1993)
				Trapa natans	68.5 ± 2.1	
	Unnao		(summer)	*Trapa natans*	54.5 ± 2.0	
				Ipomea aquatica	46.6 ± 1.5	
			(winter)	*Trapa natans*	1030.0 ± 51.5	
				Ipomea aquatica	845.0 ± 40.0	
	Eastern Ghats (Koraput, Orrisa)	NR	Local industries	*Spirodela polyrrhiza*	27 ± 1.6	Rai *et al*. (1996)
				Pistia stratiotes	29 ± 0.8	
	Mumbai	NR	Lead industries	Grass	145–1048	Nambi *et al*. (1997)
				Control grass	1.42	
	Lake Nainital	1997	NR	*Microcystis aeruginosa*	46 ± 2.5	Ali *et al*. (1999)
				Spirogyra adnata	95 ± 4.2	
				Salix babylonica (root)	37 ± 2.7	
	Residential area of greater Kolkata	1996	Lead factory	Leaf samples	214 ± 17	Chatterjee & Banerjee (1999)
	4 lakes and pounds in Lucknow	1998	NR	*Trapa natans*	75–375	Rai & Sinha (2001)
	Pond in North-Bihar	1996–97	NR	*Euryale ferox* Salisb.	331.6–1256.6	Rai *et al*. (2002)
Kazakhstan	Six districts in the East	NR	Metal production centre	Hay & pasteur grasses	1.6 ± 0.01–19.4 ± 6.2	Farmer & Farmer (2000)
Thailand	Tropical grazing land site	NR	NR	Grass	0.76– 6.62	Parkpian *et al*. (2003)

NR, not reported

[a] Names in italics are aquatic plants.

Phytoremediation

Currently, lead-contaminated soils are being remediated by a variety of engineered technologies such as isolation and containment, mechanical separation, pyrometallurgical separation, the use of permeable treatment walls, and by soil flushing and soil washing, but these methods are expensive and not feasible at all sites (Mulligan *et al.* 2001). Phytoremediation — the use of plants for removal of pollutants and restoration of the environment — is an emerging clean-up technology for which various reviews provide information on important aspects (Salt *et al.*, 1995; Cunningham & Ow, 1996; Chaney *et al.*, 1997; Salt *et al.*, 1998).

For lead remediation, phytoextraction is the more attractive and much better studied method. Phytoextraction is the uptake of metal by roots and its accumulation in the part of the plant above ground, i.e. the shoot. Plants that are capable of accumulating more metal than 0.1% of dry weight of shoot are considered to be suitable for phytoextraction. There are various reports concerning accumulation and phytoextraction of lead (Table 53).

The basic problems with lead phytoextraction are the low bioavailability of lead in soil and its poor translocation from root to shoot. Of all toxic heavy metals, lead is the least phytoavailable. Water-soluble and exchangeable lead that is readily available for uptake by plants constitutes only about 0.1% of total lead in most soils (Huang *et al.*, 1997). Soil properties influence its uptake and translocation. In addition, only a few higher plants are known to hyperaccumulate lead, mainly owing to the very low translocation of lead from the root to the shoot. Piechalak *et al.* (2002) demonstrated up to 95% lead accumulation in the roots of *Vicia faba, Pisum sativum* and *Phaseolus vulgaris* but only 5–10% was transported to parts above ground (see Table 53).

To overcome these problems, a chelate is used to increase uptake rate and to increase lead translocation from roots to shoots. Of the many chelates, EDTA has been found to be the most appropriate. EDTA solubilizes soil lead and increases its translocation from root to shoot. It has also been shown to increase rate of transpiration, an important factor in lead phytoextraction (Wu *et al.* 1999). However, there are concerns about side-effects associated with chelate application. Lead EDTA easily percolates through the soil profile and causes groundwater pollution.

A number of plants used in phytoremediation are crop plants (see Table 53) and thus there is a potential risk that plants grown as part of phytoremediation programmes will re-enter the food chain. Furthermore, a number of algae and other plant species accumulate lead. Such species, if ingested by fish, could also re-cycle lead into the food chain. Recently, a study presented the development of a plant genetically modified to accumulate lead, which seems promising for phyto-remediation (Gisbert *et al.*, 2003).

Phytoremediation does have its limitations. It is a slower process than the traditional methods. Plants remove or degrade only small amounts of contaminants each growing season, so it can take several decades to clean up a site adequately. There are limits to plant growth such as temperature, soil type and availability of water. Lastly, most plants are

Table 53. Lead accumulation/biosorption and detoxification by plants

Plant	Treatment	Lead accumulation/ phytoextraction[a]	Reference
Zea mays shoot	20–100 μM $Pb(NO_3)_2$ in nutrient solution	Accumulation: 400–500 mg/kg	Huang & Cunningham (1996)
	Lead concentration in soil, 2500 mg/kg; treatment with HEDTA at 2 g/kg for 7 days	Phytoextraction: 10 600 mg/kg dw	
Brassica juncea shoot	Lead concentration in soil, 1200–1800 mg/kg	Accumulation: 45–100 mg/kg	Blaylock *et al.* (1997)
	600 mg/kg Pb: 10 mmol/kg EDTA 0.5 mmol/kg EDTA	Phytoextraction: ~ 15 000 mg/kg 5000 mg/kg	
Zea mays, Pisum sativum shoots	Lead concentration in soil, 2500 mg/kg; treatment with HEDTA at 2 g/kg for 7 days	Phytoextraction: ~ 10 000 mg/kg	Huang *et al.* (1997)
Brassica juncea shoot	Lead concentration in soil, 0.5 mM; treatment with EDTA at 0.75 mM for 48 h	Phytoextraction: 11 000 mg/kg dw[b]	Vassil *et al.* (1998)
Helianthus annuus	1 mM $Pb(NO_3)_2$ in nutrient solution from emergence of 1st pair of leaves until growth of 3rd pair of leaves	Accumulation: shoot, 11 027 mg/kg dw roots, 17 149 mg/kg dw	Kastori *et al.* (1998)
Vicia faba	1 mM $Pb(NO_3)_2$ treatment for 96 h	46 mg/g dw (in root)	Piechalak *et al.* (2002)
Pisum sativum		50 mg/g dw (in root)	
Phaseolus vulgaris		75 mg/g dw (in root)	

[a] Accumulation refers to the natural lead uptake by the plant from soil or a nutrient solution; phytoextraction refers to lead uptake following addition of a synthetic chelating agent to the lead-contaminated soil to improve the bioavailability of the lead.

[b] The value was 400 times higher than in untreated controls.

unable to grow on heavily-contaminated soils, thus only lightly-contaminated soils can be phytoremediated.

(*j*) *Others*

Table 54 presents some data on lead concentrations in other sources of exposure.

(i) *Traditional medicine*

Some traditional medicines and customs have been found to result in exposure to high concentrations of lead, most of which cannot be quantified with any degree of accuracy. Rather than occurring as trace ingredients or trace contaminants, various lead compounds

Table 54. Lead concentrations in various sources of exposure

Location	Source	Lead concentration	Reference
Traditional remedies			
Arizona, USA	'Greta', 'azarcon'	77 000–941 000 mg/kg	Baer *et al.* (1989)
Zabreb, Croatia	Metal-mineral tonics	0.90–72 900 mg/kg	Prpic-Majic *et al.* (1996)
Cosmetics			
Morocco, UK, USA	Eye make-up (kohl) from Eastern Mediterranean countries	< 100–696 000 mg/kg	Parry & Eaton (1991)
Others			
Arizona, USA	Pool cue chalk	1–14 080 mg/kg	Miller *et al.* (1996)
Wisconsin, USA	Dental intraoral radiograph film storage boxes (lead oxide)	3352 μg (range, 262–34 000)[a]	CDC (2001)

[a] Average amount of lead present on wipe samples from eight film packets stored in lead-lined boxes

are used as major ingredients in traditional medicines in numerous parts of the world (Trotter, 1990). Lead concentrations in some traditional and complementary medicines are shown in Table 55.

Leaded 'kohl', also called 'Al kohl', is traditionally applied to the raw umbilical stump of the newborn in the belief of a beneficial astringent action. Lead metal and lead sulfide are used for inhalation of the fumes ('Bokhoor') produced from heating on hot coals, in the belief that this will ward off the devil and calm irritable infants and children (Fernando *et al.*, 1981; Shaltout *et al.*, 1981). An Asian remedy for menstrual cramps known as Koo Sar was reported to contain lead in concentrations as high as 12 mg/kg (CDC, 1999). The source of lead was thought to be the red dye used to colour the pills. The Hindus use as a treatment for diabetes ground seeds and roots, which were found to contain 8000 mg/kg lead (Pontifex & Garg, 1985).

Latin-American countries also report the use of traditional medicines with high lead concentrations. For example, the Mexican traditional remedies 'azarcon' (lead tetroxide) and/or 'greta' (mixed lead oxides), distributed as finely ground powders, may contain more than 70% lead. They are used in the treatment of 'empacho', a gastrointestinal disorder considered to be due to a blockage of the intestine (Trotter, 1990).

Some Chinese herbal medicines have metallic lead added to them (up to 20 000 mg/kg) to increase their weight and sale price (Wu *et al.*, 1996). Lead contaminants also are present in some calcium supplements; 17 of 70 brands tested had lead concentrations leading to a daily intake greater than the provisional total tolerable daily intake of 6 μg (Bourgoin *et al.*, 1993).

Table 55. Lead concentrations in herbal and folk medicines

Medicine	Concentration (µg/g)[a]	Prescribed for (where indicated)
Saptamrut loh	5.12	
Keshar gugal	2.08	
Punarvadi gugal	1.99	
Trifla gugal	4.18	
Ghasard	16 000	
Bala goli	25	
Kandu	6.7	
Arogyavardhini	63.2	Liver disease
Sankhvati	13.0	
Brahmivati	27 500	
Chyavan prash	7.30	
Trivanga bhasma	261 200	Diabetes
Diabline bhasma	37 770	Diabetes
Hepatogaurd	0.4	Liver disease
Basant malti	276 to 42 573	
Pushap Dhanva Ras	79.3 mg/tablet	
Shakti	55.9 mg/tablet	
Solution	5.27 µg/mL	Leg abscess
Powders	2.6–105 200	Leg abscess
Tablets	1.0–2816.7	Leg abscess

From Dunbabin *et al.*, (1992); Nambi *et al.* (1997)
[a] Unless otherwise specified

Medicinal herbs may be a potential source of lead exposure; analysis of 28 species showed lead concentrations (arithmetic mean ± arithmetic standard deviation) of 2.6 ± 0.4 mg/kg to 32.8 ± 3.1 mg/kg fresh weight (Dwivedi & Dey, 2002).

(ii) *Cosmetics*

Hair dyes and some cosmetics may contain lead compounds. Commercial hair dyes typically contain 3000–4000 mg/kg lead (Cohen & Roe, 1991). A later survey reported hair dyes formulated with lead acetate, with lead concentrations of 2300–6000 mg/kg (Mielke *et al*., 1997b). Lead acetate is soluble in water and easily transferred to hands and other surfaces during and following application of a hair dye product. Measurements of 150–700 µg of lead on each hand following such applications have been reported (Mielke *et al*., 1997b). In addition, lead is transferred by hand to mouth of the person applying the product, and to any other surface (comb, hair dryer, outside of product container, counter top) that comes into contact with the product. A dry hand passed through dry hair dyed with a lead-containing cream has been shown to pick up about 280 µg lead (Mielke *et al.,* 1997b).

Some traditional eye cosmetics produced locally may contain lead compounds, and their application, also to children, may result in lead exposure. Sprinkle (1995) reported blood lead concentrations of 9–24 µg/dL in nine children aged 3 months–5 years receiving daily application of such cosmetics, whereas concentrations of 2–6 µg/dL were found in nine children aged 1–6 years who had no or unknown application. Patel *et al.* (2001) also reported elevated blood lead concentrations (20.2 ± 13.0 µg/dL) in 45 children aged 6 months–6 years in India who used eye cosmetics daily.

Cosmetics used by Chinese opera actors may also contain lead (Lai, 1972).

(iii) *Ammunition*

Use of lead ammunition may result in exposure to lead dust, generated during gun or rifle discharge, at concentrations up to 1000 µg/m^3 (Elias, 1985), from lead pellets ingested by or embedded in animals that are used as food source (Burger *et al.*, 1997), and from lead pellets embedded in humans from shooting incidents (Manton, 1994; IARC, 1999). Firing-range instructors and employees may be exposed to high concentrations of lead and may show elevated blood lead concentrations (see Section 1.4.3.e).

(iv) *Miscellaneous*

Cigarette tobacco contains 2–12 µg of lead per cigarette (IARC, 2004a); the mean concentration of lead in filter-tipped cigarettes produced between 1960 and 1980 was 2.4 mg/kg. Up to 6% of lead may be inhaled, while the remainder is present in the ash and sidestream smoke (IARC, 2004a). Smoking a pack of 20 cigarettes per day, with 12 µg lead per cigarette, and inhaling 6% of the smoke, would result in daily exposure to 14 µg lead.

So-called recreational drug users who ‘sniff’ leaded gasoline vapours are at risk of toxic effects from organolead compounds as well as the hydrocarbon components of gasoline (Edminster & Bayer, 1985).

A lead poisoning hazard for young children exists in certain vinyl miniblinds that have had lead added to stabilize the plastic. Over time, the plastic deteriorates to produce lead dust that can be ingested when the blinds are touched by children who then put their hands in their mouths (Consumer Product Safety Commission, 1996; Norman *et al.*, 1997; West, 1998).

(*k*) *Blood lead concentrations from specific sources of exposure*

Blood lead concentrations resulting from exposure to a variety of specific sources, reported mainly as case reports, are presented in Table 56.

1.4.2 *Exposure of the general population*

Blood lead concentration is the most commonly used estimate of exposure to lead in the general population. Numerous reports show blood lead concentrations declining over time in many parts of the world, thereby validating global efforts to reduce lead exposures.

Table 56. Blood lead concentrations from various sources of exposure

Location	Source	Blood lead[a] (µg/dL) individual values or range[a]	Reference
Air dust			
New York, USA	Burning of newspapers in fireplace	35	Perkins & Oski (1976)
New York, USA	Dust at home from workers' clothing	Mean, 41.6–73.3	Baker *et al*. (1977)
California, USA	Dust on clothes from occupational exposure	31–36	Gerson *et al*. (1996)
New York, USA	Dust from removal of lead-based paint	20–> 80	CDC (1997a)
La Victoria and El Tejar, Ecuador	Tile-glazing activities	Median, 60 (range, 12–106)	Vahter *et al*. (1997)
Food/food containers			
Hawaii, USA	Lead-bearing cocktail glasses	131–156	Dickinson *et al*. (1972)
Ontario, Canada	Water heated in lead-soldered electric kettles	35–145	Ng & Martin (1977)
Seattle, USA	Ceramics from southern Italy	74 and 144	Wallace *et al.* (1985)
Nablus district, Israel	Contaminated flour	Mean, 80–122 (range, 42–166)	Hershko *et al*. (1989)
Vancouver, Canada	Water heated in a lead-soldered electric kettle	147–154	Lockitch *et al*. (1991)
Hungary	Contaminated paprika (lead tetraoxide)	18.8–213	Kákosy *et al*. (1996)
Vermont, USA	Apple cider prepared in lead-soldered evaporator	33–40	Carney & Garbarino (1997)
California, USA	Tamarindo candy	26–59	CDC (1998)
Michigan, USA	Lozeena (powdered food colouring)	25–84	CDC (1998)
Georgia, USA	Moonshine whiskey	> 50[b]	Morgan *et al*. (2001)
California, USA	Tamarindo candy and/or folk remedies	22–88	CDC (2002)

Table 56 (contd)

Location	Source	Blood lead[a] (µg/dL) individual values or range[a]	Reference
Traditional remedies			
California, USA	Azarcon	27–45	CDC (1981)
Minnesota, USA	'Pay-loo-ah'	60	CDC (1983)
Saudi Arabia	Traditional remedies	134–277	Abu Melha *et al.* (1987)
Guadalajara, Mexico	Azarcon (lead tetraoxide)	Blood, 29.6; urine, 49.4 µg/L	Cueto *et al.* (1989)
California, USA	Indian herbal medicine	71–80	Smitherman & Harber (1991)
California, USA	Azarcon, greta	20–86	CDC (1993)
New York, USA	Contaminated *hai ge fen* (clamshell powder)	76	Markowitz *et al.* (1994); Hill & Hill (1995)
Zagreb, Croatia	Ayurvedic metal-mineral tonics	2.6–92.1	Prpic-Majic *et al.* (1996)
Connecticut, USA	'Koo Sar' pills (Asian remedy for menstrual cramps)	42–44	CDC (1999)
Australia	Herbal remedy	Mother, 108; newborn, 244	Tait *et al.* (2002)
Cosmetics			
Nottingham, United Kingdom	Surma	Mean, 34.2	Ali *et al.* (1978)
California, USA	Traditional eye cosmetics (surma, kohl, alkohl)	Mean, 12.9	Sprinkle (1995)
Ammunition			
Texas, USA	Old gunshot wound	353	Dillman *et al.* (1979)
Texas, USA	Retained projectiles (bullets, shrapnel, buckshot)	Blood, 40–525; urine, 55–720 µg/L	Linden *et al.* (1982)
Florida, USA	Ingestion of 206 bullets	391	McNutt *et al.* (2001)
Saskatchewan, Canada	Air rifle pellets	35–56	Treble & Thompson (2002)

Table 56 (contd)

Location	Source	Blood lead[a] (µg/dL) individual values or range[a]	Reference
Others			
Oregon, USA	Curtain weight	238	Blank & Howieson (1983)
Maningrida, Australia	Petrol sniffing	42–92	Eastwell *et al.* (1983); Watson (1985)
Australia	Petrol sniffing	105	Burns & Currie (1995)
New York, USA	Ornamental clothing accessory	144–150	Esernio-Jenssen *et al.* (1996)
Hospital nurseries in the USA	Blood transfusions	Mean, 3.5 (range, 2–7)	Bearer *et al.* (2000, 2003)

[a] Unless stated otherwise
[b] Blood lead concentration in 15/38 patients

Representative data on blood lead concentrations are presented by region in Tables 57–64, and in the text by population subgroup: adults, pregnant women and neonates, and children.

(*a*) *Adults*

The UNEP/WHO Global Study to assess exposure to lead and cadmium through biological monitoring was one of the first international reliable studies with quality assurance. The geometric mean concentration of lead in blood in different populations ranged from 6 µg/dL in Beijing (China) and Tokyo (Japan) to 22.5 µg/dL in Mexico City (Mexico). The values were below 10 µg/dL in Baltimore (USA), Jerusalem (Israel), Lima (Peru), Stockholm (Sweden) and Zagreb (Serbia and Montenegro), and between 10 and 20 µg/dL in Brussels (Belgium) and Ahmedabad, Bangalore and Kolkata (India) (Friberg & Vahter, 1983).

Data from central and eastern Europe show relatively high levels of background exposure to lead at the time of the dissolution of the former Soviet Union (Table 57). There have been concerted efforts to lower exposure by phasing out the use of leaded gasoline and by controlling emissions from industries (Regional Environmental Center for Central and Eastern Europe, 1998).

In the USA, the extent of recent exposures to lead in the general population has been estimated based on blood lead measurements from the National Health and Nutrition Examination Surveys (NHANES). Geometric mean blood concentrations in adults aged

Table 57. Lead concentrations in blood in adults and children in central and eastern European countries

Country	City or area	Year(s) of study	Population	Blood lead (µg/dL) mean or range
Bulgaria	Momchilgrad	1991	Children, 5–7 years old	11.4
	Momchilgrad	1991	Teenagers, 12–14 years old	11.6
	Krichim	1991	Children	9.2
	Kurtovo Konare	1991	Children and teenagers	17.0
	Haskovo	1995	Children, 5–7 years old	10.1
	Haskovo	1995	Teenagers, 11–12 years old	11.4
	Nationwide	1995–96	Adults (men+women)	15
Czech Republic	Pribram	1992–94	Children, 1–3 years old	14.66; 6.61; 4.95[a]
			Children, 4–7 years old	10.2; 4.95; 4.67
			Children, 8–11 years old	12.50; 5.37; 4.51
			Teenagers, 12–14 years old	7.21; 4.84; 4.69
Hungary	Budapest	1992	–	11.9
	Sopron	1993	–	11.6
	Local	1994	–	7.4
	National	1995	–	6.26
	Budapest	1996	–	6.5
Poland	Five towns with no industrial lead emitters	1992–94	Men	4.25–7.68
			Women	2.38–4.83
			Children	2.39–6.23
	Based in the vicinity of zinc and copper mills	1992–94	Men	9.85–15.90
			Women	4.94–10.50
			Children	7.37–11.40
Romania (six areas of Bucharest)	North Railway Station	1983–85	Children	17.1
	Balta Alba	1983–85	Children	18.40
	Center	1983–85	Children	20.20
	Giurgiuhu	1983–85	Children	21.93
	Militari	1983–85	Children	17.84
	Pantelimon	1983–85	Children	20.51
Slovakia	Bratislava	1993	Children	3.65
	Middle Slovakia	1995	Children	4.5
	North Slovakia	1996	Children	3.04

From the final report of the National Integrated Program on Environment and Health Project (1995), presented in Regional Environmental Center for Central and Eastern Europe (1998)

–, not stated

[a] Geometric mean values for subjects living at distances from the lead smelter of less than 3 km, 3–5 km, and over 5 km, respectively

Table 58. Lead concentrations in blood in adults and children in the USA

Years of survey	Population	No. of subjects	Average age (years)	Smokers	Blood lead (µg/dL)		Reference
					GM	95% CI	
1976–80	Men + women	5537	20–74	Included	13.1	12.7–13.7	Pirkle *et al.* (1994)
1988–91	Men + women	6922	20–74	Included	3.0	2.8–3.2	Pirkle *et al.* (1994)
1999–2000	Men + women	4207	≥ 20	Included	1.8	1.67–1.83	CDC (2003a)
1978–80	Children	2271	1–5	–	15.0	14.2–15.8	Pirkle *et al.* (1994)
1988–91	Children	2234	1–5	–	3.6	3.3–4.0	Pirkle *et al.* (1994)
1991–94	Children	2392	1–5	–	2.7	2.5–3.0	CDC (1997b)
1999–2000	Children	723	1–5	–	2.2	2.0–2.5	CDC (2003a)

[a] GM, geometric mean; CI, confidence interval

20 years or older have declined by 87% from 13.1 µg/dL in 1976–80 to 1.75 µg/dL in 1999–2000 (Table 58). Concentrations were higher in men than in women, and higher in Mexican-Americans and non-Hispanic blacks than in non-Hispanic whites. In general, blood lead concentrations in adults increase slowly with age (Pirkle *et al.*, 1994; CDC, 1997b, 2003a).

Lead concentrations in the general population in several countries in Africa are summarized in Table 59. Most values were > 10 µg/dL, except for two rural areas in South Africa (Grobler *et al.*, 1985; Nriagu *et al.*, 1997a).

Reports from several Asian countries of blood lead concentrations in adults with no known occupational exposure to lead and no exposure to heavy traffic are summarized in Table 60. The values were mostly < 10 µg/dL, and few were above 13 µg/dL, with the exception of one concentration of 24 µg/dL for a rural population in Pakistan (Khan *et al.*, 1995). One study used urinary lead concentrations to monitor lead exposure in Japan. A substantial decrease in urinary lead was reported over the last 13 years. The amounts of lead excreted (geometric means) in 24-h urine samples were 4.74, 2.67 and 1.37 µg for men in 1985, 1993 and 1998, respectively, and 3.21, 2.14 and 1.02 µg for women in the same years (Jin *et al.*, 2000).

Blood lead concentrations in adults in Australia are summarized in Table 61. As observed in other parts of the world, concentrations have declined in the general population over the past two decades.

Table 59. Lead concentrations in blood in the general population in some countries in Africa

Country	City/area	Population/ age range	No. of subjects	Blood lead (µg/dL) mean (range)	Reference
Egypt	Urban area Rural area	Adults	NR	17.0–36.0 14.0–25.0	Kamal *et al.* (1991)
	Cairo	No lead exposure	50	18.2	Kamal *et al.* (1991)
Nigeria	Ibadan	Men Women		11.4 12.3	Omokhodion (1984)
	NR	Adults	24	12.9 ± 7.0 (1.7–32.5)	Ogunsola *et al.* (1994b)
	Kaduna	1–6 years	87	10.6 (max. 39)	Nriagu *et al.* (1997b)
South Africa	Urban area Rural area	Children Children	NR NR	22 11	[von Schirnding & Fuggle (1984)]
	Remote area	14–16 years	30	3.4 ± 1.5 (0.5–7.5)	Grobler *et al.* (1985)
	Cape Town	1st year-grade	200	12 (white) 18 (mixed)	von Schirnding *et al.* (1991a)[c]
	Cape Town	1st year-grade	104	18[b]	von Schirnding *et al.* (1991b)[c]
	Cape Province Mining village Village 40 km from mining area	Children Children Children	NR NR NR	14–16 16 13	Nriagu *et al.* (1996b)
	Besters Valamehlo (rural)	3–5, 8–10 years	1200 660	10 3.8	Nriagu *et al.* (1997a)
	Johannesburg	6–9 years	433	11.9 (6–26)	Mathee *et al.* (2002)
	Urban areas	Children	NR	15	Harper *et al.* (2003)[a]

Updated from Nriagu *et al.* (1996b); reference in square brackets could not be retrieved as original papers.

NR, not reported

[a] Review of several published studies

[b] Median value

[c] [It was not clear to the Working Group whether the two articles presented data from the same study population.]

Table 60. Lead concentrations in blood in adults in the general population in Asia

Country	City/area	Years of study	Population	No. of subjects	Smoking status	Blood lead (µg/dL) arithmetic mean[a] (range)	Reference
China	Shanghai	1986–88	Women	165	NR	14.1	Jiang *et al.* (1992)
	3 areas	1993–97	Women	250	Nonsmoker	4.6[b]	Zhang *et al.* (1999)
	Hubei	NR	Women				Wang *et al.* (2000)
			urban	33	NR	6.7	
			mining area	28	NR	6.7	
			rural	44	NR	5.3	
	Province of	1991–94	≥ 15 years of age	8828	NR	7.7 (ND–69.1)	Liou *et al.* (1996)
	Taiwan	1993–94	Men	1471	Included	7.3	Chu *et al.* (1998)
			Women	1332	Included	5.7	
India	Ahmedabad	NR	Men + women	200	Included	13.8	Friberg & Vahter (1983)
	Bangalore			73	Included	17.9	
	Kolkata			100	Included	10.7	
	Slums of Lucknow	1994–95	Women	500	NR	14.3 (13.0–15.7)	Awasthi *et al.* (1996; 2002)
Indonesia	Bandung	1983	Rural men	20	NR	12	Suzuki (1990)
Iraq	Bassora	NR	Men	60	NR	14.6	Mehdi *et al.* (2000)
Japan	Kanagawa	1991	Adults	62	NR	1.0 (0.6–2.4)	Arai *et al.* (1994)
	NR	NR	Men	70	NR	11.0 (5.0–17.2)	Oishi *et al.* (1996a)
			Women	68	NR	6.4 (3.8–11.4)	
	Kyoto, Sendai & Tokyo	1991–93	Women	72	Nonsmoker	3.2[b]	Zhang *et al.* (1999)
	30 sites	1991–98	Women	607	Nonsmoker	1.9[b]	Shimbo *et al.* (2000)
	NR	NR	Women	70	NR	6.4 (3.8–11.4)	Nomiyama *et al.* (2002)
Jordan	Irbid City	NR	Men	21	NR	5.7b	Hunaiti *et al.* (1995)

Table 60 (contd)

Country	City/area	Years of study	Population	No. of subjects	Smoking status	Blood lead (µg/dL) arithmetic mean[a] (range)	Reference
Pakistan	Rural area	1994–95	Men	36	NR	24.1	Khan *et al.* (1995)
Philippines	Manila	1999	Men + women	50	NR	12.6	Suplido & Ong (2000)
Republic of Korea	NR	NR	NR	26	NR	10.8	Kim *et al.* (1995a)
	Chonan	1997–99	Men + women	135	87% current	5.3 (2–10)	Lee, S.-S. *et al.* (2001); Schwartz *et al.* (2001)
Thailand	Bangkok	1993	Women	500	NR	6.2	Phuapradit *et al.* (1994)
	NR	NR	Men	30	NR	6.0 (2.1–9.7)	Wananukul *et al.* (1998)
	Chaiyapoom	NR	Rural	29	Nonsmoker	6.6 (4.0–9.0)	Suwansaksri & Wiwanitkit (2001)
United Arab Emirates	Abu Dhabi	1999	Men	100	NR	19.8; 13.3[b]	Bener *et al.* (2001)

NR, not reported; ND, not detectable

[a] Unless specified otherwise

[b] GM, geometric mean

Table 61. Lead concentrations in blood in adults and children in Australia

Reference	Location	Period of study	Population	No. of subjects	Age (years)	Blood lead concentration (µg/dL)	AM (range)	Comments
Mencel & Thorp (1976)	Sydney, NSW	1974	Adults	133	NR	12.4	2.7–51.1	
Moore *et al.* (1976)	Tasmania	NR	Clerks and students	47	18–61	14.3	SE, 0.72	Capillary blood samples
de Silva & Donnan (1977)	Melbourne, Vic.	NR	Male office workers	20	42.8	10.9	SD, 2.8	Venous blood samples
de Silva & Donnan (1980)	Victoria, Vic.	1979	Children	446	School age	11.4	3–3.7	
Calder *et al.* (1986)	Adelaide, SA, industrial suburb	1984	Boys and girls	513	≤ 4 yrs	16.3	2.7% > 30 µg/dL	
Wilson *et al.* (1986)	Port Pirie, SA	1982	Boys and girls	1239	1–14	18.2	15.4% ≥ 25 µg/dL 95.4% ≥ 10 µg/dL	
Fett *et al.* (1992)	Central Sydney, NSW, inner urban areas	1991–92	Boys and girls	158	9–48 months	11.2	50.6% > 10 µg/dL	
Threlfall *et al.* (1993)	Perth, WA	1991	Boys and girls	123	0.2–17	6.9[a]	3.2–14.7	
Gulson *et al.* (1994)	Broken Hill, NSW	1991–92	Adults and children	146	NR	–	2.7–47.1	
Taylor *et al.* (1995)	Victoria, Vic.	1993	Children	252	0.3–14	5.4[a]	1.0–36.8	
Mira *et al.* (1996)	Central and southern Sydney, NSW	1992–94	Boys and girls	718	9–62 months	7.0	16.1% > 10 µg/dL	
Chiaradia *et al.* (1997)	Goulburn, NSW	NR	Children of employees	8	2–5	5.7	SD, 1.7	Lead–zinc–copper mine employees
			Control children	10	2–5.5	4.1	SD, 1.4	
Maynard *et al.* (2003)	Port Pririe, SA (town with widespread contamination from lead smelter)	1993	Boys and girls	679	1–4	13.6	NR	Surveys evaluating interventions
		1994	Boys and girls	551		13.3	NR	
		1995	Boys and girls	803		12.1	NR	
		1997	Boys and girls	753		11.4	NR	
		1998	Boys and girls	775		10.1	NR	
		1999	Boys and girls	825		10.6	NR	

AM, arithmetic mean; NR, not reported; SE, standard error; SD, standard deviation

[a] Geometric mean

Table 62. Lead concentrations in blood in children living near the Santo Amaro smelter in Bahia, Brazil

Year of study	No. of subjects	Age (years)	Blood lead (μg/dL) mean ± SD (range)	Other bioindicators mean ± SD (range)	Reference	Comments
1980	555	1–9	59.2 ± 25.0 (16.0–152.1)	ZPP: 95.3 ± 80.2 μg/dL (3.8–782.8)	Carvalho *et al*. (1984, 1985a); Silvany-Neto *et al.* (1985); Tavares (1990)	Initial survey
	263			Lead in hair: 558 ± 644 ppm	Carvalho *et al*. (1989)	
1985	250	1–9	36.9 ± 22.9 (2.9–150.0)	ZPP: 70.4 ± 43.9 μg/dL (10.3–522.7)	Silvany-Neto *et al*. (1989); Tavares (1990, 1992)	90-m chimney built; population within 300 m from smelter transferred; EDTA treatment for 31 children; discontinued donation of smelter dross and used filters to neighbours; installation of stack filters; provided working clothes to employees
1992	100	1–5		ZPP: 65.5 ± 1.7 μg/dL[b]	Silvany-Neto *et al*. (1996); Carvalho *et al.* (1996, 1997)	Higher values found in girls; children with darker-skinned racial background; smelter slag present in home; children with pica; children of smelter workers
1998	47	1–4	17.1 ± 7.3 (2.0–36.2)		Carvalho *et al*. (2003)	Smelter closed in 1993 Sources of exposure remaining; higher blood lead found in: children with pica; smelter slag present in home; malnutrition; lead intoxication family history; sewage tubing being placed with disturbance of slag previously used on streets

[a] ZPP, zinc protoporphyrin; SD, standard deviation

[b] Geometric mean

Table 63. Lead concentrations in blood in children in Latin America and the Carribean

Country	Location	Year(s) of study	Source of exposure	No. of subjects	Age (years)	Mean blood lead (µg/dL)	Reference
Chile	Antofagasta	1997–98	Lead storage site (railway)	432	0–7	8.7 ± 1.99[a]	Sepúlveda *et al.* (2000)
			Port area	54	0–7	6.9 ± 1.94[a]	
			No exposure	75	0–7	4.2 ± 1.54[a]	
Equador	La Victoria	NR	Ceramic glazing	166	0.3–15	40.0 (6.2–119.1)	Counter *et al.* (2000)
	Zamora Province	NR	No exposure	56	1–15	6.6 (2.0–18.0)	
Jamaica	NR	1994–95	Rural	242	3–11	9.2[b] (3–28.5)	Lalor *et al.* (2001)
			Urban	90	3–11	14.0[b] (4–34.7)	
			Former mining area	61	3–11	35[b] (18–> 60)	
Mexico	Mexico City	< 1992	Urban	782 girls	5–11	10–17	Olaiz *et al.* (1996)
				801 boys	5–11	14–16.7	
	Ciudad Juárez, Chihuahua	1974	Smelter		1–9		Ordóñez *et al.* (2003)
			< 1 mile	35		38.7	
			1–2.5 miles	113		31.6	
			2.6–4 miles	198		28.7	
			4.1–6 miles	200		28.5	
			6.1–8 miles	206		27.7	
			Total	752		29.3	

NR, not recorded

[a] Geometric mean

[b] Median value

Table 64. Lead concentrations in blood in children in Asia

Country	City/area	Year(s) of study	Population	No. of subjects	Age (years)	Blood lead (µg/dL)		Reference	Comments
						AM[a]	Range		
Bangladesh	Dhaka	2000	B+G	779	4–12	12.3–17.5[b]		Kaiser *et al.* (2001)	
China	Jiangsu	NR	B+G	27	6–9	8.8	5.9–14.8	Zhou & Chen (1988)[c]	Capillary samples
	Shanghai	NR	B+G	83	8–13	18.4	ND–55.0	[Wang (1988)[c]]	Capillary samples
	Beijing	1990	B+G	287	5–7	7.8–12.3[b]	3.9–24.8	[Zheng *et al.* (1993)[c]]	Capillary samples
	Multiple sites	NR	B+G	[3746]	1–15	6.6–96.8		Shen *et al.* (1996)	Review of 17 articles published between 1986 and 1994
	Shanghai	1997	B+G	1969	1–6	9.6	0.1–69.7	Shen *et al.* (1999)	After removal of lead from gasoline
		1998	B+G	1972	1–6	8.1	1–23.9		
	Rural area	1998–2001	B+G	959	5–12	49.6	19.5–89.3	Wu *et al.* (2002)	Children exposed to parental lead-recycling small industry
			B+G	207	5–9	12.6	4.6–24.8		Non-polluted area
	Rural area	NR	B+G	469	mean, 8.5	50.5	22.0–93.8	Zheng *et al.* (2002)	Rural area near smelter
	Shantou	1999	B+G	332	1–5	10.4	3.4–38.6	Luo *et al.* (2003)	After removal of lead from gasoline in 1998
		2001	B+G	457	1–5	7.9	1.1–29.5		
China (Province of Taiwan)	Kaohsiung	1998–99	B+G	934	8–12	5.5	0.2–25.5	Wang *et al.* (2002a)	
India	Delhi	NR	B+G	82	0.2–13	9.6		Gogte *et al.* (1991)	Control
						23			Pica
						11.6			Surma
						30.8			Pica + surma
	New Delhi	NR	B+G	75	3–5	14	4–40	Kaul (1999)	Finger-prick method
	Jammu	NR	B+G	50	3–5	15	4–87		
	3 sites	NR	B+G					Kumar & Kesaree (1999)	
	urban			25	5–15	32.0	25–43		
	semi-urban			75	5–15	25.0	20–31		
	rural			50	5–15	15.0	13–22		
	Mumbai	1986–94	NR	566	6–10	8.6–14.4[b]		Raghunath *et al.* (1999)	Middle-class families
	Mumbai	1984–96	[B+G]	560	6–10	8.6–69.2[b]		Tripathi *et al.* (2001)	Capillary samples
	Delhi	1998	B+G	190	4–6	7.8		Kalra *et al.* (2003)	Children with ZPP > 50 µg/dL

Table 64 (contd)

Country	City/area	Year(s) of study	Popula-tion	No. of subjects	Age (years)	Blood lead (µg/dL)		Reference	Comments
						AM[a]	Range		
Indonesia	Jakarta	< 2001	B+G	397	6–12	8.6[b]	2.6–24.1	Albalak *et al*. (2003)	Capillary samples
Malaysia	Urban	1997	B+G	179	7–11	5.3	0.9–18.5	Hashim *et al.* (2000)	Finger-prick method
	Semi-urban			112	7–11	2.8	0.1–12.3		
	Rural			55	7–11	2.5	0.05–5.2		
Republic of Korea	Ulsan	1997	B+G	426	8–11	4.77[b]		Lee *et al*. (2002)	Lead in gasoline was reduced to 0.013 g/L in 1993.
		1999	B+G	250	8–11	5.11[b]			
		2001	B+G	242	8–11	5.21[b]			
Mongolia	6 sites	NR	NR	142	NR	0.34–1.75		Burmaa *et al*. (2002)	Highest in Ulaanbaatar
Pakistan	Karachi	NR	Boys	77	6–8	16.9		Rahman *et al*. (2002)	
		NR	Girls	61	6–8	15.12			
	5 districts in Karachi	2000	B+G	400	3–5	12.0–21.6		Rahbar *et al*. (2002)	
Saudi Arabia	Riyadh	NR	Girls	533	6–12	8.1	2.3–27.4	Al-Saleh *et al*. (2001)	
Thailand	Kanchanaburi, downstream lead refinery plant	1997	NR	48	mean, 3.4	27.8		Tantanasrikul *et al.* (2002)	Initial survey
		1998	NR	48		30.6			After environmental deleading
		1999	NR	48		30.3			Second survey

NR, not reported; B, boys; G, girls; ZPP, zinc protoporphyrin

[a] AM, arithmetic mean, unless stated otherwise

[b] Geometric mean

[c] Cited by Shen *et al.* (1996); references in square brackets could not be retrieved as original papers.

(*b*) *Pregnant women and neonates*

Lead concentrations were measured in maternal blood and umbilical cord blood from 50 parturient women at delivery in a hospital in Athens, Greece. Lead concentrations (mean ± standard deviation) for women living in industrial areas with high air pollution were 37.2 ± 4.7 μg/L in maternal blood and 20.0 ± 3.4 μg/L in umbilical cord blood (correlation coefficient, $r = 0.57$), while those for women living in agricultural areas with low air pollution were 20.5 ± 5.6 μg/L and 12.9 ± 3.6 μg/L, respectively (correlation coefficient, $r = 0.70$). The authors concluded that the placenta demonstrates a dynamic protective function that is amplified when maternal blood lead concentrations are increased (Dussias *et al.*, 1997).

Data from Kosovo (Serbia and Montenegro) showed that 86% of the pregnant women living in the vicinity of a lead smelter had blood lead concentrations ≥ 10 μg/dL, while in a comparable area not near a smelter, only 3.4% of pregnant women showed elevated concentrations (Graziano *et al.*, 1990).

Rabinowitz and Needleman (1982) reported an umbilical cord blood lead concentration of 6.6 μg/dL (arithmetic mean), with a range of 0–37 μg/dL, in over 11 000 samples collected between 1979 and 1981 in Boston, USA. A decrease in the blood lead concentration of approximately 14% per year was noted during the period of collection.

Concentrations of lead (expressed as mean ± standard deviation) in umbilical cord blood of two groups of women giving birth in a hospital in Boston, USA, in 1980 and 1990, were found to be 6.56 ± 3.19 μg/dL and 1.19 ± 1.32 μg/dL, respectively (Hu *et al.*, 1996a).

In a study conducted at a medical centre in South Central Los Angeles, one of the most economically-depressed regions in California, USA, maternal blood lead concentrations in the third trimester of pregnancy were significantly higher in a group of 1392 immigrant women (geometric mean, 2.3 μg/dL) than in a group of 489 non-immigrant women (geometric mean, 1.9 μg/dL). Years living in the USA was the most powerful predictor of blood lead concentration. Drinking coffee during pregnancy, a history of pica, and/or low calcium intake were all significantly associated with higher blood lead concentrations (Rothenberg *et al.*, 1999).

In a study conducted in the United Arab Emirates, blood samples were collected from 113 mothers of 23 different nationalities and from their neonates (cord blood). Mean maternal blood lead concentration was 14.9 ± 2.14 μg/dL (range, 6.6–27.8 μg/dL) and mean cord blood lead concentration was 13.3 ± 2.49 μg/dL (range, 6.0–30.3 μg/dL). Sixteen per cent of samples from the mothers and 9% of cord blood samples had lead concentrations > 20 μg/dL (Al Khayat *et al.*, 1997a).

There are several studies showing high blood lead concentrations in pregnant women in India (Saxena *et al.,* 1994; Awasthi *et al.,* 1996; Raghunath *et al.*, 2000). The mean blood lead concentration in a cohort of 500 pregnant women living in the slums of Lucknow, north India, was 14.3 μg/dL, and 19.2% of women had concentrations ≥ 20 μg/dL. Blood lead concentration was not associated with age, height, weight, gestation, or history of abortion, although it was higher with higher parity. Women living in inner-city neighbourhoods with heavy vehicular traffic had mean blood lead concentrations significantly higher than those living in other neighbourhoods (Awasthi *et al.,* 1996). In another study conducted in Lucknow, India, the mean maternal blood lead concentration was significantly higher in cases of abnormal delivery (22.5 μg/dL) compared with normal deliveries (19.4 μg/dL). No significant difference in placental blood, cord blood and fetal membrane lead concentrations was observed between cases of normal and abnormal deliveries (Saxena *et al.,* 1994).

(*c*) *Children*

Data on blood lead concentrations in children are presented in Tables 57–59 and 61–64.

Between 1978 and 1988, decreases of 25–45% in average blood lead concentrations in children have been reported in Belgium, Canada, Germany, New Zealand, Sweden and the United Kingdom (OECD, 1993).

Blood lead concentrations were measured in 286 children aged 0–7 years living in the three largest cities of Finland (n = 172), in rural areas (n = 54) and near a lead smelter (n = 60) (Taskinen *et al.*, 1981). Mean blood lead concentrations among children in the urban, rural and lead-smelter areas varied between 6.0 and 6.7 μg/dL, with a range of 2–17 μg/dL. There were no statistically significant differences between groups. The five children who lived within 500 m of the lead smelter had a mean blood lead concentration of 9.2 μg/dL, with a range of 5–13 μg/dL, which was significantly higher than the mean blood lead concentration among 485 children in the rest of the country. In a study carried out in Sweden, 1395 blood samples were obtained from children living in an urban or rural area or near a smelter during the period 1978–88. The mean blood lead concentration for all locations together decreased from 6.4 μg/dL (range, 1.8–25 μg/dL) in 1978 to 4.2 μg/dL (range, 1.4–12.9 μg/dL) in 1984, to 3.3 μg/dL (range, 1.5–7.1 μg/dL) in 1988. The decrease was statistically significant for all three areas studied (Skerfving *et al.*, 1986; Schütz *et al.*, 1989).

In Finland, the mean blood lead concentration for the children in two day-care centres in Helsinki was 4.8 μg/dL in 1983 (range, 2.1–8.3 μg/dL), 3.0 μg/dL in 1988 (range, 2.1–4.1 μg/dL), and 2.6 μg/dL in 1996 (range, 1.7–3.7 μg/dL) (Pönkä *et al.*, 1993; Pönkä, 1998).

In 1993, almost 30% of 431 children in a lead-mining community in the Upper Silesian industrial zone of Poland had blood lead concentrations > 10 μg/dL (Zejda *et al.*, 1995). In Belovo, Russian Federation, lead releases from a metallurgy enterprise decreased between 1983 and 1996 from 120 to 9 tonnes per year, due to almost complete cessation of activity. In 1983, mean blood lead concentrations in newborn children and their mothers living in the area were 23.4 and 25 μg/dL, respectively; in 1996, mean blood lead concentrations in 91 children (age, 7–8 years) had decreased to 9.9 μg/dL (range, 0.5–39 μg/dL), with 46% of values still exceeding 10 μg/dL (Revich *et al.*, 1998).

In a community near a smelter in Bulgaria, blood lead concentrations in 109 children varied from 8–63 μg/dL. The higher concentrations in these children were correlated with the consumption of home-grown products. Lower blood lead concentrations were observed in children whose food came from a distant market (Fischer *et al.*, 2003).

The mean blood lead concentration in children in the USA has dropped dramatically since the late 1970s (Brody *et al.*, 1994; Pirkle *et al.*, 1994, 1998; CDC, 1997b, 2003a,b). Results of the NHANES studies in children aged 1–5 years are shown in Table 58.

The NHANES II and NHANES III, Phase I, results showed that from 1976 to 1991, high blood lead concentrations correlated with low income, low educational attainment and residence in the north-eastern region of the USA (Pirkle *et al.*, 1994). Data from Phase II of NHANES III (October 1991 to September 1994) indicated that blood lead concentrations in children aged 1–5 years continued to decrease and were more likely to be elevated among those who were poor, non-Hispanic black, living in large metropolitan areas or living in older housing (with potential exposure to lead from lead-based paint); approximately 4.4% of the children aged 1–5 years had blood lead concentrations ≥ 10 μg/dL (CDC, 1997b). In addition, 1.3% of children aged 1–5 years had blood lead concentrations ≥ 15 μg/dL and 0.4% had concentrations ≥ 20 μg/dL. The downward trends continued in 1999–2000 (CDC, 2003a). For all periods of this study, mean lead concentrations were consistently lower among the older age groups, i.e. age 1–5 years, 2.2 μg/dL; 6–11 years, 1.5 μg/dL; 12–19 years, 1.1 μg/dL in the period 1999–2000 (CDC, 2003a).

A study assessing the source of lead exposure during early childhood in the USA showed that lead-contaminated floor dust was a major source of lead exposure during early childhood, whereas window sills became an increasingly important source as children stood upright (Lanphear *et al.*, 2002).

One of the most serious episodes of general population exposure to lead reported in Latin America occurred in Brazil (Table 62). For 24 years, a lead smelter processing 30 000 tonnes/year operated in the vicinity of Santo Amaro da Purificação (30 000 inhabitants) in the state of Bahia. No proper air pollution control system was used. Smelter dross (solid wastes) was distributed free of charge to the neighbouring population and spread over gardens, backyards, schools and streets, and chimney filters from the smelter were used in homes as carpets, bed spreads and rags. Four cross-sectional studies in children under 9 years of age were conducted in 1980 (Carvalho *et al.*, 1985a), 1985 (Silvany-Neto *et al.*, 1989), 1992 (Silvany-Neto *et al.*, 1996) and 1998 (Carvalho *et al.*, 2003). Blood lead concentrations were among the highest reported in the world. Most children involved in the last study were born after the smelter closed down in December 1993. Five years later, lead concentrations in blood averaged 17.1 ± 7.3 μg/dL, ranging from 2.0 to 36.2 μg/dL. Blood lead concentrations were approximately 5 μg/dL higher in children with pica, with visible presence of dross in home premises, with previous history of lead intoxication in the family and with malnutrition (Carvalho *et al.*, 2003).

In Antofagasta, Chile, a study was conducted with 432 children under 7 years of age living around a minerals storage site, 54 living near the port and 75 in non-exposed areas

(Table 63). Average concentrations of lead in blood of exposed and unexposed children were 8.7 µg/dL and 4.2 µg/dL, respectively. Forty-seven per cent of exposed children, but no unexposed children, had blood lead concentrations > 10 µg/dL. The habit of pica, the number of cigarettes smoked daily at home, the level of education of the mother and having a mother working outside the home were variables that partly explained the variation in blood lead concentrations in the exposed area (Sepúlveda *et al.*, 2000).

In view of airborne lead pollution across the border from a lead smelter in El Paso, TX, USA, an epidemiological study on lead was conducted in 1974 in Juárez City, Chihuahua, Mexico, among 752 children aged 1–9 years. The average blood lead concentration was 29.27 ± 7.30 µg/dL in children living within 8 miles of the lead source. Concentrations decreased with greater distances from the smelter (Ordóñez *et al.*, 2003; see Table 24 and Section 1.4.1(*b*)).

Lead-glazing of ceramics has for many years been a source of exposure of the population of La Victoria, Ecuador, where around 70 kilns operate within an area of 250 km^2. One hundred and sixty-six children aged 4 months to 15 years living in the area and many of them helping their parents in glazing activities had blood lead concentrations ranging from 6.2 to 119.1 µg/dL (mean, 40.0 µg/dL) compared with an average of 6.6 µg/dL in a reference population of 56 children aged 1–15 years living 500 km away in the province of Zamora. Lead isotope ratios of the soil and blood samples were highly similar and clustered for both study areas, indicating that lead in soil resulting from contamination by the glazing activities is probably one of the main routes of exposure to lead in these children (Counter *et al.*, 2000).

Blood lead concentrations among children in several Asian countries (Table 64) were basically similar to those in adults (Table 60), and were generally between 5 and 15 µg/dL (geometric mean). It should be noted, however, that finger-prick or capillary blood samples were employed in some studies (see Section 1.5 for quality assurance). Blood lead concentrations in children in Mongolia (Burmaa *et al.*, 2002) were substantially lower than in all the other studies listed in Table 64.

In a study carried out at 15 sites in India, the highest (69 µg/dL) and second highest (21 µg/dL) geometric mean blood lead concentrations were observed in children who lived near a scrap-yard and near a lead smelter, respectively. Values for children in the remaining sites were in a range of 9–14 µg/dL (Tripathi *et al.*, 2001). Wu, Y. *et al.* (2002) observed significantly higher blood lead concentrations in children who lived in an area polluted by lead from a battery-recycling plant compared with a control group. Similarly, Zheng *et al.* (2002) described elevated blood lead concentrations (up to 94 µg/dL) in children living in an area with heavy lead pollution. Tantanasrikul *et al.* (2002) found high blood lead concentrations in children in a Thai village area downstream from a lead refinery plant. Wang *et al.* (1998) reported that 22 of 36 children in a kindergarten near a battery recycling factory in Taiwan, China, had blood lead concentrations in excess of 15 µg/dL in comparison with none of 35 children in a kindergarten in a non-exposed area.

In a study of 566 children aged 6–10 years residing in 13 locations in Mumbai, India, a correlation coefficient of 0.88 was observed between air lead and blood lead concentrations. It was also found that a 1-µg/m^3 increase in lead concentration in air resulted in a 3.56-µg/dL increase in blood lead concentration in children (Raghunath *et al.,* 1999).

In another study among children in India, the differences in the mean blood lead concentrations were statistically significant ($p < 0.001$) between the urban, semi-urban and rural populations. The age-related differences in blood lead concentrations were also significant for urban, semi-urban and rural children (Kumar & Kesaree, 1999).

In a study comparing children with and without pica in Delhi, India, only six out of 82 children with no symptoms of pica had a mean blood lead concentration ≥ 30 µg/dL (30–39 µg/dL). Among 88 children with pica, 26 had high blood lead concentrations (30–92 µg/dL) (Gogte *et al.*, 1991).

Among 400 children aged 36–60 months from the city centre, two suburbs, a rural community or an island situated in the harbour at Karachi, Pakistan, about 80% had blood lead concentrations > 10 µg/dL, with an overall mean of 15.6 µg/dL. Housing near a main intersection in the city centre, application of surma (a lead-containing cosmetic) to children's eyes, father's exposure to lead at the workplace, father's illiteracy, child's hand-to-mouth activity and eating from street vendors were among variables found likely to be associated with elevated lead concentrations in blood (Rahbar *et al.*, 2002).

The phase-out of leaded gasoline in Indonesia began in Jakarta on 1 July 2001. In a study conducted before the beginning of the phase-out activities, 35% of children aged 6–12 years in Jakarta had blood lead concentrations ≥ 10 µg/dL and 2.4% had concentrations ≥ 20 µg/dL. Lead concentrations in the blood of children who lived near a highway or major intersection were significantly higher than those in children who lived near a street with little or no traffic. The source of household water was also a significant predictor of blood lead concentrations ≥ 10 µg/dL, after adjustment for age and sex (Albalak *et al.,* 2003).

Hashim *et al.* (2000) measured blood lead concentrations in urban and rural primary-school children in Malaysia; the percentage of children with blood lead ≥ 10 µg/dL was 6.36% overall, and was highest for Kuala Lumpur (11.73%). Urban schoolchildren were found to have higher blood lead concentrations than their rural and semi-urban counterparts, even after controlling for age, sex, parents' education and income levels.

1.4.3 *Occupational exposure*

Potentially high levels of lead may occur in the following industries or workplaces: lead smelting and refining industries, battery manufacturing plants, steel welding or cutting operations, construction, painting and printing industries, firing ranges, vehicle radiator-repair shops and other industries requiring flame soldering of lead solder, and gasoline stations and garages.

Workers in many occupations and job activities within or outside these industries have the potential for relatively high exposures to lead with varying degrees of frequency (Fu & Boffetta, 1995; ATSDR, 1999; NIOSH, 2001). These exposures and workers are (the asterisks indicate occupations for which there is at least one epidemiological study of lead exposure and cancer, as summarized in Section 2 of this volume): *on-going exposure* — battery-production workers*, battery-recycling workers*, foundry workers, lead chemical workers*, lead smelter and refinery workers*, leaded-glass workers*, pigment workers*, vehicle radiator-repair workers and traffic controllers; *moderate frequency of exposure* — firing-range instructors, house renovators, lead miners*, newspaper printers*, plastics workers*, rubber workers, jewellery workers, ceramics workers and steel welders and cutters; *low frequency of exposure* — automobile-repair workers, cable-production workers, construction workers, demolition workers, firing-range participants, flame-solder workers, plumbers and pipefitters, pottery-glaze producers, ship-repair workers and stained-glass producers.

Epidemiological studies have also reported exposure to organic lead compounds, at a chemical plant in Texas, USA, and at an organic lead manufacturing company in New Jersey, USA. However, there are a number of activities that present a potential for high lead exposure but for which no epidemiological data are available.

The most common route of occupational exposure to lead is through inhalation of lead fumes or lead dusts from ambient air, leading to absorption of lead through the respiratory system. Lead may also be ingested and absorbed in the gastrointestinal tract. Organic lead is absorbed through the skin (Bress & Bidanset, 1991).

The lead concentration in air can be measured as a means of monitoring occupational exposure in work areas. However, occupational exposure is more often inferred from measurement of blood lead concentrations in individual workers.

Workers occupationally exposed to lead may carry lead home on their body, clothing and tools. Thus, children of workers exposed to lead can also be at increased risk of exposure. For example, blood lead concentrations of children in households of occupationally-exposed workers were found to be almost twice those of children in neighbouring homes whose parents were not exposed to lead in their occupation (median ranges, 10–14 and 5–8 μg/dL, respectively) (Grandjean & Bach, 1986). Exposures to lead in workers' families have been identified in association with nearly 30 different industries and occupations; the most commonly reported include lead smelting, battery manufacturing and recycling, radiator repair, electrical components manufacturing, pottery and ceramics and stained-glass making (NIOSH, 1995).

The results of surveys of occupational exposure to lead in a large variety of industries in New Zealand, expressed as air lead concentrations and/or blood lead concentrations for the period 1988–89, are presented in Table 65 (Grant *et al.*, 1992).

Lead concentrations in workplace air and in the blood of exposed workers for specific job categories are presented in Tables 66–73. Whereas lead concentrations in air were reported only in a limited number of studies, blood lead concentrations are available for most studies and the exposure intensity is evaluated in terms of blood lead for the groups of exposed workers. Examples of extreme exposures reported in the literature include mean occupational air lead concentrations as high as 1200 $\mu g/m^3$ for welding structural steel, 4470 $\mu g/m^3$ for primary smelting and 5400 $\mu g/m^3$ within a storage-battery plant (WHO, 1977).

Table 65. Occupational exposure to lead in men in New Zealand, 1988–89

Occupation in order of decreasing mean blood lead concentration	No. of workers	Blood lead (µg/dL)		
		Mean	SD	Range
Radiator repairer	51	78.7	47.6	11–155
Smelter/furnaceman	57	78.7	51.8	14–148
Muffler repairer	33	70.4	33.1	31–109
Scrap metal worker	69	66.2	60.0	14–145
Foundryman general	58	64.2	49.7	23–128
Metal moulder	24	64.2	66.2	14–181
Container repairer	13	60.0	26.9	40–61
Engine reconditioner	33	53.8	33.1	23–154
Panel beater	22	55.9	47.6	23–115
Metal machinist	35	55.9	43.5	18–111
Printer	4	55.9	33.1	28–69
Gas cutter/welder	17	43.5	49.7	6–90
Spray painter	42	43.5	29.0	17–80
Plastic worker	55	43.5	35.2	9–124
Metal polisher	29	43.5	55.9	10–119
Paint removal worker	8	41.4	22.8	19–54
Painter/decorator	208	41.4	51.8	5–181
Leadlight worker	11	39.3	29.0	14–64
Metal extruder	16	35.2	31.1	18–77
Garage mechanic	47	35.2	43.5	9–82
Miscellaneous lead product worker	65	31.1	35.2	5–113
Pottery/ceramics worker	3	29.0	24.8	9–46
Workers exposed to exhaust fumes	6	26.9	26.9	14–47
Plumber	10	26.9	20.7	12–46
Cable jointer	174	26.9	26.9	5–91
Car assembler	25	26.9	31.1	5–76
Electroplater	17	22.8	18.6	9–46
Boat builder	30	20.7	18.6	7–47
Bright solderer	9	20.7	20.7	11–49
Petrol pump attendant	10	20.7	14.5	5–33

Adapted from Grant *et al*. (1992)
SD, standard deviation

A NIOSH Health Hazard Evaluation (HHE) is a study of a workplace in the USA conducted to learn whether workers are exposed to hazardous materials or harmful conditions. The HHE is not necessarily representative of an industry or general work practices, since the inspections and measurements are typically done in response to a request by an employee, an officer of a labour union that represents employees, or any management official on behalf of the employer. Table 74 presents data from a series of HHE reports where blood and air concentrations of lead have been measured.

Table 66. Lead concentrations in blood of occupationally exposed subjects: lead–acid battery factories

Country or area	Year(s) of survey	Job/task	Study population	No. of subjects	Age (years)	Job history (years)	Smoking status	Blood lead (µg/dL)		Lead in air (µg/m^3)		Reference
								AM[a]	Range/SD	AM[a]	Range/SD	
Brazil	[1984]	Battery repair[b]	M	5	15–66	≤ 1	NR	35.0[c]		NR		Carvalho *et al.* (1985b)
				11		1–3	NR	37.3[c]				
				23		≥ 4	NR	47.7[c]				
				6	15–18			36.7[c]				
				33	19–66			44.0[c]				
Bulgaria	1992–96	Lead–acid battery	M	103	39.1	9.7	Included	56.2		NR		Vaglenov *et al.* (2001)
China	1950–83	Lead–acid battery										Wang (1984)
		Charging	NR	30	NR	NR	NR	26.2[d]	NR	500		
		Plate moulding	NR	34	NR	NR	NR	25.6[d]	NR	60		
		Printing	NR	30	NR	NR	NR	22.8[d]	NR	5		
China (Province of Taiwan)	NR	Lead–acid battery	M	118	37.0	> 6 months	80%	67.0	± 26	190		Lai *et al.* (1997)
			W	101	36.3	> 6 months	2%	45.0	± 18.7			
	NR	Lead–acid battery	M	120	18–67	0.2–35	38% smokers	67.7	± 28.2	≥ 0.1 in 46% of samples		Wang *et al.* (2002b)
			W	109	18–71	0.2–17		48.6	± 17.0			
	1989–98	Lead–acid battery	17 M 13 W	30	38.3	13.1	NR	20–60[d,e]		NR		Hsiao *et al.* (2001)
	1991	Lead–acid battery	M + W	284	NR	NR	Included	34.7	± 15.0	NR		Chuang *et al.* (1999)
	1997		M + W	392	NR	NR	Included	23.9	± 12.4	NR		
Finland	NR	Lead–acid battery	M + W	91	40.6	12.2	NR	30		NR		Erkkilä *et al.* (1992)
Irak	1996	Lead–acid battery										Mehdi *et al.* (2000)
		Charging	M	11	NR	> 4	40% smokers	36.4	± 11.40	NR		
		Repair	M	8	NR	> 4		58.0	± 13.35	NR		
		Casting	M	18	NR	> 4		71.7	± 24.80	NR		

Table 66 (contd)

Country or area	Year(s) of survey	Job/task	Study popu-lation	No. of subjects	Age (years)	Job history (years)	Smoking status	Blood lead (µg/dL)		Lead in air (µg/m^3)		Reference
								AM[a]	Range/SD	AM[a]	Range/SD	
Israel	1975	Administration	NR	3	41.3	13.3	Most smokers	28.6	20–34	14.5	11.9–17.0	Richter *et al.* (1979)
		Maintenance	NR	3	41.3	5.5		44.0	43–46	23	–	
		Assembly	NR	6	47.0	9.8		55.0	41–73	49.3	48–50.7	
		Miscellaneous	NR	17	35.2	4.3		59.5	43–87	84.5	71–98	
		Grid smelting and casting	NR	10	43.9	13.1		58.4	43–73	190	118–299	
		Plate drying and formation	NR	15	31.9	4.6		75.2	48–105	399	266–475	
		Oven smelting	NR	3	36.3	6.5		76.3	64–90	885	–	
		Pasting/drying/ oxide formation	NR	4	33.5	6.4		90.7	79–108	1187	1060–1315	
Japan	NR	Lead battery, mostly	M	214	NR	≥ 2	NR	48.9[c]	17.0–101.0	NR		Fukui *et al.* (1999)
			W	44	NR	≥ 2	NR	49.1[c]	28.0–75.0	NR		
Philippines	1990	Lead–acid battery	M	199	33.8	10.7	NR	64.5[b]	23–121	NR		Makino *et al.* (1994)
Republic of Korea	NR	Lead–acid battery	NR	66	40	≥ 3 months	NR	45.7	± 15.7	NR		Kim *et al.* (1995a)
		Casting and pasting		5	39			40.6	± 8.8	83	40–154	
		Plate forming, finishing		17	44			49.2	± 17.4	170	12–468	
		Assembling		22	39			47.2	± 11.6	145	15–411	
		Others		22	39			42.6	± 18.7	NR		
	NR	Lead–acid battery	14 M, 78 W	92	40.1	8.6	NR	27.6		19[c]		Hwang *et al.* (2000)
		Cast-on-strap		37				29.6		32[c]		
		Plate processing		3				36.8		29[c]		
		Battery cell setting		19				22.6		13[c]		
		Finish processing		21				22.4		9[c]		
		Supervisor		12				44.5		27[c]		
	1998	Lead–acid battery	M	156	36.3	8.8	68% smokers	32.0	± 13.0	NR		Hwang *et al.* (2001)
			W	56	47.0	6.2	Nonsmokers	19.8	± 9.2	NR		

Table 66 (contd)

Country or area	Year(s) of survey	Job/task	Study population	No. of subjects	Age (years)	Job history (years)	Smoking status	Blood lead (µg/dL)		Lead in air (µg/m³)		Reference
								AM[a]	Range/SD	AM[a]	Range/SD	
Singapore	NR	Lead–acid battery	M									Chia *et al.* (1991)
			Chinese	11	39.1	10.8	Included	23.6	12.4	35	± 31	
			Malay	25	31.7	7.5	Included	34.3	10.5	51	± 39	
	NR	Lead–acid battery	M	50	38.3	10	NR	32.5	19.1–50.9	88.6	± 176.3	Ho *et al.* (1998)
	1987–89	Lead–acid battery	NR	61	NR	NR	NR	28.4	12.9	NR		Chia *et al.* (1993)
South Africa	NR	Lead–acid battery	M	382	41.2	11.6	52% smokers	53.5	23–110	145	10–5480	Ehrlich *et al.* (1998)
Turkey	NR	Lead–acid battery	M	71	32.7	NR	73% smokers	34.5	13.4–71.8	NR		Süzen *et al.* (2003)
USA	1947–72	Lead–acid battery	M	1083	NR	> 1	NR	62.7		NR		Wong & Harris (2000)

NR, not reported; M, men; W, women

[a] Arithmetic mean, unless stated otherwise

[b] Nineteen different establishments recycling batteries; 76.9% of the workers operating in areas < 30 m^2 and involved in fusion of lead

[c] Geometric mean

[d] Median value

[e] Values read from graph

Table 67. Lead concentrations in blood of occupationally exposed subjects: mining/primary smelter

Country	Year of survey	Job/task	Study population	No. of subjects	Age years mean (range)	Years of employment	Smoking status	Blood lead (µg/dL)		Lead in air (µg/m^3)		Reference
								AM[a]	Range/ SD	AM[a]	Range	
Canada	1994	Primary smelter	M + W	368	NR	NR	NR	22–25	NR	NR		Fleming *et al.* (1998)
Italy	1977–78	Primary smelter	M	1388	NR	> 1	NR	NR		47.6	1–1650	Cocco *et al.* (1997)
Japan	NR	Copper smelter	M		42.9 (21–60)		Included					Karita *et al.* (2000)
		Blending		13			–	8.9	± 5.5	7	5–8	
		Smelting		51			–	13.5	± 7.2	29	6–67	
		Converter		28			–	15.7	± 7.3	41	17–78	
		Anode		31			–	25.7	± 6.1	313	165–436	
							Current	26.3	14–39			
							Former	21.0	19–23			
							Never	25.9	15–34			
Kazakhstan	1998	Smelter and mining	NR	38	NR	NR	NR	34	13–> 65	NR		Kaul *et al.* (2000)
Sweden	1987	Primary smelter	Active	70	37.4	14.3	NR	32[b]	5.0–47.4	NR		Gerhardsson *et al.* (1993)
			Retired	30	67.9	32.6	NR	9.9[b]	3.3–20.9			
Sweden	1950–87	Primary smelter	M	3979	NR	NR	NR	62.1–33.1[c]		NR		Lundström *et al.* (1997)
		Other metal workers						55.9–16.6[c]				
		Other personnel						53.8–12.4[c]				
United Kingdom	1970–79	Cadmium plant	M	123	NR	> 1	NR	28		50% > 2000 in whole plant		Ades & Kazantzis (1988)
		Furnace area	M	426	NR	> 1	NR	59				
		Sinter area	M	343	NR	> 1	NR	56				
USA	1976	Primary smelter	M	173	NR	9.9	NR	56.3		3100		Steenland *et al.* (1992)

NR, not reported; M, men; W, women

[a] Arithmetic mean, unless stated otherwise

[b] Median value

[c] Decrease over the study period

Table 68. Lead concentrations in blood of occupationally exposed subjects: secondary smelter

Country or area	Year(s) of survey	Job/task	Study popu-lation	No. of subjects	Age years mean (range)	Job history (years)	Smoking status	Blood lead (µg/dL)		Lead in air ($\mu g/m^3$) AM[a]	Reference
								AM[a]	Range/ SD		
China (Province of Taiwan)	NR	Battery recycling									Wang *et al.* (1998)
		Furnace	NR	19	37	11 months	NR	87	14	NR	
		Fragmentation	NR	10	35	15 months	NR	69	16	NR	
		Office, guards	NR	5	52	31 months	NR	38	4	NR	
Ghana	NR	Battery recycling	23 M, 2 W	25	(18–60)	≥ 5	NR	108	60–270	NR	Ankrah *et al.* (1996)
Japan	NR	Secondary lead smelter	19 M, 3 W	22	47 (22–63)	5	NR	43	8–78	NR	Tomokuni *et al.* (1992)
Philippines	NR	Secondary lead smelter (battery recycling)	M	107	32.1	6.6	NR	80.8[b]	19–153	NR	Makino *et al.* (1994)
			W	6	27.8	4.0	NR	44.7[b]	35–61	NR	
Republic of Korea	1996	Secondary lead smelter	83 M, 5 W	88	NR	> 1 month	NR	52.4	17.7	324	Kim *et al.* (2002)
		A	M + W	12				47.4	18.8	310	
		B	M + W	17				47.2	20.7	194	
		C	M + W	18				49.7	13.1	464	
		D	M + W	25				55.4	19.7	316	
		E	M + W	16				60.0	12.1	290	
Sweden	1969–85	Secondary smelter	M	664	28 at entry	2.8[b]	NR	62.1–33.1[c]		NR	Gerhardsson *et al.* (1995a)
USA	1947–72	Smelters (primary, second, recycling)	M	254	NR	> 1	NR	79.7		NR	Wong & Harris (2000)

NR, not reported; M, men; W, women; A–E, five different lead smelters

[a] Arithmetic mean, unlewss stated otherwise

[b] Median value

[c] Decrease over the study period

Table 69. Lead concentrations in blood of occupationally exposed subjects: leaded glass

Country or area	Years of survey	Job/task	Study population	No. of subjects	Age (years)	Job history (years)	Smoking status	Blood lead (µg/dL)		Lead in air (mg/m^3)		Reference
								AM[a]	Range	AM[a]	Range	
China	NR	Lead-coloured glass	Women	36	21–35	2–17	Never	55.6	25.8–79.3	NR	0.4–1.2	Murata *et al.* (1995)
Japan	1989–90	Lead-coloured glass	NR	5	29–55	2–17	NR					Hirata *et al.* (1995)
		high exposure		(15)[b]				67.1	38–102	1050	741–1658	
		low exposure		(60)[b]				52.3	38–69	286	22–1331	
	NR	Lead glass processing and lead pigment production	Men	160	36	1–28	NR	55.1	18.1–87.9	NR		Oishi *et al.* (1996a)
			Women	138	28	1–28	NR	54.7	21.5–99.4	NR		

NR, not reported

[a] Arithmetic mean

[b] Number of samples collected during 15 months

Table 70. Lead concentrations in blood of occupationally exposed subjects: welders and solders

Country or area	Year of survey	Job/task	Study population	No. of subjects	Age (years)	Job history (years)	Smoking status	Blood lead (µg/dL)		Lead in air µg/m^3)		Reference
								AM[a]	Range/SD	AM[a]	Range	
Welding												
Jordan	NR	Radiator welding	M	22	27.7	1–40	NR	32.8[b]		NR		Hunaiti *et al*. (1995)
Malaysia	NR	Shipyard welding	M	51	> 18	1–17	Included[c]	12	4–31	NR		Mokhtar *et al*. (2002)
Mexico	NR	Radiator repair	NR	73	33.2	NR	Included	35.5	6.7–79.4	19.1	0–99	Dykeman *et al*. (2002)
				29			Smoker	40.4	13.9–79.4			
				30			Nonsmoker	32.3	14.6–56.9			
Philippines	1999	Radiator mechanic	M + W	16	40.2	16.2	NR	20.0	± 10.6	NR		Suplido & Ong (2000)
	NR	Welding mechanic	M	29	NR	NR	Nonsmoker	9.1	5.0–17.0	NR		Suwansaksri *et al.* (2002)
Thailand	NR	Mechanic	NR	40	NR	NR	Never	11.2	3.9–17.0	0.1–0.5		Suwansaksri & Wiwanitkit (2001)
USA	1992	Radiator repair	M	63	39	11	39% current	29[d]	6.6–94	NR		Dalton *et al.* (1997)
	NR	Radiator repair	NR	56	39.5	NR	52% current	37.1	16–73	NR		Goldman *et al*. (1987)
	1990	Radiator repair	NR	7	NR	NR	NR	NR	17–35	PBZ: 209	< 20–810 TWA: < 10–> 40	Tharr (1993)
	1986	Radiator repair	NR	53	37.1	14.3	60% current	31.7	5–58	Area: 40	0–281	Lussenhop *et al*. (1989)
										PBZ: 113	0–590	
Soldering												
Philippines	NR	Electronic industry	M	21	25.4	1.8	NR	14.9[b]	7–45	NR		Makino *et al*. (1994)
			W	193	21.9	1.8	NR	9.9[b]	3–47	NR		
Singapore	1987	Electronics industry	NR	118	NR	NR	NR	16.1	± 8.5	110	10–1240	Chia *et al*. (1993)

NR, not reported; M, men; W, women; PBZ, personal breathing zone; TWA, time-weighted average

[a] Arithmetic mean, unless specified otherwise

[b] Geometric mean

[c] Stratification by smoking did not reveal a significant difference between values.

[d] Median value

Table 71. Lead concentrations in blood of occupationally exposed subjects: professional drivers and traffic policemen

Country or area	Year(s) of survey	Job/task	Study population	No. of subjects	Age (years)	Job history (years)	Smoking status	Blood lead (µg/dL)		Lead in air (µg/m^3)		Reference
								AM[a]	Range/ SD	AM[a]	Range	
China	1998	Taxi and bus drivers	M	164	NR	NR	75% smokers	10.8[b]	± 1.26	NR		Zhou *et al.* (2001)
Egypt (Alexandria)	NR	Traffic controllers	M	45	20–60	Max., 40	NR	68.3	37–97	NR		Ahmed *et al.* (1987)
Egypt	NR	Traffic policemen	M	126	48.7	9–36	NR	29.2	7.5	NR		Kamal *et al.* (1991)
India	NR	Traffic constables	M	88	41.7	2.7	30%	11.2	0.5–40.2	NR		Potula & Hu (1996a,b)
		Bus drivers	M	22	43.6	5.6	77%	12.1	0.5–35.7	NR		
Indonesia	1983	Policemen	M	24	NR	NR	NR	31	± 18	NR	0.7–6.0	Suzuki (1990)
		Drivers	NR	22	NR	NR	NR	25	± 17	NR	0.7–6.0	
Jordan	NR	Bus drivers, gasoline station workers	NR	47	NR	NR	NR	7.6		NR		Hunaiti *et al.* (1995)
Pakistan	1994–95	Traffic exposed	M	212	19–59	> 1	Included	52.2		NR		Khan *et al.* (1995)
		Traffic police		36				53.4				
		Transportation staff		150				51.1				
		Shopkeepers		36				52.1				

NR, not reported; M, men

[a] Arithmetic mean, unless stated otherwise

[b] Geometric mean

Table 72. Air and blood lead concentrations measured at indoor and outdoor firing ranges

Country	Year(s) of study	Settings/task	No. of subjects and sex	Age (years)	Job history (years)	Blood lead (µg/dL)		Lead in air (µg/m^3)		Reference
						AM[a]	Range	AM[a]	Range	
China (Province of Taiwan)	NR	Employees in indoor range	10	NR	4–21	37.2	22.4–59.6	GA, 134; PBZ, 413	NR	Chau *et al.* (1995)
New Zealand	1990–91	Indoor small-bore rifle range	52 M + W	17–68	Recreational shooters	End of season, 55.0; start of season, 33.3		PBZ, 120 GA, 140–210		George *et al.* (1993)
Sweden	NR	Indoor range								Svensson *et al.* (1992)
		Powder gun	22 M + W	42.4	10.2	13.8[b]	6.9–22.8	660	112–2238	
		Air gun	21 M + W	46.8	13.7	8.4[b]	2.0–22.2	4.6	1.8–7.2	
	1994	On- and off-duty police officers	75 M 3 W	43 32	NR > 9 years	5.0 3.7	1.0–18.2	NR		Löfstedt *et al.* (1999)
United Kingdom	NR	Indoor range for police officers	7	NR	NR	30–59		30–160		Smith (1976)
	NR	Soldiers	35	21.9	4.2	19.25	9.6–30.1	TWA: 190		Brown (1983)
USA	1985	Indoor range		NR	NR			Showroom, 2.7		Novotny *et al.* (1987)
		Full-time employee	2			59–77		Firing line, 13.6		
		Part-time employee	2			17–49		Midway to target, 57.4; Target, 90.5		
	1987	Covered outdoor range	15	NR	NR	5.6 (pre-exposure) 10.7 (day 2) 14.9 (day 5) 8.7 (day 69)		GA, 68.4 PBZ, 128.5	3.8–298.6 34.7–314.3	Tripathi *et al.* (1989)

Table 72 (contd)

Country	Year(s) of study	Settings/task	No. of subjects and sex	Age (years)	Job history (years)	Blood lead (μg/dL)		Lead in air (μg/m^3)		Reference
						AM[a]	Range	AM[a]	Range	
USA (contd)	1987	Indoor range with training 3 Feb.–28 April	17 M + W	24–40	Trainees					Valway *et al.* (1989)
	Jan.-Feb.					6.45	< 5–23.1	1483–1860	304–2688	
	March (early)					51.4	31.2–73.3	2906–3226	994–5589	
	March (late)					44.6	27.1–62.3	1231	553–2567[c]	
	May					39.8	23.1–51.2			
		Lead bullet						1410		
		Nylon-coated						78.3		
		Copper jacketed						43.1		
	1987	Covered outdoor range using copper-jacketed bullets	6	NR	NR	Before shooting, 6.0 ± 1.7 After shooting, 6.5 ± 1.5		GA, 9.53 PBZ, 5.88	5.50–14.56 0.42–7.66	Tripathi *et al.* (1990)
	1987–88	Uncovered outdoor range		NR	NR					Goldberg *et al.* (1991)
	June 1987		7			28–66		–		
	July 1987					–		460–510 (3-h TWA)		
	Dec. 1987		7			25–70		–		
	April 1988		5			–		100–170 (3-h TWA)		
	June 1988					28–38		–		
	1987	Covered outdoor range		NR	Instructors					Tripathi *et al.* (1991)
		Non-jacketed bullets	2			14.2–24.2[d]	10–27	67.1–211.1	36.7–431.5	
		Jacketed bullets	2				13.1–22.1		5.4–8.7	
	1991–93	University rifle range		College students	Recreational shooters					Prince & Horstman (1993)
		Old ventilation system				11.8–16.4	5–21	176	24–239	
		New ventilation system				13.2–13.6	8–23	129	67–211	

GA, general area; NR, not reported; PBZ, personal breathing zone; TWA, time-weighted average

[a] Arithmetic mean, unless stated otherwise

[b] Median value

[c] New ventilation system installed

[d] Range of means of three sampling dates

Table 73. Lead concentrations in blood of occupationally exposed subjects: miscellaneous

Country	Year(s) of survey	Job/task	Sex	No. of subjects	Age (years) mean and/or range	Years of employment	Smoking status	Blood lead (µg/dL)		Lead in air (µg/m^3)		Reference
								AM[a]	Range/SD	AM[a]	Range	
Mechanics/garage												
Denmark	1976	Automobile mechanics	M	138	16–68	NR	NR	40.0–44.8	50–125	3.19	0.2–9.2	Clausen & Rastogi (1977)
Ghana	NR	Automobile mechanics	M	25	17–46	2–29	NR	27.8	0–60	NR		Ankrah *et al.* (1996)
	NR	Gasoline retailers	M + W	40	20–46	0.1–17	NR	8.6	0–20	NR		Ankrah *et al.* (1996)
India	NR	Automobile mechanics	M	22	20–45	NR	NR	NR	24.3–62.4	NR		Kumar & Krishnaswamy (1995b)
	NR	Workers in petrol storage bunkers	NR	22	10–15	> 1	NR	39.3	± 3.7	NR		National Institute of Nutrition (1995–96)
Jordan	NR	Mechanics	M	62	NR	NR	NR	8.1[b]		NR		Hunaiti *et al.* (1995)
Thailand	NR	Repair mechanics	M	23	NR	NR	Non-smokers	8.4	3.9–14.5	NR		Suwansaksri *et al.* (2002)
United Arab Emirates	1999	Heavy industry, garage and painting	M	100	34.8	8.3	NR	77.5		NR		Bener *et al.* (2001)
Others												
Finland	1973–82	Lead-exposed industry workers	M	18 329	33.8 at entry	0–46	NR	29.0–14.5[b,c]		NR		Anttila *et al.* (1995)
			W	2412	37.5 at entry	0–46	NR	20.7–6.2[b,c]				
India	NR	Silver jewellery makers	M	9	25–65	5–40	NR	120.8	40.0–210.0	NR		Behari *et al.* (1983)
	1981	Papier-mâché workers	M + W	30	10–70	NR	NR	69.1	23–122	NR		Kaul & Kaul (1986)
	NR	Silver jewellery workers	M	7	25–70	12–50	NR	113.4	71.0–208.1	NR		Kachru *et al.* (1989)
	NR	Printing press	M	23	20–50	15–30	NR	41.9	± 7.0	NR		Kumar & Krishnaswamy (1995a)
	NR	Papier-mâché workers	M	70	17–40	3–26	NR	68.1	18.2–272.7	NR		Wahid *et al.* (1997)
India	NR	Printing press	M + W	25	18–35	3–5	NR	88	± 30	NR		Agarwal *et al.* (2002)
						6–9		59	± 22			
						9–15		36	± 11			
Italy	NR	Electrician	M	1	20	6	NR	66		NR		Franco *et al.* (1994)

Table 73 (contd)

Country	Year(s) of survey	Job/task	Sex	No. of subjects	Age (years) mean and/or range	Years of employment	Smoking status	Blood lead (μg/dL)		Lead in air ($\mu g/m^3$)		Reference
								AM[a]	Range/SD	AM[a]	Range	
Japan	NR	Ceramic painting	M	58	54.7	1–53	Refrain for 12 h	16.5[b]	3.5–69.5	NR		Ishida *et al.* (1996)
			W	70	52.2	3–47		11.1[b]	2.1–31.5	NR		
	NR	Pigment (lead stearate) production	M	49	48.0 (27–63)	14.5 (2–34)	NR	18.0	7–36	NR		Yokoyama *et al.* (1997)
	NR	Crystal toy production	W	123	27.3 (17–44)	7.2 (0.8–25)	NR	55.4	22.5–99.4	920	390–1910	Nomiyama *et al.* (2002)
	NR	Cloisonné production	NR		NR	NR	NR			NR		Arai *et al.* (1994)
		Glazing		49				47.8	11.3–111			
		Silver-plating		16				11.3	3.2–19.5			
Jordan	NR	Metal casting	M	26	NR	NR	NR	41.6[b]		NR		Hunaiti *et al.* (1995)
		Car painting	M	85	NR	NR	NR	10.7[b]		NR		
Malaysia	NR	Shipyard	M		> 18	< 1–17	Included			NR		Mokhtar *et al.* (2002)
		Painting		15				16	8–38			
		Fabrication		19				12	3–28			
Nigeria (SW)	NR	Lead-exposed industry workers	NR	86	24.8	NR	Included	56.3	26–97 40% > 60	NR		Adeniyi & Anetor (1999)
Pakistan	1994–95	Tannery	M	46	19–59	> 1	Included	60.6	± 3.8	NR		Khan *et al.* (1995)
Philippines	NR	Refrigerator production	M	59	25.7	4.7	NR	21.5[b]	8–38	NR		Makino *et al.* (1994)
			W	6	21.8	2.1	NR	17.5[b]	14–22	NR		
Republic of Korea	1999	Various (24 facilities)	M + W	723	39.4	6.3	61% of smokers	31.7	5.4–85.7	NR		Todd *et al.* (2001a)[d]
	1997–99	Various (26 facilities)	639 M, 164 W	803	40.4	8.2	57% of smokers	32.0	± 15	NR		Schwartz *et al.* (2001)[d]
Singapore	1989	Plastics	NR	104	NR	NR	NR	26.0	± 15.8	NR		Chia *et al.* (1993)
		Metal products	NR	70	NR	NR	NR	32.5	± 13.1	NR		
		Solder production	NR	22	NR	NR	NR	25.0	± 9.1	NR		
		Paint production	NR	88	NR	NR	NR	14.3	± 6.8	NR		
		Telecommunication	NR	218	NR	NR	NR	15.4	± 5.7	NR		
		Ship building	NR	92	NR	NR	NR	17.9	± 6.7	NR		
	NR	PVC compounding	M	61	38.3	ca. 10	NR	23.9	6.7–75.8	35.7	ND–277	Ho *et al.* (1998)

Table 73 (contd)

Country	Year(s) of survey	Job/task	Sex	No. of subjects	Age (years) mean and/or range	Years of employ-ment	Smoking status	Blood lead (µg/dL)		Lead in air (µg/m^3)		Reference
								AM^a	Range/SD	AM^a	Range	
United Kingdom	NR	Painters and decorators	M	3	22–51	NR	NR	[85.5]	84.2–87.1	NR		Gordon *et al*. (2002)
Uruguay	[1993]	Lead–acid battery and lead scrap smelter^e	M	31	NR	9.5	12	49.7	24.4–87.0	NR	3–1300	Pereira *et al.* (1996)
USA	1984	Electronics industry	M + W	151	> 11	NR	NR	8.0	1–22	NR	61–7000	Kaye *et al*. (1987)
	1994	Custodial activities	NR	13	40	8.5	NR	5.4	2.8–10	0.1–3.9	ND–36	Tharr (1997)
	1994–96	Labourers	M	60	38	15.5	NR	11.2	1.2–50	NR		Reynolds *et al.* (1999)
		Painters	M	83	39	16.4	NR	7.0	1.5–26.3	NR		

NR, not reported; M, men; W, women; ND, not detectable

[a] Arithmetic mean, unless stated otherwise

[b] Geometric mean

[c] Decrease over the 10-year study period

[d] [The participants in the study by Todd *et al.* (2001a) most likely are included in the study by Schwartz *et al.* (2001).]

[e] Two storage battery plants (n = 16, n = 8); lead scrap smelter (n = 6); one self–employed storage battery reconditioner

Table 74. NIOSH Health Hazard Evaluation reports with air and/or blood lead concentration data, 1978–2003

Industry	Year(s) of study	Blood lead (µg/dL)			Air lead ($\mu g/m^3$)				Reference
		No. of workers tested	AM[a]	Range	No. of samples taken	Type of sampling	AM[a]	Range	
Bridge, tunnel and elevated highway construction: deleading	1980								Landrigan *et al.* (1980)
Grit blasting		13	33	25–47	4	PBZ	305	10–1090	
Scraping and priming		19	61	30–96	3	PBZ	391	24–1017	
Bridge, tunnel and elevated highway construction: repainting	1990–91								Sussell *et al.* (1992a)
Inside containment					8	PBZ	[13 671]	3620–29 400	
Inside containment, inside hood					6	PBZ	[78]	9–194	
Outside containment					16	PBZ		5–6720[b]	
						GA		ND–8170	
Heavy abrasive blasting	Spring 1991	23		5–61					
Moderate abrasive blasting	Summer 1991	12		13–43					
Bridge, tunnel and elevated highway construction: renovation	1993	22	7.2	2.2–16.5					Ewers *et al.* (1995)
Blaster/painter					24	PBZ	250	3–1800	
Apprentice					11	PBZ	110	1–680	
Recycling equipment operator					2	PBZ	140	100–180	
Commercial testing laboratories	1986	10		> 17–192					Gunter *et al.* (1986)
Lakewood, CO					8	PBZ + GA	321	90–800	
Sparks, NV					14	PBZ + GA	114	4–490	
Copper foundries	1991	10	21	10–39	7	PBZ	NA	ND–172	Clark *et al.* (1992)
Electric services	1991	43	20	< 5–43	18	PBZ	[9.4]	1.2–55	Venable *et al.* (1993)
Electric services	1995	NR	NR		43	PBZ	NA	ND–181	Mattorano (1996)
Electronic components	1993	NR	NR		3	PBZ	NA	ND–36	Blade & Bresler (1994)
Electronic components	1993	7	19	9–27			NR		Guo *et al.* (1994)
Fabricated metal products	1987	3	31	25–43	4	PBZ	[803]	7.3–1900	Lee (1987)
Fabricated plate work	1991	9	32	10–51			NR		Hales *et al.* (1991)

Table 74 (contd)

Industry	Year(s) of study	Blood lead (µg/dL)			Air lead (µg/m^3)				Reference
		No. of workers tested	AM[a]	Range	No. of samples taken	Type of sampling	AM[a]	Range	
Fabricated plate work	1991	17	34	11–77					McCammon *et al.* (1991)
Lead burners					3	PBZ	[254]	215–307	
Tinning					3	PBZ-LT	[354]	282–390	
Grinding					4	PBZ-LT	[32]	0–46	
General contractors, industrial buildings and warehouses	1989	16	[10]	3–21					Stephenson & Burt (1992)
Oxyacetylene cutting					6	PBZ	522	160–1300	
Other renovation tasks					9	PBZ	NA	ND–2	
General contractors, single family houses: lead paint abatement	1989–91	95		ND–27	1402 1233	PBZ GA	3.1[c] 2.0[c]	< 0.4–916 < 0.4–1296	Sussell *et al.* (1992b)
General contractors, single family houses	1993	53	5.2[c]	NR–17.5	13 37 77	PBZ GA Task-based PBZ	3.2[c] 0.6[c] 0.2–9.1[c]	0.05–12 0.1–25 0.03–120	Sussell *et al.* (1997)
General contractors, single family houses	1998	NR	NR						Sussell & Piacitelli (1999)
Manual paint scraping					5	PBZ-ST	NA	< 1–250	
Power paint removal					6	PBZ-ST	[5054]	54–27 000	
General contractors, single family houses	1996–98	40	16	1–65	20 152	PBZ Task-based PBZ	29[c] 1.3–150	1.5–1100 0.17–2000	Sussell *et al.* (2000)
General contractors, single family houses	1999	NR	NR		128 130	PBZ GA	22[c] 1.5[c]	ND–660 ND–37	Sussell & Piacitelli (2001)
General contractors, single family houses	1999	NR	NR		15 5 79	PBZ GA Task-based PBZ	100[c] [2.2] 71[c]	39–526 0.29–6.1 1.4–2240	Sussell *et al.* (2002)
Glass products, stained glass art studio	1986	3	[19]	7–33	7	PBZ + GA	80	10–260	Gunter & Thoburn (1986a)
Glass products, made from purchased glass	1991	18	12	< 10–24	4	PBZ	18	7–35	Lee (1991)
Glass products, made from purchased glass	1993	2	2	1.8–2.1	17 13	PBZ GA	NA NA	ND–80 ND–0.7	Donovan (1994)
Gold ores (fire assay)	1987	NR	NR		4 5	PBZ GA	76 48	36–117 14–100	Daniels (1988)

Table 74 (contd)

Industry	Year(s) of study	Blood lead (µg/dL)			Air lead (µg/m^3)				Reference
		No. of workers tested	AM[a]	Range	No. of samples taken	Type of sampling	AM[a]	Range	
Gold ores (fire assay)	1989								Daniels & Hales (1989)
Assay laboratory personnel		6	42	23–65	1	PBZ	850[d]		
Non-assay laboratory personnel		5	18	7–36	6	GA	NA	ND–110	
Gold ores (fire assay)	1989	6	42	23–65	1	PBZ	170		Daniels *et al*. (1989)
					4	GA	NA	ND–170	
Gold ores (fire assay)	1989	6	37	13–55	3	PBZ	[112]	15–200	Lee *et al*. (1990a)
					5	GA	[26]	6–61	
Gold ores, assay laboratory	1989	2	< 40		1	PBZ		10[d]	Hales & Gunter (1990)
					3	GA		10–30[d]	
Grey iron foundries	1985	NR	NR		4	PBZ	NA	ND–70	Gunter (1985)
					3	GA	53	30–70	
Heavy construction	1991	6							Sussell *et al*. (1992c)
Before blasting			34 before job	15–44	6	PBZ	ND–35		
During blasting, outside containment				6–43	5	PBZ	ND–47		
			28 during job		4	GA	620–3000		
During blasting, inside containment, inside helmet						PBZ		16–25	
Industrial inorganic chemicals	1980–81	79	35	NR–69	75	PBZ	13–79	0–359	Landrigan *et al*. (1982)
Industrial valves	1989	25	15	< 20–33	2	PBZ	[91]	87–94	Kinnes & Hammel (1990)
					4	GA	[69.5]	32–120	
Inorganic pigments	1981	228	8–32						Slovin & Albrecht (1982)
Bagging zinc oxide					11		[33]	9–96	
Mixing zinc oxide					5		[34]	16–68	
Mixing barium ores					7		[9]	ND–15	
Mixing of inert clays					4		[2]	ND–8	
Motor vehicle parts and accessories	1981	66	23	11–52	25	PBZ	37	7–113	Zey & Cone (1982)
Motor vehicle parts and accessories	1983	14	31 ± 12		7	PBZ	[49]	25–104	Ruhe & Thoburn (1984)
Motor vehicle parts and accessories	1986	5	< 29–60		4	PBZ	[172]	40–380	Gunter & Thoburn (1986b)
					4	GA	[68]	20–190	

Table 74 (contd)

Industry	Year(s) of study	Blood lead (μg/dL)			Air lead ($\mu g/m^3$)				Reference
		No. of workers tested	AM[a]	Range	No. of samples taken	Type of sampling	AM[a]	Range	
Motor vehicle parts and accessories	1988	8	[29]	8–44	10	PBZ + GA	160	10–290	Gunter & Hammel (1989)
Motor vehicle parts and accessories	1987–88	28	[9]	< 5–43		NR	NR		Driscoll & Elliott (1990)
Motor vehicle parts and accessories	1989	2	[34]	30–37	2	PBZ	[70]	60–80	Gunter & Hales (1990a)
Motor vehicle parts and accessories	1989	7	32	17–64					Gunter & Hales (1990b)
Radiator mechanics		5	38	23–64	4	PBZ	[28]	10–50	
Delivery employees		2	17.5	17–18	2	GA	[55]	20–90	
Motor vehicle parts and accessories	1989								Gunter & Hales (1990c)
Radiator mechanics		4	[30]	13–41	4	PBZ	[98]	30–220	
Delivery employees		2	[18]	14–21					
Motor vehicle parts and accessories: mechanics and delivery employees	1989	4	[21]	11–33	3	PBZ	[43]	20–60	Gunter & Hales (1990d)
					1	GA	90		
Nitrogenous fertilizers	1991	13		4–13	9	PBZ		ND–7	Decker & Galson (1991)
					7	GA		ND–12	
Non-ferrous foundries (castings)	1988	18	[34]	4–67	6	PBZ	[294]	38–520	Montopoli *et al.* (1989)
Police protection (indoor firing range)	1982	NR	NR		5	PBZ	[1130][d]	940–1300[d]	Bicknell (1982)
					6	GA	[1120][d]	750–1520[d]	
Police protection (indoor firing range)	1987–88	NR	NR		4	PBZ	142–2073	102–3361	Reh & Klein (1990)
						8-h TWA		13–194[d]	
Police protection (indoor firing range)	1991	NR	NR		5	PBZ	14	7–23	McManus (1991)
						8-h TWA		< 3[d]	
Police protection (indoor firing range)	1991	NR	NR						Echt *et al.* (1992)
Student					26	PBZ	26–32[d]	1–116[d]	
Range officer					14	PBZ	16–18[d]	0.15–53[d]	
General area					13	GA		0.15–2450	
Police protection (indoor firing range)	1991	NR	NR		10		5.4[d]	1–16[d]	Lee & McCammon (1992)

Table 74 (contd)

Industry	Year(s) of study	Blood lead (µg/dL)			Air lead (µg/m^3)				Reference
		No. of workers tested	AM[a]	Range	No. of samples taken	Type of sampling	AM[a]	Range	
Police protection (outdoor firing range)	1991	NR	NR		16	PBZ	ND–8[d]	NR	Rinehart & Almaguer (1992)
Police protection (indoor firing range)	1992	NR	NR		3	PBZ	6[d]	5–7[d]	Cook *et al.* (1993)
					13	GA	NA	ND–845	
Police protection (in- and outdoor firing ranges)	1989–91								Barsan & Miller (1996)
Instructor		7–14	8–15	< 4–27	NR	PBZ	12.4	ND–52	
Technician		5	10–16	6–28	12	PBZ	0.6	ND–2.7	
Gunsmith		5–11	11–12	< 4–24	18	PBZ	0.6	ND–4.5	
Custodian		6	< 4		3	PBZ	NA	ND–220	
Police protection (indoor firing range)	1997–98	NR	NR						Harney & Barsan (1999)
1997 (during shooting)					9	PBZ + GA	144[d]	4–190[d]	
1998 (during shooting)					20	PBZ + GA[e]	230[d]	ND–640[d]	
					8	PBZ + GA[f]	433[d]	100–960[d]	
Pressed and blown glass and glassware	1984	12	20	2–36	4	PBZ	52	30–60	Gunter & Thoburn (1985)
					2	GA	75	70–80	
Pressed and blown glass and glassware	1986	9	13	4–33	16	PBZ + GA	NA	ND–80	Gunter (1987)
Pressed and blown glass and glassware	1997	NR	NR		7	GA	[17]	1.6–51	Hall *et al.* (1998)
Primary smelting and refining of copper	1984	49	11	0–24	15	PBZ + GA	NA	< 3–60	Gunter & Seligman (1984)
Secondary smelting and refining of non-ferrous metals	1989	12	29	5–63	5	PBZ	NA	< 2–40	Gunter & Daniels (1990)
					2	GA	NA	< 2–50	
Primary and secondary smelting and refining of non-ferrous metals	1981	3	32	26–37	6	PBZ	123	5–295	Apol (1981)
					9	GA	NA	ND–1334	
Refuse systems	1990–91	NR	NR		6	PBZ	NA	ND–30[d]	Mouradian & Kinnes (1991)
					4	GA	NA	ND–30[d]	
Scrap and waste materials	1987	6		4–33	10	PBZ + GA	NA	ND–2.3	Hills & Savery (1988)
Scrap and waste materials	1991	15	66	9–86		NR			Gittleman *et al.* (1991)
Scrap and waste materials	1993	16	20	4–40		NR			Malkin (1993)

Table 74 (contd)

Industry	Year(s) of study	Blood lead (µg/dL)			Air lead (µg/m^3)				Reference
		No. of workers tested	AM[a]	Range	No. of samples taken	Type of sampling	AM[a]	Range	
Ship breaking, ship repair, dismantling ships	1998	NR	NR						McGlothlin *et al.* (1999)
Inside a ship					4	PBZ	[355]	253–435	
Process area					5	PBZ	[189]	41–399	
Inside barge tank					5	PBZ	[198]	79–356	
Under a barge					4	PBZ	NA	< 0.6–2.5	
Shipbuilding and repairing	1985	10	38	25–53	7	PBZ	257	108–500	Landrigan & Straub (1985)
Shipbuilding and repairing	1994	NR	NR		14	PBZ-ST	[133]	3–900	Sylvain (1996)
Shipbuilding and repairing	1997	67	4.4	0–18	347	PBZ	32	0–1071	Kiefer *et al.* (1998)
Special trade contractors: cleaning of lead-based paint	1992	NR	NR		36	PBZ-ST	66	5–360	Sussell *et al.* (1993)
					5	PBZ	30	6–73	
					18	GA-ST	44	4–180	
Steel works, blast furnaces (including coke ovens)	1984	26	33		27	PBZ	40	< 3–190	Gunter & Thoburn (1984)
Steel works, blast furnaces (including coke ovens)	1980–82	79	8–15	1–33	42	NR	NR	NR–79	Hollett & Moody (1984)
Steel works, blast furnaces (including coke ovens)	1989	22	18		20	PBZ	12	< 3–31	Lee *et al.* (1990b)
Steel works, blast furnaces (including coke ovens)	1990	NR	NR		12	[PBZ]	[16]	1.3–44.2	Tubbs *et al.* (1992)
Storage batteries	1983–84	317	10–39	3–58	675	PBZ	30	1–1600	Singal *et al.* (1985)
Storage batteries	1987								Matte & Burr (1989a)
Location 1		27	31–47	NR–64	26	PBZ	[652]	40–5300	
					2	GA	[7]	4–10	
Location 2		12	65[c]	NR–89	10	PBZ	[860]	50–3400	
Location 3		6	28–> 60		3	PBZ	[100]	30–190	
					3	GA	[57]	10–100	
Storage batteries	1987	23	64[c]	28–86	7	PBZ	21[c]	NR–66	Matte & Burr (1989b)
Storage batteries	1991	43	41	12–66	12	PBZ	[276]	9–846	Clark *et al.* (1991)
					2	GA	[59]	10–107	

Table 74 (contd)

Industry	Year(s) of study	Blood lead (µg/dL)			Air lead (µg/m^3)				Reference
		No. of workers tested	AM[a]	Range	No. of samples taken	Type of sampling	AM[a]	Range	
Storage batteries	1994–95	111		30–43					Esswein *et al.* (1996)
Pasting operation					19	PBZ	291	68–495	
					4	GA		1–165	
First assembly					12	PBZ	108	15–418	
					5	GA		13–39	
Pouching					7	PBZ	50	31–77	
					8	GA		11–51	
Grid casting					3	PBZ		12–43	
					6	GA		16–141	
Tanks, fabricated plate work	1991	22	23	4–38	22	PBZ	[352]	23–1970	McCammon *et al.* (1992)
Valves and pipe fittings	1981	2	< 30		2	PBZ	[45]	10–80	Ruhe (1982a)
Valves and pipe fittings	1981	2	< 30		2	PBZ	[839]	321–1356	Ruhe (1982b)

AM, arithmetic mean; PBZ, personal breathing zone; NA, not applicable; ND, not detected; NIOSH, National Institute for Occupational Safety and Health (USA); NR, not reported; GA, general area; ST, short-term; TWA, time-weighted average; LT, long-term; [....] calculated by the Working Group

[a] Unless otherwise stated

[b] Highest value probably a contaminated sample; next highest values at 202 µg/m^3

[c] Geometric mean

[d] 8-h TWA value calculated from a short-term sample, assuming no other lead exposure during the day than during sampling

[e] Measured with 37-mm cassette

[f] Measured with Institute of Occupational Medicine (IOM) sampler

(*a*) *Lead–acid battery workers*

Blood lead concentrations have been studied most extensively in workers in lead storage-battery factories (Table 66). Occupational exposure to lead may occur during the production of lead–acid batteries, when grids are manufactured either by melting lead blocks and pouring molten lead into molds or by feeding rolled sheets of lead through punch presses. In addition, a lead oxide paste is applied into grid spaces. Average lead concentrations in blood were generally in the range 20–45 µg/dL. Particularly high concentrations (> 65 µg/dL) were detected in workers engaged in grid casting in a study in Iraq (Mehdi *et al.*, 2000), in workers at several workstations in a study from Israel (Richter *et al.*, 1979) and in a study in Taiwan, China (Wang *et al.*, 2002b).

(*b*) *Workers in mining and primary smelting*

The most commonly mined lead ore is *galena* (87% lead by weight), followed by *anglesite* (68%) and *cerussite* (78%). Workers in lead smelter and refinery operations such as sintering, roasting, smelting and drossing are exposed to lead sulfide, sulfates and oxides. Miners of copper and zinc also are exposed to lead.

Relatively high blood lead concentrations (> 60 µg/dL) have been recorded in such workers, in particular in two studies in Nigeria (Adeniyi & Anetor, 1999) and in Uruguay (Pereira *et al.*, 1996) (Table 67).

(*c*) *Workers in secondary smelting*

Battery-recycling workers in secondary smelters are exposed to lead as they convert used batteries and other leaded materials to lead of varying purity. From Table 68, it appears that the mean blood lead concentrations reported for workers in secondary lead smelters were higher than for workers in other occupations (see Tables 66–73). Of the different job categories within secondary smelting, the highest mean blood lead concentrations (87 µg/dL) were observed in workers in charge of furnace operation (Wang *et al.*, 1998). In some individual workers, blood lead concentrations in excess of 150 µg/dL were measured (Makino *et al.* 1994).

(*d*) *Workers in leaded-glass manufacturing*

Leaded glassware is made by combining lead oxide compounds with molten quartz. This process results in lead fumes and dusts, and glass-blowing is an additional activity that involves potential contact with lead. Production of leaded glass has been associated with high lead exposure, with mean blood lead concentrations in excess of 50 µg/dL in all studies (Table 69).

(*e*) *Workers in welding/soldering*

Typical solders contain 60% lead and the high temperatures involved in flame solder work volatilize some of this lead. Workers repairing vehicle radiators are exposed to lead dusts during radiator cleaning in addition to lead fumes during flame soldering (Tharr, 1993).

Surveys on welding work in radiator-repair workers (Table 70) generally showed mean blood lead concentrations in the range of 10–35 µg/dL. A study of 56 mechanics working in radiator shops in the Boston area, USA, reported that 80% had blood lead concentrations greater than 30 µg/dL and 16 had concentrations > 50 µg/dL (Goldman *et al.*, 1987). Relatively high blood lead concentrations (up to 47 µg/dL) were also reported among women engaged in soldering in an electronics plant (Makino *et al.*, 1994).

Welders are exposed to lead in the welding fumes generated by gas metal arc welding of carbon steel. However, in one study, lead concentrations in the welding fumes were found to range from 1.0 to 17.6 µg/m^3, well below the established permissible exposure limit for the workplace (Larson *et al.*, 1989).

(*f*) *Professional drivers and traffic controllers*

Professional drivers (e.g. taxi and bus drivers) and traffic policemen are exposed to lead in ambient air from vehicle exhausts (Table 71). The blood lead concentrations reported are distributed over a wide range, from 10 µg/dL (Zhou *et al.*, 2001) to > 60 µg/dL (Ahmed *et al.*, 1987), probably as a result of variations in traffic intensity and use of leaded gasoline.

(*g*) *Firing-range instructors*

Lead exposure associated with the discharge of firearms at indoor firing ranges began to be monitored in the early 1970s. Over the last 20 years, numerous exposure assessments have been performed at both indoor and outdoor firing ranges (Table 72). Several sources of airborne lead have been identified: fragmentation of bullets during firing; the explosive vaporization of the primer, which can contain both lead styphnate and lead peroxide; and inadequate ventilation of the range (Landrigan *et al.*, 1975b; Fischbein *et al.*, 1979; Muskett & Caswell, 1980; Dams *et al.*, 1988). Instructors are generally exposed to the highest concentrations of airborne lead and tend to have the highest blood lead concentrations due to their regular duties, which include supervising the range, cleaning and test-firing weapons, and preparing training ammunition from commercially purchased components. A positive correlation was reported between exposure of firearms instructors to elemental lead at covered outdoor firing ranges and increased blood lead concentrations (Tripathi *et al.*, 1991). Concentrations of airborne lead can be significantly reduced (97–99%) by using a lead-free primer and bullets jacketed with nylon, brass or copper (Valway *et al.*, 1989; Robbins *et al.*, 1990; Tripathi *et al.*, 1990, 1991; Goldberg *et al.*, 1991; Löfstedt *et al.*, 1999; Bonanno *et al.*, 2002).

(*h*) *Other occupational exposures*

Several studies have found elevated blood lead concentrations in other occupational settings, such as in employees working in automobile garages. Mean blood lead concentrations in children working in petrol storage bunkers in India for more than one year were almost double (39.3 ± 3.7 μg/dL) those of age-matched unexposed children (23.1 ± 0.5 μg/dL) (National Institute of Nutrition, 1995–1996).

Silver jewellery workers are exposed to high concentrations of lead and may have blood lead concentrations > 200 μg/dL (Behari *et al.*, 1983; Kachru *et al.,* 1989).

People working in arts and crafts may be exposed to lead in paints, ceramic glazes and lead solder used in sculpture and stained glass (Hart, 1987; Fischbein *et al.*, 1992).

Newspaper printing has been associated with lead exposure (Agarwal *et al.*, 2002). In one study, more than 3/4 of the monocasters showed some clinical symptoms of lead poisoning (Kumar & Krishnaswamy, 1995a). Where computerized printing techniques have replaced the traditional printing techniques, however, lead exposure is no longer a significant concern in this profession.

1.5 Analysis

Analysis of lead and lead compounds in various matrices has been reviewed (Fitch, 1998).

1.5.1 *Environmental samples*

Although lead occurs in the environment in the form of a range of inorganic or organic compounds, it is always measured and expressed as elemental lead. Determination of lead in environmental samples requires sample collection and sample preparation, often by wet or dry ashing or acid digestion to solubilize lead in aqueous solution before analysis. Care must be taken during sampling and sample preparation to avoid contamination or loss of lead (WHO, 1995).

The techniques most commonly used for the analysis of particulate lead and inorganic lead compounds in air, water, dust, sediments, soil and foodstuffs include flame atomic absorption spectrometry (AAS), graphite furnace–atomic absorption spectrometry (GF–AAS), inductively coupled plasma–mass spectrometry (ICP–MS), inductively coupled plasma–atomic emission spectrometry (ICP–AES), anode-stripping voltametry (ASV) and X-ray fluorescence (XRF).

Organic lead species such as tetramethyl lead and tetraethyl lead can be trapped cryogenically or by liquid or solid sorbents. Gas chromatography (GC) coupled with GF–AAS or photoionization detection (PID) can be used to differentiate between organic lead species (Birch *et al.*, 1980; De Jonghe *et al.*, 1981; Chakraborti *et al.*, 1984; NIOSH, 1994a; ATDSR, 1999).

Selected methods used for the analysis of lead in various matrices are presented in Table 75.

Table 75. Selected methods for analysis of lead in various matrices

Matrix	Method[a]	Detection limit	Method number	Reference[b]
Air	Flame AAS	2.6 µg/sample	Method 7082	NIOSH (1994b)
	GF–AAS	0.02 µg/sample	Method 7105	NIOSH (1994a)
	ICP–AES	0.062 µg/sample	Method 7300	NIOSH (2003a)
	ASV	0.09 µg/sample	Method 7701	NIOSH (2003b)
	XRF	6 µg/sample	Method 7702	NIOSH (1998)
	AAS or AES	0.01 µg/mL (qual.) 0.05 µg/mL (anal.)	Method ID-121	OSHA (2002a)
	ICP–AES	2.1 µg/sample (qual.)	Method ID-125G	OSHA (2002b)
	ICP–AES	0.071 µg/mL (qual.) 0.237 µg/mL (quant.)	Method ID-206	OSHA (2002c)
	XRF	22 µg/sample	Method OSS-1	OSHA (2003)
Air (TEL)[c]	GC–PID	0.1 µg/sample	Method 2533	NIOSH (1994c)
Air (TML)[d]	GC–PID	0.4 µg/sample	Method 2534	NIOSH (1994d)
Water	ICP–AES	42 µg/L	Method D1976	ASTM (2002)
	ICP–MS	0.08 µg/L	Method D5673	ASTM (2003a)
	XRF	1 µg/L	Method D6502	ASTM (2003b)
	AAS	100 µg/L	Method 239.1	US EPA (1978)
Ambient water	ICP–MS	0.0081 µg/L	Method 1640	US EPA (1997a)
	GF–AAS	0.036 µg/L	Method 1637	US EPA (1996c)
	ICP–MS	0.015 µg/L	Method 1638	US EPA (1996d)
Marine water	GF–AAS	2.4 µg/L	Method 200.12	US EPA (1997b)
	ICP–MS	0.074 µg/L	Method 200.10	US EPA (1997c)
Soil, wastes and groundwater	AAS	100 µg/L	Method 7420	US EPA (1986b)
	GF–AAS	1 µg/L	Method 7421	US EPA (1986c)
Marine sediment and soils	GF–AAS	0.2 µg/g	Method 140.0	NOAA (1998a)
	ICP–MS	0.15 µg/g	Method 172.0	NOAA (1998b)
	XRF	0.2 µg/g	Method 160.0	NOAA (1998c)
Aqueous and solid matrices	ICP–AES	28 µg/L	Method 6010C	US EPA (2000)
Food	GF–AAS	0.1 mg/kg	Method 999.10	AOAC (2000a)
	AAS	NR	Method 972.25	AOAC (2000b)
Evaporated milk and fruit juice	ASV	5 ng/sample	Method 979.17	AOAC (2000c)
Sugars and syrups	GF–AAS	3.3 µg/kg	Method 997.15	AOAC (2000d)
Edible oils and fats	GF–AAS	18 µg/kg	Method 994.02	AOAC (1994)

Table 75 (contd)

Matrix	Method[a]	Detection limit	Method number	Reference[b]
Ceramic foodware	AAS GF–AAS	NR NR	Method 4-1 Method 4-2	US FDA (2000a) US FDA (2000b)
Paint, soil, dust, air	ICP–AES AAS GF–AAS	Variable, NR Variable, NR Variable, NR	Method E1613	ASTM (1999)

NR, not reported

[a] AAS, atomic absorption spectrometry; ASV, anode-stripping voltametry; GD–PD, gas chromatography–photoionisation detector; GF–AAS, graphite furnace atomic absorption spectrometry; ICP–AES, inductively-coupled plasma atomic emission spectrometry; ICP–MS, inductively-coupled plasma mass spectrometry; XRF, X-ray fluorescence

[b] NIOSH, National Institute for Occupational Safety and Health; OSHA, Occupational Safety and Health Administration; ASTM, American Society for Testing and Materials; AOAC, Association of Official Analytical Chemists; US EPA, US Environmental Protection Agency; NOAA, National Oceanic and Atmospheric Administration; US FDA, US Food and Drug Administration

[c] TEL, tetraethyl lead

[d] TML, tetramethyl lead

Use of lead isotope ratios in source attribution and apportionment

Stable lead isotopes have been used to identify the source(s) of lead in environmental and biological samples (source attribution and apportionment). Lead isotopes vary over geological time because they are the end-product of radioactive decay of uranium and thorium. Thus, lead deposits of different geological age have different lead isotope ratios; e.g. the major Broken Hill lead–zinc–silver mine deposit in Australia formed approximately 1700–1800 million years ago has an isotope ratio expressed as the $^{206}Pb/^{204}Pb$ ratio of 16.0. In contrast, geologically younger deposits formed approximately 400–500 million years ago, found on the same continent and in various places around the world, have a $^{206}Pb/^{204}Pb$ ratio of about 18.0 (Gulson, 1986, 1996a).

Techniques have been developed to measure lead isotope ratios in environmental and biological samples. Lead is extracted from samples by acid digestion and separated from potentially interfering cations (iron, zinc) by anion-exchange chromatography. Lead isotopes are measured as ratios (e.g. $^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, $^{206}Pb/^{204}Pb$) by solid source thermal ionization–mass spectrometry or ICP–MS (Franklin *et al.*, 1997; Eades *et al.*, 2002).

Lead in the environment and in humans (and animals) is often a mixture of lead originally derived from different mines, and it is possible to estimate the relative contribution of the different sources. Where there are two major sources, the estimation is straightforward. For example, if the lead present in a blood sample with a $^{206}Pb/^{204}Pb$ ratio of 17.5 comes from two major sources, the skeleton (ratio of 17.0) and diet (ratio of 18.0), there is an equal contribution to blood from both sources. For three or more sources, the attribution becomes more complex and requires application of specialized computational procedures (Franklin *et al.*, 1997).

1.5.2 *Biological indicators of lead contamination in soil and water*

Lead affects many physiological parameters in plants (Singh *et al.*, 1997). Plants and some fungi synthesize cysteine-rich low-molecular-weight peptides called phytochelatins (class III metallothioneins) in response to heavy metal stress (Grill *et al.*, 1985). Phytochelatins have the general structure $(\gamma\text{-Glu-Cys})_n\text{-Gly}$ ($n = 2–11$); the majority of legumes (of the order Fabales), on the other hand, synthesize homophytochelatins in which the carboxy-terminal glycine is replaced by β-alanine (Grill *et al.*, 1986). For example, when exposed to lead, roots of *Vicia faba* synthesize phytochelatins, *Phaseolus vulgaris* synthesizes homophytochelatins, and both phytochelatins and homophytochelatins are induced in *Pisum sativum* (Piechalak *et al.*, 2002). These peptides are involved in accumulation, detoxification and metabolism of metal ions including lead (Grill *et al.*, 1985; Mehra & Tripathi, 2000). Phytochelatins detoxify metal by thiolate coordination (Grill *et al.*, 1987). They are synthesized enzymatically from glutathione or its precursor by the enzyme γ-glutamyl cysteine dipeptidyl transpeptidase, also called phytochelatin synthase; the enzyme is present constitutively in cells and is activated by heavy metal ions (Grill *et al.*, 1989). Thus, phytochelatins are synthesized enzymatically in response to exposure to many metals including lead (Grill *et al.*, 1987; Scarano & Morelli, 2002).

Phytochelatins can be detected by high-performance liquid chromatography (HPLC) (Grill *et al.*, 1991) and thus have the potential to be used as plant biomarkers of heavy metal contamination of soil and water. There are ample laboratory and field data indicating that phytochelatins are biological indicators of exposure to metals, including lead (Ahner *et al.*, 1994; Pawlik-Skowronska, 2001; Pawlik-Skowronska *et al.*, 2002).

1.5.3 *Biological samples*

Lead distribution between blood, soft tissue and hard tissue is complex (see Section 4.1 for details). The time required for equilibration of lead between tissues is dependent upon the type of tissue and varies from hours to decades. In addition, equilibration between tissues is subject to a variety of physiological states that affect bone metabolism. Hence, exposure to lead can be estimated by the analysis of various human tissues, either directly for lead or indirectly for biomarkers of exposure to lead. The tissues include blood, plasma, urine, saliva, bone, teeth, nails and hair. The following section summarizes the methods used for the direct determination of lead in tissues and the indirect determination of exposure to lead using biomarkers. Methods that measure distribution of lead throughout the body are discussed in Section 4.1.

(*a*) *Analysis in hard tissues*

(i) *Bone*

Exposure to lead over time results in the progressive accumulation of lead, predominantly (> 95% of total lead burden) in bones (Barry, 1975). Hence, the analysis of lead in bones is a suitable approach to determine exposure to lead during the lifetime of an individual. Using GF–AAS to measure lead concentrations in bone tissue from individuals from prehistoric and modern times, it has been estimated that the body burden of lead in humans in the late 20th century is more than twice that of the late Roman times (Drasch, 1982). Since GF–AAS analysis cannot be performed on human bone *in vivo*, various XRF methods have come into use as a direct measure of lead in bone (Todd & Chettle, 1994). XRF is based on the property of lead to emit X-rays when it is exposed to photons of an appropriate energy; the fluorescence from lead accumulated in bone provides a low-risk, non-invasive measure of total lead content. In the 1990s, XRF analysis was limited to research institutions and was deemed unlikely to become a useful screening tool for exposure to lead (Todd & Chettle, 1994). Intrinsic variability in the instruments used, variability of lead deposition between the two main compartments of bone (cortical versus trabecular), patients' bone density and the use of a minimal detectable limit all increase the complexity of data analysis in epidemiological studies (Hu *et al*., 1995; Kim *et al*., 1995b). Efforts continue to improve understanding of the variables that affect the XRF signal (Hoppin *et al*., 2000; Todd *et al*., 2000a, 2001b) and to use XRF for meaningful epidemiological analysis (Hoppin *et al*., 1997; Roy *et al*., 1997; Markowitz & Shen, 2001). XRF has been used successfully to study the factors involved in the mobilization of lead from bone (Schwartz *et al*., 1999; Oliveira *et al*., 2002). With the understanding that bone lead is probably the best overall indication of lifetime exposure to lead (Börjesson *et al*., 1997; Hu, H. *et al*., 1998), it is reasonable to consider application of XRF to the analysis of the contribution of exposure to lead to the development of cancer.

(ii) *Teeth*

The dentin of shed deciduous teeth (also known as baby teeth) is a suitable source for analysis of prior and current lead exposure in children during their teeth-shedding years (Gulson, 1996a; Kim *et al*., 1996a) but this method suffers from the limited availability of samples. It has been estimated that deciduous tooth lead (measured in ppm or μg/g) correlates with about half the value of blood lead (measured in μg/dL), but that this correlation does not hold for the permanent, adult teeth (Rabinowitz, 1995). The studies to determine lead concentrations in teeth each include a specific method for digestion of the tooth, followed by analysis of lead by ASV, ICP–MS or AAS.

(iii) *Hair and nails*

Available data on analysis of lead in hair can be divided into three groups. The first group of studies describe hair analysis as a general toxicological screen for heavy metals. In this case, the primary concerns are sample preparation, i.e. washing, with the intent to remove surface contamination. A recent study of six commercial laboratories advertising multimineral hair analysis showed high variability between laboratories, thus giving cause for concern about the validity of these results (Seidel *et al.*, 2001). The second use of hair lead analysis has been for patients suspected of having chronic, mild or subacute lead poisoning (Kopito *et al.*, 1967). The third documented use is in epidemiologial studies (Tuthill, 1996). However, an analysis of the distribution of heavy metals in tissues of 150 corpses concluded that hair was not an appropriate tissue for monitoring exposure to lead (Drasch *et al.*, 1997). In general, the available data do not support the use of hair as a resource for analysis of exposure to lead.

The use of nails seems attractive as a non-invasive approach to determining exposure to lead. However, lead concentrations in nails is not a reliable indicator of exposure to lead (Gulson, 1996b).

(*b*) *Analysis in soft tissues and body fluids*

(i) *Blood*

The benchmark for analysis of lead exposure is the determination of blood lead concentrations by AAS. Using this method, lead is typically reported in μg/dL, which can be converted to concentration in μM (μmol/L) by dividing the value reported in μg/dL by 20.7.

Analytical methods have changed over time because health-based standards and guidelines have changed. For example, the intervention level set by CDC in the USA has dropped from 60 μg/dL to 35 μg/dL in 1975, to 25 μg/dL in 1985, and to 10 μg/dL in 1991 (CDC, 1991).

Analytical methods used to determine lead concentrations in whole blood detect both the lead associated with proteins in the erythrocytes and that in the plasma (Everson & Patterson, 1980; Cake *et al.*, 1996; Manton *et al.*, 2001). The relationship between lead in whole blood, in erythrocytes and in plasma is discussed in detail in Section 4.2.1. Lead in blood is in equilibrium between the plasma and the erythrocytes. Since the plasma fraction has a greater bioavailability than the lead pool in the red blood cells and is in equilibrium with extravascular compartments, the lead content of plasma should be considered to be a better estimate of the internal dose than the concentration of the metal in whole blood (Cavalleri & Minoia, 1987; Schütz *et al.*, 1996). To obtain an accurate quantification of low concentrations of lead in plasma, Everson and Patterson (1980) introduced the technique of isotope-dilution mass spectrometry and concluded that prior studies had grossly overestimated the amount of lead in the plasma compartment of blood. ICP–MS was also shown to be sensitive enough for monitoring low concentrations of plasma lead, and plasma samples could be frozen prior to analysis without any alteration in the analytical results (Schütz *et al.*, 1996).

As whole blood became the material of choice for the determination of lead exposure, various atomic absorption techniques were introduced and evaluated for this purpose. By the late 1980s, the popularity of GF–AAS stemmed from its high sensitivity (0.05 μg/dL) and small sample-size requirements (< 50 μL); however, there was considerable variation in the different sample preparation techniques and an optimal method could not be defined (Subramanian, 1989). By 2001, commercial laboratories used predominantly electrothermal atomization atomic absorption spectroscopy, ASV and ICP–MS (Parsons *et al.*, 2001). A comparison of GF–AAS and ICP–MS performed in a Japanese laboratory showed the two methods to be equally sensitive but the latter took only one fifth of the time. ICP–MS results tended to be 10–20% lower than those obtained by atomic absorption analysis (Zhang *et al.*, 1997c).

For screening purposes, the simplest blood lead test is conducted with a capillary blood sample obtained from a finger-prick. Concerns over false positives due to skin surface contamination with environmental lead dust have resulted in the recommendation that a positive capillary blood lead test result be followed by a test on venous blood. Following the recommendation of universal screening of children in the USA (CDC, 1991; American Academy of Pediatrics, 1998), an analysis of the cost effectiveness of strategies for screening of lead poisoning concluded that a screening method based on direct analysis of venous blood was the least expensive (Kemper *et al.*, 1998). Other studies have shown an excellent correlation between the results of capillary blood lead analysis and venous blood lead analysis, thus advocating the former as an appropriate method for screening purposes (Parsons *et al.*, 1997).

Regardless of the method chosen, blood lead analysis is the only diagnostic for lead exposure for which there exists an international standard for quality control (ACGIH, 2001; WHO, 1996; see Section 1.6) and an external quality assurance programme (Schaller *et al.*, 2002).

(ii) *Urine*

Urine is a readily available biological sample for the direct analysis of lead content by AAS. This method has been used successfully to monitor relative levels of exposure in workers with chronic occupational exposure to lead (Vural & Duydu, 1995; Jin *et al.*, 2000). One study argued against the routine use of urine as a surrogate for blood lead analysis because of the poor correlation between the two values on an individual person basis, particularly at blood lead concentrations < 10 μg/dL (Gulson *et al.*, 1998b).

(iii) *Placenta*

During development of biomonitoring methods, non-invasive tissue acquisitions are frequently sought and analysis of lead in placental tissue has been suggested and evaluated as a possible indicator of exposure. However, studies show that placenta is not a suitable tissue for exposure monitoring, because lead is not distributed uniformly throughout the tissue (Lagerkvist *et al.*, 1996a).

(iv) *Sweat and saliva*

Lead concentrations in sweat and saliva have been evaluated and are not recommended for exposure monitoring because of the poor correlation with blood lead concentrations (Lilley *et al.*, 1988; Koh *et al.*, 2003).

1.5.4 *Biomarkers of lead exposure*

(*a*) *Biomarkers related to haeme biosynthesis*

It has long been known that lead interferes with haeme biosynthesis (Chisolm, 1964; Lamola & Yamane, 1974). Aberrations in the haeme biosynthetic pathway form the basis for many of the methods used for biomonitoring of human exposure to lead.

Haeme is the tetrapyrrole cofactor component of haemoglobin responsible for direct binding of oxygen. An early step in the pathway of haeme biosynthesis is the synthesis of the monopyrrole porphobilinogen from δ-aminolevulinic acid (ALA). This reaction is catalysed by the enzyme porphobilinogen synthase (PBGS) also commonly known as δ-aminolevulinate dehydratase (ALAD). Despite the fact that the recommended IUPAC name is PBGS, ALAD is still commonly used in the clinical literature. The inhibition of PBGS by lead manifests itself in a decrease in measurable PBGS activity in blood and an accumulation of the substrate ALA in serum, plasma and urine.

Porphobilinogen continues on the pathway to haeme through the action of additional enzymes to form the immediate haeme precursor protoporphyrin IX, also called free protoporphyrin, erythrocyte protoporphyrin (EP) or, erroneously, zinc protoporphyrin (ZPP). Insertion of iron into protoporphyrin IX is then catalysed by the enzyme ferrochelatase to form haeme. When iron is lacking, ferrochelatase inserts zinc into protoporphyrin IX to form ZPP. There is a tight and not fully understood interrelationship between haeme biosynthesis and iron homeostasis such that exposure to lead is seen to increase ZPP (Labbé *et al.*, 1999). Hence, between 1974 and 1991, measurement of ZPP was the method recommended by CDC in the USA for screening for exposure to lead (CDC, 1975).

One limitation in using these biomarkers is that they can be perturbed by conditions other than exposure to lead. The correlation between these biological parameters and a direct measure of blood lead may include significant scatter (Oishi *et al.*, 1996b) and may not be useful at low blood lead concentrations (Schuhmacher *et al.*, 1997). There are both genetic and environmental factors other than lead that can effect ALA in urine or serum, PBGS activity in blood and ZPP in blood (Moore *et al.*, 1971; Labbé *et al.*, 1999; Kelada *et al.*, 2001).

(i) *PBGS (ALAD) activity in blood*

PBGS activity in blood is the most sensitive biomarker of lead exposure (Toffaletti & Savory, 1976; Schuhmacher *et al.*, 1997). Human PBGS is a zinc metalloenzyme in which the catalytically essential zinc is in an unusually cysteine-rich environment that has a very high affinity for lead relative to the corresponding region in other zinc metalloenzymes. Although the activity of PBGS in blood shows normal biological variation, a comparison of the enzyme activity before and after various treatments that displace the inhibiting lead enables the determination of lead-specific enzyme inhibition (Granick *et al.*, 1973; Chiba, 1976; Sakai *et al.*, 1980). The PBGS assay is either a colorimetric determination of the complex of porphobilinogen with Ehrlich's reagent (Berlin & Schaller, 1974) or a quantification by HPLC of the porphobilinogen formed (Crowne *et al.*, 1981). Despite the sensitivity of PBGS to inhibition by lead, determination of the enzyme activity is not widely used in the clinical setting to determine lead exposure. In part, this is due to the fact that the inhibition of PBGS activity is only observed at low levels of exposure and reaches a plateau above 50–80 μg/dL lead (Toffaletti & Savory, 1976). The PBGS assay also gained a reputation for being complex and irreproducible. This may be due to the fact that the enzyme recovers its activity during the assay procedure, thus producing a variation in specific activity with incubation time (Jaffe *et al*., 1991, 2001). Because assays used clinically require the analysis of a stopped mixture, a fixed incubation time is used, which may vary between laboratories.

PBGS in erythrocytes has a very high affinity for lead (Simons, 1995) and an individual's allotype for the gene encoding PBGS appears to affect the percentage of lead bound by the protein (Bergdahl *et al*., 1997). Hence, a variety of epidemiological studies have suggested that an individual's PBGS allotype affects the pharmacodynamics of lead poisoning (Sakai, 2000). PBGS activity in blood can also be affected by the condition of hereditary tyrosinaemia, wherein an aberrant metabolic by-product of tyrosine acts as a PBGS inhibitor (Lindblad *et al*., 1977) (see Section 4.2).

(ii) *ALA in urine and plasma*

Haeme precursors in urine were among the first biomarkers used for detection of lead intoxication. The synthesis of ALA is the primary regulatory target for haeme biosynthesis: haeme down-regulates ALA synthase expression directly by decreasing the half-life of ALA synthase mRNA (Hamilton *et al*., 1991). Thus, inhibition of PBGS by lead, which results in a decrease in haeme biosynthesis, will upregulate ALA biosynthesis, and increase ALA concentrations in plasma and urine. An increased concentration of plasma ALA in turn increases the affinity of zinc for PBGS, thus giving some reprieve from the lead-induced inhibition of PBGS (Jaffe *et al*., 2001). This interrelationship between lead, PBGS and ALA contributes to the complex clinical correlations between lead exposure and accumulation of ALA in urine. ALA concentrations in plasma increase slowly below blood lead concentrations of 40 μg/dL and rapidly above this concentration. Significant correlations are found in both the slow and rapid phases (Sakai, 2000). Plasma ALA (expressed in μg/L) is generally found to be about five times the value measured in urine (expressed in mg/g creatinine) (Oishi *et al*., 1996b).

Analysis of ALA in biological fluids is generally performed either by colorimetry after chemical transformation of ALA into an Ehrlich's-positive pyrrole (Tomokuni & Ichiba, 1988a) or by fluorometry after HPLC analysis using pre- or post-column derivatization (Tabuchi *et al*., 1989; Okayama *et al*., 1990; Oishi *et al*., 1996b).

(iii) *Zinc protoporphyrin in blood*

In the 1970s, the CDC approved ZPP as the preferred biomarker for the monitoring of lead exposure in the USA. The approved assay used spectrofluorometry, could readily be carried out on-site and was widely adopted for screening childhood lead poisoning. However, ZPP is generally not elevated in individuals with blood lead concentrations below 30 μg/dL (Schuhmacher *et al*., 1997). With the current cut-off for lead poisoning in young children being 10 μg/dL blood lead (CDC, 1991), ZPP has generally fallen out of favour in the USA.

Although ZPP is not expected to be elevated in individuals casually exposed to low concentrations of lead, it continues to be a valuable tool for monitoring occupational exposure (Lee, 1999; Sakai, 2000) and bioresponse to lead (Lauwerys *et al*., 1995). Also, elevation of ZPP is a diagnostic commonly used to detect iron deficiency (Labbé *et al*., 1999).

(*b*) *Biomarkers related to pyrimidine nucleotide metabolism*

Although it has received far less attention than PBGS, the enzyme pyrimidine 5′-nucleotidase (P5′N), also known as uridine monophosphate hydrolase-1, is extremely sensitive to inhibition by lead (Paglia & Valentine, 1975). As with other biomarkers, both genetic and environmental factors can affect P5′N activity (Rees *et al*., 2003). By analogy to the clinical manifestations of hereditary deficiencies in P5′N, the majority of the haematological features of lead poisoning can be explained by inhibition of P5′N (Rees *et al*., 2003). Although not yet widely used, recent studies suggest that P5′N activity in blood is an excellent biomarker for exposure to lead, although less sensitive than PBGS (Kim *et al*., 1995a). The three-dimensional structure of human P5′N is not yet known, but the documented sequence contains a cysteine-rich cluster (Amici *et al*., 2000), which may be the site of lead binding.

P5′N catalyses the hydrolysis of pyrimidine nucleoside 5′-monophosphate to pyrimidine nucleoside and monophosphate (inorganic phosphate). Assays for P5′N activity fall into two categories. Colorimetric assays are based on the determination of inorganic phosphate. These tests require pre-assay sample dialysis and/or lengthy assay times and are not used for monitoring purposes (Sakai, 2000). Assays based on determining pyrimidine nucleosides have been introduced, using either a radiolabelled nucleoside (Torrance *et al*., 1985) or HPLC analysis of the liberated pyrimidine nucleoside (Sakai & Ushio, 1986). A significant correlation was reported between log P5′N and blood lead concentrations over the range of 3–80 μg/dL (Sakai, 2000). Measurements of concentrations of pyrimidine nucleosides in blood have been suggested as alternative biomarkers for exposure to lead (Sakai, 2000).

(*c*) *Other biomarkers*

Nicotinamide adenine dinucleotide synthetase activity in blood has been suggested as a biomarker for exposure to lead, but this method has received little attention apart from the work of Sakai (2000). Recent investigations into the biological chemistry of lead suggest that lead can bind to a variety of proteins that normally bind zinc and/or calcium, most notably transcription factors. These observations may lead to the future development of alternative biomarkers for measurement of exposure to lead (Godwin, 2001).

1.6 Regulations and guidelines

Regulations and guidelines for lead concentrations in blood in non-occupationally exposed populations, ambient air and drinking-water have been defined in many countries and are given in Table 76.

Regulations and guidelines for occupational exposure to lead and lead compounds from several countries are presented in Table 77; maximum permissible lead concentrations in blood of occupationally exposed populations for several countries are presented in Table 78.

Many countries have set guidelines for lead in drinking water, gasoline, paint, foods, industrial emissions, and other products such as ceramic-ware and solder (Consumer Product Safety Commission, 1977; US DHUD, 1987; OECD, 1993; US Food and Drug Administration, 1994).

JECFA first evaluated lead in 1972, when a provisional tolerable weekly intake of 50 μg/kg bw was established. The value was reconfirmed by the Committee in 1978. In 1986, a provisional tolerable weekly intake of 25 μg/kg bw was established for infants and children for lead from all sources. This value was extended to the general population in 1993 and was reconfirmed in 1999 (WHO, 2000b; JECFA, 2002).

Analytical methods have changed over time (see Section 1.5) because health-based standards and guidelines have changed. A historical review of the CDC guidelines in the USA shows a progressive downward trend in tiered screening and intervention guidelines for childhood lead poisoning. Maximum permissible blood lead concentrations in the USA dropped from 35 μg/dL in 1975 to 25 μg/dL in 1985 to 10 μg/dL in 1991 (CDC, 1975, 1985, 1991). Efforts to maintain this downward trend (Bernard, 2003) may continue to drive development of increasingly sensitive analytical techniques.

The Commission of European Communities reports the following binding biological limit values [maximum allowed lead levels] and health surveillance measures for lead and its ionic compounds: (1) biological monitoring must include measuring the blood lead concentration using absorption spectrometry or a method giving equivalent results. The binding biological limit is 70 μg lead/dL blood; (2) medical surveillance is carried out when exposure occurs to a concentration of lead in air that is greater than 0.075 mg/m^3, calculated as a time-weighted average over 40 h per week, or when a blood lead concentration greater than 40 μg/dL is measured in individual workers; (3) practical guidelines for biological monitoring must include recommendations of biomarkers (e.g. ALA, ZPP, ALAD) and biological monitoring strategies (European Commission, 1998).

The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a biological exposure index (BEI) for lead in blood of 30 μg/dL. Women of childbearing age whose blood lead exceeds 10 μg/dL are at risk of delivering a child with a blood lead concentration above the current CDC guideline of 10 μg/dL (ACGIH Worldwide, 2003). The ACGIH considers analysis of lead in blood by GF–AAS, ASV or ICP–MS to be sufficiently sensitive for concentrations below the recommended BEI (ACGIH, 2001).

Table 76. International standards and guidelines for lead concentrations in blood, air and drinking-water

Country	Blood (μg/dL)	Air (μg/m³)	Drinking-water (μg/L)
Australia	10 (GP)	0.5 (federal) 1.5 (states)	10–50 (OECD)
Austria			50
Belgium		2.0	
Brazil			10
Canada	10 (GP)	1.0–2.5 (BC) 2.0 (QC) 5.0 (MB, NF, ON)	10
Czech Republic		0.5	50
Denmark		0.4	50
European Union	40[a]	1.0; 40[a]	50
Finland		0.5	10
France		2.0	50
Germany	15 (GP) 10 (C+W)	2.0	40
India			100
Ireland		2.0	50
Israel		0.5	50
Italy		2.0	50
Japan			10
Mexico			50
Namibia		1.5	50
Netherlands		0.5	50
New Zealand		1.0	50 (OECD)
Norway			20
Republic of Korea		1.5	50
Russian Federation		0.3	
Serbia and Montenegro		100–200	50
South Africa		4.0	50–100
Spain		2.0	50
Sweden			10 (OECD)
Switzerland	10–15 (F) 10 (C)	1.0	50 (OECD)
United Kingdom		2.0	50
USA	10 (GP)	1.5	15 (OECD)[a]
WHO	20 (GP)		10

From OECD (1993); International Lead and Zinc Study Group (2000); Ministry of Health, Brazil (2004); IOMC (1998)

BC, British Columbia; C, children; F, fetus; GP, general population; MB, Manitoba; NF, Newfoundland; ON, Ontario; QC, Quebec; W, women of childbearing age

[a] Action level

Table 77. Regulations and guidelines for occupational exposure to lead and lead compounds

Country/Agency	Exposure limit (mg/m^3)	Interpretation[a]
Lead		
Argentina	0.15	TWA
Australia	0.15 (dust and fume)	TWA
Austria	0.10 (men); 0.02 (women)	TWA
Belgium	0.15	TWA
Canada	0.15	
Alberta	0.05 (dust and fume)	TWA
Ontario	0.05 (excluding tetraethyllead)	TWA
Quebec	0.15	TWA
China	0.3 (fume)	Ceiling
	0.05 (dust)	Ceiling
Czech Republic	0.05	TWA
Denmark	0.10	TWA
European Union	0.15	TWA
	0.10 (dust and fumes < 10 µm)	TWA
Finland	0.10	TWA
France	0.15	TWA
Germany	0.1 (excluding lead arsenate and lead chromate)	TWA (MAK)
	8	STEL (MAK)
India	0.15–0.20	TWA
Ireland	0.15 (excluding tetraethyl lead)	TWA
Israel	0.10 (men); 0.05 (women of fertile age)	TWA
Italy	0.15	TWA
Japan	0.10 (excluding alkyls)	TWA
Malaysia	0.05	TWA
Mexico	0.15 (dust and fume)	TWA
Morocco	0.20	TWA
Namibia	0.15	TWA
Netherlands	0.15 (dust and fume)	TWA
New Zealand	0.1 (dust and fume)	TWA
Norway	0.05	TWA
Peru	0.20	TWA
Poland	0.05	TWA
Republic of Korea	0.05	TWA
Serbia and Montenegro	0.05	TWA
South Africa	0.15	TWA
Spain	0.15	TWA
Sweden	0.10 (total)	TWA
	0.05 (respirable)	TWA
Thailand	0.20	TWA
United Kingdom	0.15	Ceiling (OES)
	0.15	TWA
USA		
ACGIH	0.05	TWA (TLV)
NIOSH	< 0.1	TWA (REL)
OSHA	0.05	TWA (PEL)

Table 77 (contd)

Country/Agency	Exposure limit (mg/m^3)	Interpretation[a]
Lead acetate		
Norway	0.05 (dust and fume)	TWA
Lead hydrogen arsenate ($PbHAsO_4$)		
Canada		
Alberta (as As)	0.15	TWA
	0.45	STEL
China, Hong Kong SAR (as $PbHAsO_4$)	1.5	TWA
Mexico (as Pb)	0.15	TWA
	0.45	STEL
USA (as As)		
NIOSH	0.002	Ceiling (REL)
OSHA	0.01	TWA (PEL)
Lead arsenate (as $Pb_3(AsO_4)_2$)		
Australia	0.15	TWA
Belgium	0.15	TWA
Canada		
Quebec	0.15	TWA
China	0.05 (dust)	TWA
New Zealand	0.15	TWA
USA		
ACGIH	0.15	TWA (TLV)
NIOSH (as As)	0.002	Ceiling (REL)
OSHA (as As)	0.01	TWA (PEL)
Lead chromate (as Cr)		
Australia	0.05	TWA
Belgium	0.012	TWA
Canada		
Alberta	0.05	TWA
	0.15	STEL
Ontario	0.012	TWA
Quebec	0.012	TWA
China	0.012	TWA
China, Hong Kong SAR	0.012	TWA
Finland	0.05	TWA
Germany	0.1 (dusts and aerosols)	TWA (TRK)
	0.05 (NOS[b])	TWA (TRK)
Malaysia	0.012	TWA
Netherlands	0.025	STEL
New Zealand	0.05	TWA
Norway	0.02	TWA
Spain	0.012	TWA

Table 77 (contd)

Country/Agency	Exposure limit (mg/m^3)	Interpretation[a]
USA		
ACGIH	0.012	TWA (TLV)
OSHA	0.001	TWA (REL)
Lead chromate (as Pb)		
Belgium	0.05	TWA
Canada		
British Columbia	0.012	TWA
China, Hong Kong SAR	0.05	TWA
Malaysia	0.05	TWA
Spain	0.05	TWA
USA		
ACGIH	0.05	TWA (TLV)
Lead (II) oxide		
Finland	0.1	TWA
Lead phosphate (as Pb)		
Norway	0.05	TWA
USA		
ACGIH	0.05	TWA (TLV)
OSHA	0.05	TWA (PEL)
Lead sulfide		
China	5	Ceiling
Tetraethyl lead (as Pb)		
Australia	0.1 (sk[c])	TWA
Belgium	0.1 (sk)	TWA
Canada		
Alberta	0.1 (sk)	TWA
	0.3 (sk)	STEL
British Columbia	0.075 (sk)	TWA
Quebec	0.05 (sk)	TWA
China	0.02 (sk)	TWA
	0.06 (sk)	STEL
China, Hong Kong SAR	0.1 (sk)	TWA
Finland	0.075 (sk)	TWA
	0.23 (sk)	STEL
Germany	0.05 (sk)	TWA (MAK)
	0.1 (sk)	STEL (MAK)
Ireland	0.1 (sk)	TWA
Japan	0.075 (sk)	TWA
Malaysia	0.1 (sk)	TWA
Mexico	0.1 (sk)	TWA
	0.3 (sk)	STEL
Netherlands	0.05 (sk)	TWA
New Zealand	0.1 (sk)	TWA

Table 77 (contd)

Country/Agency	Exposure limit (mg/m^3)	Interpretation[a]
Norway	0.01 (sk)	TWA
Poland	0.05 (sk)	TWA
	0.1 (sk)	STEL
Spain	0.1 (sk)	TWA
Sweden	0.05 (sk)	TWA
	0.2 (sk)	STEL
USA		
ACGIH	0.1 (sk)	TWA (TLV)
NIOSH	0.075 (sk)	TWA (REL)
OSHA	0.075 (sk)	TWA (PEL)
Tetramethyl lead (as Pb)		
Australia	0.15 (sk)	TWA
Belgium	0.15 (sk)	TWA
Canada		
Alberta	0.15 (sk)	TWA
	0.5 (sk)	STEL
Quebec	0.05 (sk)	TWA
China, Hong Kong SAR	0.15 (sk)	TWA
Finland	0.075 (sk)	TWA
	0.23 (sk)	STEL
Germany	0.05 (sk)	TWA (MAK)
	0.1 (sk)	STEL (MAK)
Ireland	0.15 (sk)	TWA
Malaysia	0.15	TWA
Mexico	0.15 (sk)	TWA
	0.5 (sk)	STEL
Netherlands	0.05 (sk)	TWA
New Zealand	0.15 (sk)	TWA
Norway	0.01 (sk)	TWA
Spain	0.15 (sk)	TWA
Sweden	0.05 (sk)	TWA
	0.2 (sk)	STEL
USA		
ACGIH	0.15 (sk)	TWA (TLV)
NIOSH	0.075 (sk)	TWA (REL)
OSHA	0.075 (sk)	TWA (PEL)

From ACGIH Worldwide (2003); European Commission (1998); International Lead and Zinc Study Group (2000)

ACGIH, American Conference of Governmental Industrial Hygienists; NIOSH, National Institute for Occupational Safety and Health; OSHA, Occupational Safety and Health Administration

[a] TWA, time-weighted average; STEL, short-term exposure limit; MAK, maximum allowable concentration; OES, occupational exposure standard; TLV, threshold limit value; REL, recommended exposure limit; PEL, permissible exposure limit; TRK, technical exposure limit

[b] NOS, not otherwise specified

[c] sk, skin notation

Note: For the most current information on these regulations and guidelines, the reader is referred to the relevant regulatory authority.

Table 78. Regulations and guidelines for maximum lead concentrations in blood in occupational settings

Country	MLL[a] (µg/dL)	Country	MLL[a] (µg/dL)
Australia	50 (men, and women not capable of reproduction); 20 (women of reproductive capacity)	Japan	60
Austria	45–70	Luxembourg	70
Belgium	80	Morocco	60
Canada	50–80	Namibia	80
Czech Republic	50	Netherlands	70
Denmark	50–70	Norway	2 µmol/L [41.4 µg/dL] (men)
Finland	50	Peru	60 (men)
France	70–80	South Africa	80 (men); 40 (women)
Germany	70 (men); 30 (women under 45 years)	Spain	70
Greece	70–80	Sweden	50 (men and women over 50 years); 30 (women under 50 years)
Ireland	70	Thailand	80
Israel	60 (men); 30 (women of reproductive age)	United Kingdom	60 (men); 50 (adolescents under 18 years); 30 (women of reproductive capacity)
Italy	70	USA	50

From International Lead and Zinc Study Group (2000)

[a] MLL, maximum lead level