Translated from *Uspekhi Khimii* **59** 1777–1798 (1990) U.D.C. 504.054:546.3

Emission of toxic metals into the atmosphere and their accumulation in the surface layer of the Earth

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ABSTRACT. Natural emissions of metals and certain metalloids into the atmosphere are compared with anthropogenic emissions. The physico-chemical properties of metal-containing aerosols are discussed from the standpoint of the danger of environmental pollution and the distances to which these metals get dispersed in the atmosphere. The results of pollution of objects in the environment with metals on local, regional, and global levels are analysed. An assessment is made of the likely future pollution of the soil with metals.

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I. Introduction

Polution of the environment by toxic metals and their compounds is a problem with several specific features. It is common knowledge that metals and other elements are subject to natural processes of migration and circulation. They systematically enter the atmosphere from terrestrial and ocean surfaces and from the space. They are also emitted by volcanic eruptions, forest fires, and other natural phenomena. Metals enter the atmosphere and disperse in it; then, after being washed out and precipitated, they are once again deposited on land and ocean surfaces. Human activity leads to additional amounts of these metals—some of them toxic—being extracted from the interior of the Earth and transported into the biosphere. As a result in certain instances environmental pollution may reach levels that are dangerous not only to the biota but also to humans. There is also an increased flow of toxic metals into layers of the biosphere supporting life and an interference with natural circulation of these metals. The picture of pollution of the biosphere and individual ecosystems is complicated by the fact that several metals and trace elements are necessary for the life-supporting processes in the biota. There are many geochemical regions on the Earth where biological objects experience a shortage of certain elements, including metals. Here the introduction of additional amounts of these elements has a beneficial effect on the biota, not a detrimental one. To assess the danger of introducing extra amounts of metals into the environment we shall use the concept of maximum permissible concentration (MPC) in each individual case. For soil we shall also make comparisons with natural background pollution.

We shall make a distinction between local pollution around the source of emission (to a distance of several kilometres, or several tens of kilometres, regional pollution (to a distance of several hundred or thousand kilometres), and global pollution (on a hemispherical or global scale). The high levels of environmental pollution in specific localities and areas where metals are processed or mined are very worrying, of course. But human activities today are conducted on such a large scale that it is the danger of global environmental pollution that has become the acute problem. Metal pollution of the environment on a global scale does not have, as yet, such tangible negative consequences as the rise in atmospheric concentrations of CO_2 or freon. But one should take into account the dynamics of global changes in metal content.

In this review we shall concentrate on pollution of the environment with such metals as Pb, Cd, As, Hg. Nature preservation experts believe that these metals should be the first to be studied.[1,2] We shall also discuss several toxic elements presenting first- and second-degree danger (Se, Cu, Co, Ni, Cr, Sb).[3] In individual cases we shall discuss, for comparison, data on certain trace elements.

II. Comparison of natural and anthropogenic sources of metals and some metalloids emitted into the atmosphere

Under natural conditions metals and metalloids are introduced into the atmosphere in the form of aerosols and vapours. These originate from dust swept up by the wind from the surface of the soil (wind erosion), from volcanic eruptions, forest fires, and cosmic dust. They also originate from the transfer of these elements through the ocean surface, from the flow of submicrometer particles and cold emission from vegetative cover, and from evaporation from the Earth's surface. It is customary to estimate the natural input of metals in the form of aerosols into the atmosphere by the product of the total amount of dust from a specific source and its elemental content. This product is expressed as mass fraction. The averaged composition of aerosols of various origins is given in the literature.[4–6] Data on the amount of dust annually emitted by natural sources into the atmosphere has wide variations: according to some it is 150–1500 million tonnes,[6] according to others it is 740–3400 million tonnes.[4] On the average wind erosion produces annually 500 million tonnes of dust (according to various authors from 200 to 1000);[4,7] volcanic eruptions produce 150 (10–200) million tonnes; forest fires 130 (20–50) million tonnes; the ocean 1000 million tonnes;[4] and vegetation from 75 to 1000 million tonnes.[7] It has been suggested that because of the rapid removal of sea salt from the

atmosphere only 10% of the amount emitted into the atmosphere is carried to the continents.[8,9] The estimates for cosmic dust are highly contradictory. On the one hand, even according to highest estimates, only the inflow of 'cosmic' nickel is comparable to the amount of this element brought into the atmosphere by soil dust.[4] On the other hand, some consider that it has been precisely the inflow of cosmic dust that has built up the trace element composition of the aerosols, the soil, the ocean, and the vegetation over many thousands of years.[10,11] In that case it is not meteoric matter but comet matter that would be the main source. This hypothesis raises some doubts because the concentrations of elements in the atmosphere over continents, over the ocean, and in polar regions differ widely. The emission of aerosols into the atmosphere by vegetation has been experimentally confirmed.[12–14] The fluxes of various elements from this source are as follows: Pb, 1.6; Cu, 2.5; Ni, 0.8–1.6; Cd, 0.2; As, 0.26; Se, 0.14; V, 0.2 thousand tonnes per year.[7,15,16] It is difficult to estimate the elemental composition of the emissions from the composition of the source itself because of fractionation. Thus, the amount of trace elements (Ag, Cu, Zn, As, Sb, etc.), compared to the amount of Fe, is considerably higher in the dust-forming soil particles than their average content in the surface layer of the soil.[17] Similar fractionation at the atmosphere–ocean[18–20] interface is due to the different degrees of enrichment (10–20 fold) of the ocean surface film with various elements. This is also due to different concentrations of these elements in the walls of bubbles formed in a rough sea.[8,21,22] Because of the high temperatures that develop in forest fires and volcanic eruptions it is mainly volatile elements that are emitted into the atmosphere.[4,8] Direct measurements of local concentrations of elements in the smoke produced by forest fires and in volcanic ashes show that these concentrations may differ by an order of magnitude or even more.[5,7]

A number of metals and metalloids may enter the atmosphere in gaseous phase. Thus, from 0.04[21] or 0.09[4] to 0.16 thousand tonnes of aerosol mercury is emitted into the atmosphere annually.[25] The source of gaseous selenium in the atmosphere are selenium-containing organic substances.[26–28] The gaseous fraction of elements (in relation to the total amount of each element) emitted in volcanic eruptions) is large: for Hg it is 64–78%; for Cd 25–40%; for Zn 22–36%; for Pb 4–7%; for As 33–49%; and for Sb 74–85%.[8]

The above data indicate that there is no single way of estimating the natural inflow of metals into the atmosphere. Of the values given by different authors only those for the trace elements brought into the atmosphere with soil dust are more or less in agreement. The greatest differences are in values obtained for elements introduced into the atmosphere in aerosol or vapour form; also for elements emitted in volcanic eruptions or forest fires.[5,7]

The most convenient way to estimate anthropogenic emissions of metals and metalloids into the atmosphere is by the amount of each element emitted per unit of it produced or per unit of fuel burnt (Table 1). Another method is used for aerosol emissions: it is based on the average concentration of metals in the dust of large cities all over the world and the global emission of industrial dust into the atmosphere. The anthropogenic emission of aerosols into the atmosphere obtained in this way is the product of these values.[4,6] The wide scatter of values for global anthropogenic emissions is due to several factors: different estimates of the total amount of emitted industrial dust and of the concentration of metals in it; different production technologies and different levels of waste purification; the difficulty of estimating emissions in vapour phase; the fact that the account emitted depends on the temperature of the source and volatility of the element.[4,5] Below we give a few examples of uncertainty in the initial data used for calculations. According to

Table 1. Emission of toxic metals per unit of production.[5,12,25,29,30]

Source of emissions	Units	As	Cd	Cr	Ni	Pb	Sb	V	Zn	Cu
Thermal power										
burning of coal	mg MWh^{-1}	42—170	18—54	310—1200	340—1470	240—2600	33—140	210—1000	216—1280	220—1000
burning of liquid fuel		87	44	155	3700	450		13 300	325	620
Industrial combustion of fuel										
coal	g $tonne^{-1}$	0.3—1.3	0.1—0.7	1.7—12	2.2—14.5	0.5—7.2	0.2—1.4	1.2—9.7	1.7—11.4	1.4—9.8
liquid fuel	g $klitre^{-1}$	1.2	0.4	7	52	6.4*		187	4.5	8.8
Refuse incineration	g $tonne^{-1}$	0.52	2.1	1.1	0.33	18—50	4.55	25	260	3.7
Burning of wood	g $tonne^{-1}$	0.3—0.5	0.2—0.3		3.1—4.7	4.7—7.0			39—58	12—19
Nonferrous metallurgy	kg $tonne^{-1}$	0.4—3.0	0.2—1.3			0.3—6.4				
Primary metal production	kg $tonne^{-1}$									
zinc, cadmium		0.6	0.1—0.5			1.2—25			15.7—17.6	0.14
copper, nickel		1—3	0.2—1.3		9	2.3—3.6	0.1		0.84—0.97	1.7—3.6
lead		0.18	0.002—0.005		0.09	3—7.7			0.11	0.06—0.07
Production from scrap metal	g $tonne^{-1}$									
copper			4.0			54—214	3		500—1630	150
zinc									9000	
lead			2.5			770			300	
Ferrous metallurgy		6—8	0.08—0.4	4—40	1.3—10	38—60			20—155	0.5—4.5
Mining of metal ores	g $tonne^{-1}$	0.1	0.5		9000	910			0.1**	100

*The emission of lead from the combustion of petrol containing tetraethyl lead is 0.37 g $litre^{-1}$.[25]

**Calculated per gramme of mined Zn + Cu + Pb.

Ostromogilskii et al.[4] the total emission of industrial dust is 80 million tonnes per year, whereas according to Izrael' et al.[6] it is between 60 and 600 million tonnes. Besides, the elemental composition of the ore or fuel (even the same type of ore or fuel) depends to a great degree on where it has been minded.[31] There is no reliable estimate of the fraction of the metals contained in raw materials and fuel that is emitted into the atmosphere as a result of industrial processes. According to Ostromogilskii et al.[4] when coal is burnt, about 10% of the Al, Co, Fe, Mn, and Sc that it contains is emitted into the atmosphere. For Cr, Cu, Ni, and V the amount is about 30%; for As, Br, Hg, Sb, and Se it is close to 100%. The gas-phase component for these elements in the emissions from metallurgical works is up to 30% for Cr, Se, Br, and Cd; up to 70% for As; and up to 100% for Hg. As a rule, the largest emissions of metals into the atmosphere come from iron-and-steel works and nonferrous metal works and by plants that burn fuel.[32] The Pb emissions come mainly from motor transport.[5]

Table 2 gives generalized data on the emission of metals and metalloids into the atmosphere from natural and anthropogenic sources. Our expert estimates of the emissions of elements into the

Table 2. Emission of elements from natural and anthropogenic sources into the atmosphere.

Element	Main sources of emission		Natural emissions,*1 1000 t year^{-1}	Anthropogenic emissions,*1 1000 t year^{-1}	Mobilization coefficient*2	Refs.
	natural	anthropogenic				
Ag	Wind erosion, forest fires	Nonferrous metallurgy	0.11 0.06—0.15	3.1 2.2—5.0	28	[4, 21, 33]
Al	Wind erosion	Nonferrous and ferrous metallurgy	$48 \cdot 10^3$	$9.1 \cdot 10^3$	0.19	[4]
As	Volcanos, wind erosion	Nonferrous metallurgy fuel combustion	8 (21)*3 3—13	40 25—80	5 (~2)*3	[4, 7, 8, 12, 21, 25, 34]
Cd	Forest fires, volcanos	Nonferrous and ferrous metallurgy, fuel combustion	1.0 0.3—7.0	7.7 5.5—11.0	7.7	[4, 7, 21, 25]
Co	Wind erosion	Fuel combustion	7.0 5.4—13	4.0 2.7—5.0	0.72	[4, 7, 8, 21, 32, 35]
Cr	Ditto	Ferrochromium production, fuel combustion	60 44—130	50 21—94	0.83	[4, 7, 8, 21, 32, 35]
Cu	Wind erosion, volcanos (ocean)	Nonferrous metallurgy, fuel combustion, ferrous metallurgy	20*4 18—22 (130)	140 56—260	7.0	[4, 7, 8, 21, 30, 35, 36]
Fe	Wind erosion, volcanos	Ferrous metallurgy	$36 \cdot 10^3$ $(30—43) \cdot 10^3$	$7.4 \cdot 10^3$ —	0.2	[4, 8]
Hg	Evaporation from continents and the ocean, wind erosion	Processes that use mercury	20*3 2.5—150	6.0 1.7—11.0	0.3	[4, 8, 11, 21, 24, 25, 32]
Mn	Wind erosion	Ferrous metallurgy, fuel combustion	600 516—750	215 107—320	0.36	[4, 7, 8, 21]
Ni	Wind erosion, cosmic dust	Fuel combustion, nonferrous and ferrous metallurgy	27 8.5—54	80 43—98	3.0	[4, 7, 15, 21, 30, 35, 36]
Pb	Wind erosion, volcanos, forest fires	Motor transport, nonferrous and ferrous metallurgy	27 4—45	425 300—470	16	[4, 7, 21, 33, 37]
Sb	Wind erosion	Fuel combustion, nonferrous metallurgy	1 0.5—1.8	24 18—38	34	[4, 8, 21, 33, 35, 36]
Se	Destruction of organic matter in the ocean, volcanos	Fuel combustion, manufacture of glass	0.6 (10)*5 0.4—3.0 (6—14)*5	7 1.1—11.7	11.7 (0.7)*5	[4, 7, 21, 25, 27, 35, 36, 38]
V	Wind erosion, volcanos	Fuel combustion, ferrous metallurgy	65 40—79	170 110—210	2.6	[4, 7, 35, 36]
Zn	Forest fires, wind erosion, vegetation	Nonferrous and ferrous metallurgy, fuel combustion	90 36—200	500 315—840	5.5	[4, 7, 8, 21, 33, 35, 36]

*1 The upper numbers give our estimate, the lower ones—the scatter of values obtained by other authors.

*2 The ratio of anthropogenic emissions to natural emissions.

*3 The values in parentheses take the gas fraction into account.

*4 The maximum estimate of the large emission of the element from the ocean into the atmosphere.[8] According to Ref. 22 this emission was even larger (170×10^8 t year^{-1}).

*5 The estimates in parentheses take into account the destruction of organic matter, especially in the oceans.[25] According to a similar estimate,[35] it is 48×10^3 t year^{-1}.

atmosphere that are listed in Table 1 were obtained by taking account of the density of distribution of values quoted by different authors.

These data apply to 1979–1980. Data are available in the literature on the emission of metals in certain European countries[7,29] and in certain regions of the USSR.[39] It should be noted that 77–87% of Pb, Cd, Hg, and As emissions occur at the latitude of 30°–70° north.[25,33,37]

Metals and metalloids with a mobilization coefficient over 1.0 can be arranged in the following sequence:

$$Sb > Ag > Pb > Se > Cd > Cu > Zn > As > Ni > V.$$

Metals with a mobilization coefficient under 1.0 can be arranged in the following sequence:

$$Fe, Al < Hg < Mn < Co < Cr.$$

There may, of course, be a much greater contribution of anthropogenic emissions on a regional and local level.

III. Physicochemical properties of aerosols

To get a correct picture of the scale and the pattern of distribution in the environment of metals and other elements that are emitted into the atmosphere and of the danger they pose to man and the biota we need data on a whole range of physicochemical properties of aerosols that contain these elements.

Vapour and aerosol-phases

Conventional air filters for aerosols (Petryanov filters, for instance) usually do not trap gaseous and fine submicrometer particles. Therefore if activated carbon[40] or a freezer set to −50 to −60 °C[41–43] is mounted behind the filter, it is possible to assess the fraction of metals and trace elements present in the atmosphere in the form of vapour or finely dispersed aerosols. Mercury has the highest fraction, from 70 to 99% of the total content.[44–46] This fraction increases as air temperature rises and decreases with growing dust content. In Japan seasonal changes have been noted in the concentration of mercury: the total concentration of mercury in the air and the fraction of it in the gas phase and in submicrometer particles is lower in winter than in summer.[47] Of the eighteen trace elements discussed in the literature,[40–42,48] Fe, Sc, Mn, V, Ba, occur mainly in the aerosol phase (over 70%). The fraction of As, Se, Br, Ag, Cd in the gas phase and submicrometer particles often exceeds 50% of their total content. The same is true for lead emitted by car engines, though its fraction fluctuates widely.[49] The aerosol fraction of Co, Cu, Zn, and Sb is low in some cases and very high in others. In the air of industrial towns the contribution of the aerosol fraction seems to be greater. Thus, in Frankfurt the aerosol fraction of Fe, Cd, Pb, Mn, and Cu is not less than 90%.[50] In the cities of the USA 96–98% of As occurs in the form of aerosols.[51] Near the ocean this value drops to 93.5%.

Density of aerosol particles

In most calculations and measurements the density of particles that contain metals and trace elements, is usually taken to be constant and equal to 1–2 g cm^{-3}. But in reality it does depend on the size of the particles. According to Watson et al.,[52] finely dispersed aerosols have a density of 1.7 g cm^{-3}, whereas that of coarsely dispersed aerosols is 2.6 g cm^{-3}. In a detailed study[53] it was noted that the density of the particles had a tendency to increase as they grew in size. Thus, if the particles are subdivided according to size into different ranges and the relationship between Fe, Mn, Zn and Cu content in the aerosol and the particle density is plotted for each range, in the range with larger particles the distribution maximum will shift to the region of denser particles. In that case the maximum will become broader. In some cases there may be two distribution maxima. Thus, one maximum for Fe, Mn, Zn and Cu occurs at a density of 2.5–2.7 g cm^{-3}, while another occurs at a density over 3.3 g cm^{-3}. As a rule the denser particles originate from the soil and consist mainly of oxides (the density of SiO_2 is 2.7 g cm^{-3}). Anthropogenic aerosols have a lower density, but they can coagulate with soil dust.

Similar results were obtained for the three-dimensional relationships between the Pb, Cd, Zn, Fe, Hg, Br, As, Cr, Co, and Mn content in road dust and the size and density of the particles of magnetic and non-magnetic aerosols.[54] Moreover, in some cases it was possible to determine the origin of the elements from the density and size of the particles (exhaust fumes, tyre rubber evaporation, soil dust, etc.). The major part of road dust consists of particles with a density of 2.2–2.9 g cm^{-3}.

Solubility of the aerosol

The fraction of water-soluble metal and metalloid compounds in the aerosol grows as the particle size decreases.[21,25] Thus, in rural areas the fraction of the soluble compounds of Cd, Pb, Mn and Zn in the aerosols for particles with a diameter $d \approx 0.1$ to 0.3 μm was 90%, and for $d \approx 5$ to 10 μm it was 80, 25, 75, and 55% respectively.

As a result, the fraction of water-soluble metal compounds in the precipitation grows with the distance from the source of emission.[56,57] In many cases this growth can be approximated by an exponential relationship. It has been found that the fractions of soluble Pb, Cd, and Cu compounds in the snow cover around a steel plant (USSR) increase linearly up to a distance of 30–40 km.[59] An increase in the fraction of soluble compounds was observed for 21 elements. However, there are isolated cases where the relationships between distance and the fraction of soluble forms is more complex; in a few cases this fraction may even decrease.[60]

The fraction of soluble Pb, Fe, Mn, and Zn compounds in aerosols over urban areas (19, 4, 33, 69%, respectively) is considerably lower than in aerosols over the ocean (84, 53, 74, 79%, respectively).[50] It has been also noted that the fraction of acid-soluble forms of metals and trace elements in aerosols tends to be smaller over continents than over oceans.[61] In rural and 'clean background' areas the fraction of soluble forms of the elements in the snow cover was (%): Pb, 21; Zn, 65–100; Cd, 65; Cu, 40–80; Co, 60; Cr, 80–85; Ni, 80; Sb, 60–70; Se, 80–100; V, 60%.[32,62] In contrast to this, near motorways the main fraction of Pb, Mn, and Ti is in a nonsoluble form.[63] In rural regions in Sweden the fraction of gaseous mercury in soluble state reaches its maximum in winter (up to 5–10%).[23]

The solubility of metal-containing compounds was found to depend on their origin. Thus, both in urban and rural areas metals and trace elements in aerosols of soil origin (e.g., Sc, La, Co, Fe) are mostly in nonsoluble form. In contrast to this, volatile trace elements of anthropogenic origin (As, Cd, Sb, Se, Cr, Cu) are found mainly in soluble form.[46] The fraction of soluble compounds is much greater in rainfalls than in dry precipitations. This is especially true for Cu (90 and 30% respectively) and Pb (83 and 5%). The fraction of soluble forms of these metals decreases with increasing pH and the concentration of insoluble Fe.[64]

Size of aerosol particles

Aerosol particles that contain metals and other elements range in size from 5×10^{-3} to 20–40 μm or more.[65] The content of dispersed elements in the aerosol is largely determined by the nature of its sources. Furthermore, it varies with the distance from the source of emission. This is due to the different residence times of particles of different sizes in the atmosphere. In aerosols emitted into the atmosphere as a result of refuse incineration 65 mass% consisted of 0.1–2 μm particles. In the emissions of iron and steel works 57% of the total amount of metals consisted of particles smaller than 2 μm.[65,66] The content of dispersed elements depends largely on the degree of purification: the better the purification, the higher the fraction of finely-dispersed aerosols that contain a large amount of volatile elements (Pb, Sb, Se, Cd, Zn, As, S).[67,68] The degree of purification has a much smaller effect on the mass fraction of such metals as Fe, Al, Ni, Mn, Co, Cu in the emissions from metallurgical works. The bulk of these metals is concentrated in particles with $d > 2$ μm.[67,69] In motorcar exhaust fumes, Pb, Br, and Cl are contained in small particles ($d < 0.5$ μm). But in the presence of large particles from road and soil dust these aerosols coagulate rapidly.[70,71] Table 3 lists the selective median (by mass) diameters of metal-containing aerosols. Two extremes are compared: the urban atmosphere and the atmosphere of the 'cleanest' and remote background areas. Aerosol particles containing most of the elements discussed earlier (except Fe, Mn, Co, Pb) have a tendency to have a smaller diameter in remote background areas than in urban or suburban regions. In the Antarctica, for instance, up to 90–95% of As, Se, Zn, Br, S, and up to 60–70% of Sc and Mn is contained in particles with $d \leqslant 0.6$ μm.[9,79] Similar estimates for the Arctic and the Antarctic are given in the literature.[66,80] However, no such relationship is observed in certain continental regions, for instance in Central Asia. This is due to the special features of the natural and anthropogenic sources in these regions.[40] According to Table 3, volatile elements (Pb, As, Cd, Zn, Cu, Se, Sb) are, as a rule, found in smaller particles than nonvolatile ones (Fe, Mn, Co, Al, etc.). This fact is corroborated by other evidence, not listed in the table: the median diameters of particles that contain Fe and Al are in the range of 2.5–7.0 μm, whereas particles containing Pb, Se, Cd, V, Zn, and Sn are characterised by $d < 1$ μm.[67]

As particles become larger, there is also a tendency for the mass fraction of nonvolatile metals in aerosols (for instance, in aerosols of soil origin) to increase. The reverse is true of volatile elements (and high-temperature sources).[71,75,78,81] The distribution of metals according to the size of aerosol particles is governed by the logarithmic normal law.[74,82] One can get not only unimodal distributions, but bimodal and trimodal distributions as well.[71,83,84]

Thus, 0.25 μm and 3 μm modes have been established for Se,[85] 0.5 and 2.5 μm modes for Pb and Br,[86] and 0.8 and 4 μm modes for Hg,[47] and so on. In many cases each distribution mode can be related to the presence of an aerosol of certain origin.[14,86] Thus, the mode in the coarsely dispersed part of the distribution is believed to be connected with soil dust.[14] The size of the aerosol particles (the metal carriers) has a different seasonal dependence in different cities.[74] It depends on precipitation[43] and on the direction of the wind with respect to the aerosol source.[70,87] In remote background areas (e.g. in polar regions) the size of the aerosol particles changes as different air masses arrive.[88,89] As a rule, with increasing altitude the aerosol particles become smaller.[81]

Enrichment of aerosols with metals

The enrichment factor

$$K_{en} = (X_i/q)_{atm}(X_i/q)_s,$$

is often used to estimate the degree of fractionation of metals and

Table 3. The size of aerosol particles that contain metals and metalloids.

Region	Mass median diameter,* mm											Refs.
	Pb	Cd	Cu	Fe	Mn	Zn	Ni	Co	As	Se	Sb	
Sudbury (Canada) (emissions from a copper-smelting plant)	0.7—1.9	0.7—5.3	4.4—9.0	9.0	4.2—5.0	0.8—6.6	9			0.7—1.0		[72]
Environs of Sudbury (Canada)	0.5—0.9	0.9—1.3	1.7—4.1	4.7—7.1	2.0—4.2	0.5—0.8	5.6—9.0		0.55—1.0	0.7—1.0		[72]
Liene (Belgium)		2.0	0.6	5.1		1.7						[73]
Large American cities	0.5 (0.3—1.0)	2.5 (1.5—3.2)	1.7 (1.1—5.8)	4.7 (2.0—9.5)	1.9 (1.2—3.1)	1.4 (1.0—1.7)	1.3 (1.0—1.5)	1.5				[71, 74]
Trebanos (England)	0.7	1.2		3.3	1.6	1.0						[71]
Ankara (Turkey)				4.5		1.2		4.5	0.8	0.5	1.2	[75]
Siberian towns (USSR)		0.9	0.5	1.2	1.1	0.5		3.0	1.9		0.9	[76]
				4.4	0.8	0.5		1.5	1.4		0.6	
Remote background areas			0.45			0.6—0.7	0.6			0.4	0.5	[32]
National Olympic Park (Washington, USA)	0.9	0.3	0.4			0.3						[71]
Semi-desert, pastures (Montana, USA)				3.0	3.0	0.6		0.2	0.5	0.3	0.3	[77]
Forest area in Tennessee	0.5				3.4	0.6						[21]
The Bermudas	0.4—0.6	0.5—0.7	0.8	2—4	2—4	0.6—0.8		1.5	0.3	0.4	0.3	[71, 78]
Eniwetok Atoll (Atlantic ocean)	0.25		0.96	0.72	0.88	0.4		0.75				[21]

*The variation range for average sizes of particles in various towns is shown in parentheses.

trace elements in aerosols. X_i and q are the concentrations of the required and the reference (typical for a particular aerosol source) elements. The subscripts 'atm' and 's' refer to the atmospheric aerosol and the source respectively. Fe, Al, and Sc (their global abundance values) are usually chosen as reference elements for soil dust, and Na or Cl for oceanic dust (ocean water).[73,90,91] The values of K_{en} reported in the literature are largely based on global abundance values. In this way it is possible to achieve a certain universality which is needed for the comparison of data on a global level. K_{en} values referred to for Al and Sc are listed in the literature.[73,90] They mainly related to areas that are at some distance from industrial sources.

These data are presented in the diagram shown in Fig. 1 for the plotting of which 500 values of K_{en} for 42 elements have been used. The elements can be divided into three groups: highly enriched ($K_{en} > 25$), moderately enriched ($3.6 < K_{en} < 25$), and slightly enriched ($K_{en} < 3.6$). As a rule, the volatile elements (I, Pb, As, Cd, Se, Hg, and others) are characterised by the highest values of K_{en}. The moderately enriched group includes Cs and Na, while the slightly enriched group consists mainly of nonvolatile elements (Fe, Ni, Sc, Mn, etc.). There is a wide variation of K_{en} values. Incidently, the values of K_{en} may vary widely even when measurements are made at one and the same site.[92] As the particles become smaller, the enrichment factor, especially for volatile elements, becomes substantially larger.[77,78,93] The results of such measurements carried out in Accra (Ghana) could be fitted with an exponential function.[75] K_{en} for nonvolatile and lithogenic elements does not increase so markedly with decreasing particle size, or it may even not increase at all.[78,93]

In some cases there is a bimodal distribution of K_{en} according to particle size.[68,78] Distribution of K_{en} as a function of geographical position depends on the location of anthropogenic and natural sources of aerosols.[5,17,21,60,77] It is mainly small particles, the most highly enriched with volatile elements, that are carried to great distances.[67] Apparently that is why replacement of global abundance values by concentrations of the elements in local soils affects the value of K_{en} considerably.[77] Quite often the K_{en} values for one and the same element emitted into the atmosphere from different sources, even in the same region, differ quite widely.[94–96] In towns K_{en} values are largely determined by industrial and transport emissions. In emissions from metallurgical works and thermal power stations the order of magnitude of K_{en} for Cd, Zn, As, Pb, and Cu is 10^2-10^3, and for Fe $K_{en} \approx 1.0$.[60] In continental rural areas K_{en} is lower than over the oceans. In polar regions (especially over the Antarctic) it is higher than over the oceans; in the southern hemisphere it is higher than in the northern hemisphere.[73,97,98] However, no such relationship has been observed in other studies.[42,90,99,100] It is not clear why the evidence is so contradictory. Possibly the different values taken for K_{en} play some part in this. There are very few data as yet on K_{en} values in the troposphere and the stratosphere.[101]

Chemical compounds of metals and metalloids

The following compounds were found in the emissions and the ambient atmosphere around plants for smelting Pb, Zn, Cd, and Cu: PbS, $PbSO_4$, $PbO.PbSO_4$, ZnO, ZnS, metallic Pb, CdO, $Zn(PO_3)_2$, metallic Cd, $Cd(OH)_2$, metallic Cu, $CuSO_4$.[102–104] The aerosol matrices contained also SiO_2, S, graphite, K_2O, Na_2O, as well as compounds of major metallic constituents, Fe_2O_3, Al_2O_3, Al_2SiO_3. As a rule, the large particles contain oxides, and the small ones sulphates.[102,105] Fourteen lead compounds were detected near the highway in a rural area and in the exhaust fumes themselves.[102,106] The following gaseous tetraalkylated lead compounds were found near two petrol stations in the USA (% of total): $(CH_3)_4Pb$, 18–46; $(CH_3)_3C_2H_5Pb$, 12–31; $(CH_3)_2(C_2H_5)_2Pb$, 5 and 12; $CH_3(C_2H_5)_3Pb$, 2 and 7; $(C_2H_5)_4Pb$, 63 and 4. However, in the residential areas of large cities and in rural areas the amount of the first compound rose to 75 and 85% of total respectively, while the last three compounds were not detected at all. This implies that ethylated lead compounds degrade much faster than methylated ones.[102,107] Lead alkyls were found in the precipitations that came down in England[108] and Norway.[109] In this case tetraethyl lead is broken down in 48 hours and sometimes cannot be detected. Organometallic compounds of Pb, H, As, and Se, which are formed when these elements react with methane, were found in the atmosphere of several towns in Japan, for instance.[110] Gaseous mercury is present in the atmosphere mainly (up to 80% of total) in molecular form (Hg^0). Part of it gets oxidised and forms unidentified compounds of Hg(II). In that case the mercury is converted into soluble form.[23] Up to 30% of Hg over Europe is in the form of dimethyl mercury, whereas over the ocean only 5% is in this form.[111] The atmosphere of remote background regions contains 11–65% Hg^0, 12–25% divalent inorganic mercury, 21–34% methyl mercury, and 1–46% dimethyl mercury.[24]

The total amount of mercury in vapour state in the air over the Almadena mercury mine (in Spain) was made up of the following: Hg^0, 17–100%; methyl mercury, 0–66%; inorganic Hg(II), ~30%. There was also a small amount of dimethyl mercury.[112] As

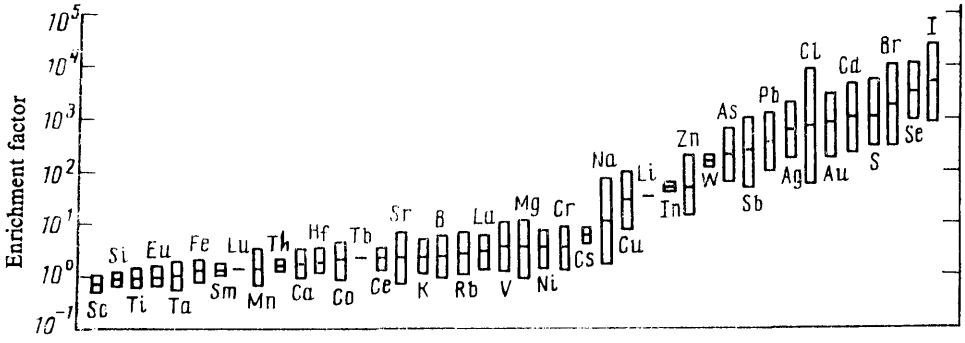


Figure 1. Enrichment factor, K_{en}, for elements in atmospheric aerosols in relation to global abundance ratio (with Al taken as the reference element).[90]

regards arsenic, in Japan up to 10% of it is found in aerosols in the form of organic compounds.[113] The organic particles consist mainly of dimethyl arsinic acid. In summer its concentration rises. Bromine compounds such as methylene bromide, methyl bromide, bromoform, and others were found in the atmosphere of Alaska, New Zealand and elsewhere.[114]

IV. Spatial distribution of concentrations of metals and some metalloids of anthropogenic origin in natural environment

The distance to which a pollutant may spread in the atmosphere largely depends on at least two factors: on how quickly it (a) disintegrates and (b) is transferred to the surface of land and ocean as 'dry' or wet precipitation. These processes have been discussed in detail in reviews,[115–118] and the respective theoretical calculation have also been performed.[119–122] The concentration of vapours of elements in atmospheric precipitations is governed by Henry's law. The Henry coefficient for Hg vapour is 0.48.[116] Dry precipitation of aerosols is connected with sedimentation due to gravity and turbulent air flow directed towards the surface of the Earth. It increases markedly with the height and density of vegetation.[119,123,124] The rate of dry precipitation falls as aerosol particles decrease in size to 1–2 μm, and then rises slightly again at $d < 0.1$ μm because of improved diffusion of very small particles towards the surface of vegetation in the boundary layer (near the Earth's surface where the wind velocity is zero).[15,119,124] The removal of the aerosol admixture from the atmosphere with precipitation is the result of two processes: capture of the aerosols by cloud drops inside the cloud (rainout) and by raindrops below the cloud (washout).[115–118] The mode of capture may vary widely: Brownian and convective diffusion, inertial capture, thermophoresis, etc.

Of the aerosols deposited by precipitation, 0.1–1 μm[116–119,124] particles have the smallest washout rate. In other size ranges the washout rate may be higher by one or several orders of magnitude. According to certain estimates, snow washes out aerosols much more effectively than rain.[117,125] The opposite applies to gases.[118] Snow flakes can capture aerosol particles of different sizes equally well and do so very effectively.[126] This contradicts the theory and needs to be confirmed. As a result, the total (dry and wet precipitation) rate of removal of aerosols from the atmosphere also falls at first as the particle size decreases approximately to 1 μm. In the 0.1–1 μm range the rate remains very small. Then for the even smaller (submicrometer) particles the rate rises once more. However, aerosol filters are unable to catch such particles effectively.[40,42,43] This should be taken into consideration when analysing the behaviour of the aerosol. Let us roughly assume that the rate of removal of aerosol particles from the atmosphere increases with particle size. There is experimental evidence that after precipitation the concentration in the air of the coarsely dispersed fraction of the aerosol drops more sharply than the concentration of the finely dispersed one.[43,127,128] In remote background areas the larger soil particles were also washed out more rapidly than the anthropogenic ones.[89]

The average residence time of atmospheric aerosol in the troposphere is believed to be 1–3 days. But when there is local precipitation of very large particles the residence time is no more than several hours. The residence time of gases in the troposphere is measured by months and years.[117,129]

Chronic exposure of metals and trace elements has the most serious effects. It is therefore important to know the mean monthly and annual concentrations of metals and trace elements in the atmosphere to allow us to assess the danger they pose. The highest concentrations, often in excess of maximum permissible concentrations (MPC), were observed in large cities and around emission sources, especially in the vicinity of metallurgical plants. Thus, in Mexico City cadmium concentrations were 10 times higher than MPC, Zn concentrations were 20 times higher, and Pb concentrations several times higher.[130] There is similar pollution in the cities of the FRG[131] and the USSR. In rural areas, in remote background terrestrial areas, over oceans and in polar regions the concentration of metals in the atmosphere is significantly lower. Thus, for Pb there is a difference of 4–5 orders of magnitude. In the centres of large cities concentrations of Pb in the air amount to $(1-10)\times10^{-6}$ g m^{-3}. In suburbs and rural areas it is lower by 1–2 orders of magnitude.[132] The average concentration of Pb in background areas is (g m^{-3}): for polar regions 0.1×10^{-9}; for 35°–65° N. lat., 10^{-9}; for 0–30° N. lat., 0.2×10^{-9}; for 0–30° S. lat., 0.3×10^{-10}; for 25°–55° S. lat., 15×10^{-10}; for Antarctica $10^{-11}-10^{-12}$.[133–135] In several cases a relationship was observed between lead concentration and the number of dwellers in the city.[136] Cadmium concentrations in the air of USA cities varies within the limits $(1-100)\times10^{-9}$ g m^{-3}. In British cities the average concentration of arsenic is 2.8×10^{-9} g m^{-3}. In rural areas in the USA it is $(4.0-0.3)\times10^{-9}$ g m^{-3}. In Antarctica it is 0.01×10^{-9} g m^{-3}.[21,135,137] The concentration of arsenic in the air of British cities is 6.4×10^{-9} g m^{-3}; at the South pole it is 6×10^{-12} g m^{-3}.[21]

It is interesting to note that the concentrations of Fe, Se, Co and of rare-earth elements, which are usually found in the larger particles, fall tens of times more rapidly with distance from the continent than the concentrations of Se, Sb, and other elements.[138] In the past decade a distinct tendency to lower the air pollution levels of Pb, Zn, Cu, Cd, V, and Mn has become evident in a number of foreign cities and remote background areas.[134,139–143]

There is much less difference between the concentrations of mercury, which is mostly present in vapour state. Thus, the Hg concentrations in USA cities is between 5 and 50 ng m^{-3}; in rural areas it varies from 3 to 9 ng m^{-3}; and over the waters of the Pacific and the Atlantic oceans it is 1–3 ng m^{-3}; in the Southern hemisphere it is only half that in the Northern hemisphere.[23,144] Around certain natural sources the Hg content may amount to 10^3 ng m^{-3}.[145] The vertical distribution of metals in the troposphere is complicated, with a general tendency for the concentration to decrease with height. There is an alternation of maxima, which reflects the fact that there are temperature inversions, advections of various air masses, and other factors.[101,146–148]

In Swiss cities in summer time the distribution of Cd, Cu, Mn, Pb, and Zn concentrations at 515–1500 m above sea level was found to be homogeneous.[149] In the USSR the maximum concentration of Hg in the lower troposphere was observed over the Urals.[150] There are very few experimental data on the amount of organic compounds of metals in the air and the precipitations. The concentration of tetraalkyl lead in European and American cities in 1978–1981 was 83 ng m^{-3}; on roads and in traffic tunnels it was up to 100–200 ng m^{-3}; in housing estates it was 20 ng m^{-3}; and in rural areas 1.7 ng m^{-3}.[151] In Norwegian cities it varied from 11 to 81 ng m^{-3}.[109] Earlier publications gave the concentration of tetraalkyl lead in city air as several micrograms per m^3.[49,132] Let us remember that MPC for a single exposure to tetraalkyl lead in a working zone is 75 g m^{-3}.[152] Most of the arsenic in atmospheric

precipitations is in the form of inorganic compounds.[153] The average concentrations of arsenites and arsenates in the region of the Hawaiian Islands were 0.007 and 0.012 parts per billion respectively; in the area around the Tacoma, WA, USA smelting works they were 1.06 parts per billion.

Soil and snow cover become polluted with metals brought from the atmosphere with 'dry' and wet precipitations. The spatial distribution of metals in these media around the source of emission follows the same pattern as in the surface layer of the Earth. The greatest danger of pollution is within the 10–20 km radius around the emission sources[154,155] and further.[68,72] The boundary of the polluted soil area is very arbitrary, because it is difficult to separate the natural (background) metal-content in the soil from the amount of metals derived from anthropogenic sources. The average levels of pollution of natural media by a local source are inversely proportional to the square of the height of the emission.[156] But the higher the emission takes place, the larger the amount of metals carried to great distances (regional and global pollution). The configuration of the local zone and the degree of its pollution also depend on the wind rose, the vigour and duration of the emissions, the particle size composition, and the frequency of precipitations when wind direction varies.[157,158] What is precipitated locally consists mainly of coarse particles (according to Izrael' et al.[6] global precipitations consist of particles with $d < 5$ μm). The relationship between the level of pollution of natural environment with metals and the distance from the source of emission is thought to follow approximately an exponential dependence in some cases, and a power dependence in others,[159,160–162] with the exponent close to -1.[72,163–166] The parameters of both the exponential and the power distributions are essentially determined by the velocity of the wind, how often it blows in a particular direction, by the height and vigour of the emissions, as well as by other factors. It is difficult to decide which of the above functions gives a more objective picture of the real situation. However, the theoretical dependence of aerosol concentration on the distance from the source becomes, after passing the maximum, close to a power dependence.[118] More complicated models of local precipitations, based on the theory of aerosol distribution in the atmosphere, are discussed in the literature.[119,167,168] From 10 to 40% of the respective emissions of Pb, Zn, Cu into the atmosphere were found to be precipitated in the local zone around a number of metallurgical works in the USSR.[169] By other estimates local precipitation of several metals around iron-and-steel works amounted to 15–37% of the emission of the respective element; around thermal power stations it amounted to 40–50% of the emission of the respective elements.[159]

Measurements taken in the region of the Sudbury copper works (in Canada)[69,72] showed that in a 40 km radius the following amounts of metals were precipitated from emissions from two chimneys 194 and 381 m high in the absence of natural precipitations: Fe, 15.2; Al, 8.9; Ni, 2.6%; finer aerosols Pb, Zn, and Cd, less than 2%. On days when there were natural precipitations the figures were: Fe, 68; Cu, 100; Ni, 36; Zn, 92; Al, 80; Cr, 14.2; Cd, 9.7%. On dry days the fraction of precipitations in the above zone for emissions from a chimney 93 m high was: Fe, 100; Ni, 29; Al, 58; Pb, 13; Cd, 1%. For Hg the respective indices were considerably lower: for operating chlorine-alkali plants the fraction of local mercury precipitations in a 10 km radius was from ~7%[170] to 10%;[23] in a 3 km radius it was 5%.[171]

It has been postulated that Hg can go through repeated precipitation and evaporation cycles,[46] finally accumulating in the polar regions in low-temperature conditions. But so far there has been no direct confirmation of this hypothesis.

Local zones with soil highly polluted with metals are often regarded as technogenic geochemical anomalies.[172,173] These zones are doubly dangerous because in such zones the fraction of metals in mobile and exchangeable state, and, consequently, easily assimilated by plants, is often significantly higher than in remote background areas.[154,165,174,175] In the zone of local precipitation the aerobic assimilation of metals by plants through their leaves and stalks plays a prominent role. This effect decreases with distance from the source of emission.[176,177] The combined effect of the extremely toxic compounds of sulphur and nitrogen with metals causes plant diseases and the destruction of forests and other vegatation, and reduces crop yields.[178–180]

Regional precipitations, and the more so global precipitations, usually do not lead to a significant increase of the amount of metals in the soil. However, it was established that in Norway the soil contained different amounts of lead: from 100 to 120 p.p.m. in the south to background levels of 10 p.p.m. in the north. This difference may be due to lead emission in Western Europe.[181] Areas of snow cover considerably polluted with metals extend over 10 to 13 thousand km^2 around Norilsk and Monchegorsk.[182]

Because car exhaust fumes are emitted close to the ground, soil and snow become polluted with lead and other metals in areas adjoining the highways to distances not greater than some tens and hundreds of metres.[86] Only 0.2–0.7% of Pb and 1.7–5.5% of Zn in this zone are in an exchangeable state.[183]

Technogenic toxic metals enter the oceans mainly from the atmosphere. Nearer the continental shelf river discharges start to play a greater role and both these factors become commensurate.[21] The maximum concentration of Pb in the surface layers of the Pacific ocean (up to 14–16 ng m^{-3}) is observed at mid-latitudes (20°–40° north lat.). Lead concentration is lower in the tropical zone (down to 6 ng m^{-3}), and in the southern hemisphere it is only 4–5 ng m^{-3}.[184,185] The natural level of lead in the surface layers of the northern Atlantic and Pacific oceans is exceeded by a factor of 8 to 20 and in the southern part of the Pacific ocean it is exceeded by a factor of 2. The vertical profile of Pb concentration has its maximum in the layer 0–2.5 km in depth. In deeper layers the concentration drops 6- to 7-fold.[21,184,185] The Cd, Zn, Cu, and Ni content in the ocean grows with depth down to 1000–1500 m, and in individual cases even to greater depths.[21,187] It is difficult to speak of the fraction of anthropogenic metals in this case. We can assume that deep in the oceans the concentrations are still at preindustrial levels, because vertical exchange takes a very long time.

It is interesting to trace how the anthropogenic emission of metals into the atmosphere increases the pollution of the environment on a global level on the example of polar regions, where biota is most sensitive to outside influences. In winter, when the polar front moves far down south, large masses of pollutants move into the arctic regions to form an aerosol haze there.[188–191] This haze contains sulphur and nitrogen compounds, polycyclic aromatic hydrocarbons, organic compounds, and soot, as well as metals and metalloids.[137,192–195] In winter, because precipitations are few and there is stagnation in the atmosphere, the lifespan of fine aerosol in these regions can last up to 2–3 weeks.[46] Plotting circulation paths in conjunction with the use of reference materials, together with other methods allows us to conclude that the polluted air masses move into the Arctic from Europe and to some extent from North America. Most of these masses settle in the European part of the USSR and in the Urals.[196,197] No similar phenomena have been

observed in the Antarctic. In spite of the presence of an anthropogenic polar 'haze', measurements of Hg, Cd, Zn, As, Cu, Sb, and Se concentrations in different layers of a glacier in Greenland gave no reliable proof of an increase in these concentrations in the industrial period.[133,198,199] This may be due to methodological difficulties (external pollution of the samples)[133,134] and to the wide scatter of data. It has been found that even in the pre-industrial period the concentrations of metals in the atmosphere were much higher during glaciation than in the interglacial ages.[134,200] The metals must have been of soil origin because the data correlate with Al. Pb is the exception: its content in the ice of Greenland in the period from 800 to 1950 AC increased 200 times (from 1.4×10^{-12} to 200×10^{-12}).[201] According to other evidence, by 1965 the content of Pb amounted to 230×10^{-12}; then by 1983 it decreased several times because a number of countries had prohibited the use of ethylated petrol.[134] In the Antarctic also no rise was observed in the concentrations of metals and metalloids (Hg, Cd, As, Fe, Zn etc.) in layers of ice dating from the industrial period.[133,199,202–204] Here too Pb was the only exception. However, estimates of the rise in its concentration in the industrial period are somewhat contradictory. In the ice of Antarctica lead concentrations increased 4- to 5-fold.[202–205]

There is also a different estimate.[133] According to it, the concentration of Pb in the ice layer increased to a somewhat lesser degree: from $(1-2)\times10^{-12}$ to $(2-5)\times10^{-12}$. Attempts were made[134] to assess the concentration of lead in the air of Antarctica in the preindustrial period on the basis of the current contents of lead in the glacier and in the atmosphere (7×10^{-12} and 1×10^{-12} g m^{-3}, respectively).

It is difficult to estimate the danger of regional and global pollution of the atmosphere with metals because there are no standards as yet. Such pollutions are relatively low-level, but they spread over large areas. Local pollutions are estimated by comparison with MPC, but this method has significant drawbacks. Every MPC refers to a specific metal or substance,[152,206,207] whereas in natural conditions there is a mixture of toxic substances. Some of them have a joint synergic effect on the Biota, whereas others have an antagonistic effect. Attempts to develop some standards for pollution of the environment by mixtures of toxic substances remain purely formal so far.[208] The concept of 'maximum permissible load' on the ecosystem has been proposed, but so far it has found no practical application.[209] It is still not clear what units should be used to measure this load. We believe that biomarkers characterizing the reaction of biological objects to pollution should be used to assess the danger of pollution of the environment by a combination of toxicants.[210] Suggestions have been made concerning the assessment of soil and air pollution with metals.[158,211,212] The concept of the maximum permissible emission (MPE) is widely used to safeguard against dangerous pollution levels. MPE is the emission after which the atmospheric concentration of a toxic substance does not exceed its MPC.[213] This concept has also been applied to the content of toxic metals in the soils around metallurgical works.[214] In general, it is necessary to set up such MPE values which would guarantee that the MPCs would not be exceeded in all natural environments. A serious drawback of MPCs for the atmosphere consists in these standards being determined with no regard for the dispersion properties of the aerosols, whereas it is mainly the finely dispersed aerosols that settle in the respiratory tract and the lungs. Most of Pb, Cd, Cu, Zn, Mn, and Fe from the atmospheric aerosols settle in the lungs (10–40% of the inhaled amount). If we consider the whole respiratory tract, including the nasopharynx, 50–90% of Fe, 30–42% of Pb, 40–70% of Cd, 28–62% of Zn inhaled are deposited there.[71]

V. Conclusion

Today there is a high level of air and soil pollution because of the emissions of metals into the atmosphere. In many cases the pollution exceeds the MPC. This is mainly true for large cities and centres of industry, especially if they contain nonferrous metal works or iron-and-steel works. Excessive amounts of toxic metals in the environment, especially if there are other toxicants as well, lead to diseases in man (including cancer). They also promote diseases of arboraceous vegetation and its destruction, and they reduce crops.[177,179,215–217]

A further rise in the pollution level is to be expected in the foreseeable future. This applies especially to soil, the surface layers of the oceans and the polar regions. It will be caused by a greater volume of emissions and by the accumulation of precipitations. Thus, the average annual global increase of emissions of metals into the atmosphere in 1950–1975 was for Pb, 3.1%; for Cd, 4%; and for Ni, 6.7%.[218] According to Ostromogil'skii et al.,[25] the worldwide emission of Pb will rise in the period 1980 to 2000 by 10%; for As and Cd this increase will amount to 20%. It takes from several months to several years to double the natural background amount of metals in a surface layer of soil 1 cm thick near a metallurgical plant.[165,219] In American cities it takes several tens of years to double the background amount of Pb, Cd, Zn in a 2.5 cm thick surface layer of soil; in residential areas it takes a hundred years or longer.[220] In rural and remote background areas the natural concentration of most metals in the 1 cm thick surface layer of soil also doubles in tens and hundreds of years.[165]

Calculations predicting the level of pollution of the environment with Pb, Cd, As, and Hg were carried out for 1980–2000 on the basis of the 'box' model.[25] One can expect the concentrations of Pb, Cd, and As in the air of nonindustrial terrestrial regions in the northern hemisphere to grow by several percent (up to 10%). In Antarctica they can be expected to grow by 25, 15, and 10% respectively. The Pb concentration in the surface layer of the northern part of the Atlantic ocean will almost double by 2010. In other parts of the ocean it will rise by tens of percent.

The maximal level of pollution of soil and ocean, which accumulate the metals emitted into the atmosphere, will be established after all the industrial reserves of these metals have been exhausted and they themselves have been dispersed over the globe. Even rough estimates[221] show that the amount of lead, mercury, cadmium, and arsenic in the soil will be tens and hundreds of times greater than at present. The migration of elements from the surface layer of soil into rivers and oceans is a very slow process. Because of that the achieved high levels of pollution of the soil with metals will be maintained for a long time (for hundreds or even thousands of years). This makes it so important to strive already today to reduce sharply the emissions of metals into the atmosphere and their dispersion in the environment by adopting progressive technologies and waste-free manufacturing processes.

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