Estimated heavy metal emissions to the atmosphere due to projected changes in the Brazilian energy generation matrix

A.G. Vaisman · L.D. Lacerda

Abstract An estimate of heavy metals emissions to the atmosphere due to the projected changes in the Brazilian energy generation fuel matrix is presented. Present use of fossil fuel combustion for energy production is projected to increase from the present 14.5% to 29.6% of the total energy generation in Brazil in 2005. Most of this increase will be based on coal- and natural-gas-burning plants. The changes will result in an increase of about 100% in the average emissions (in tons year^{-1}) of As (9.4 to 17.7), Cr (7.0 to 16.6) and Hg (2.4 to 4.1), 50% of Cd (1.2 to 1.8), and 20% of Ni (101 to 123) and Pb (23.3 to 29.9). Although relatively small for most heavy metals when compared to other industrial sources, the changes in the energy matrix will be particularly important for Hg, reaching a maximum emission of 12 tons (t) year^{-1}, representing 15% of the total emissions of Hg to the atmosphere in Brazil. The use of Brazilian coals and the location of most coal-burning plants in a relatively small region in the south of the country strongly suggest that monitoring programs should be implemented during the building of the new plants. At a regional level the expected increase in Hg emissions to the atmosphere due to coal burning in Brazil, although small relative to North America and Europe, will equal the total amount estimated for South and Central America.

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Introduction

Non-nuclear fuel-burning power generation is an important source of trace metal emissions to the atmosphere. It is particularly important for certain elements such as Hg, contributing to nearly 60% of its global anthropogenic atmospheric releases (Pirrone et al. 1996). Until recent years, power generation in Brazil relied almost entirely on hydroelectric dams, which supplied about 96% of the country's total electric energy in 1992. In 2001, the hydroelectric sector accounted for 82% of Brazil's power generation, while non-nuclear fuel-burning plants were generating only 14.5%. By the year 2005, these figures will be 68.5% and 29.6%, respectively, meaning a significant change in the Brazilian energetic matrix (ANEEL 2002). These numbers reflect a drastic change of the Brazilian Federal Government's policies, triggered by the power supply shortage of 2001. Extremely low precipitation levels throughout the country's main fluvial basins, which emptied most reservoirs, caused this shortage. This situation led the government to implement an emergency consumption reduction program, including compulsory reductions in electric power consumption that ranged between 15 and 25%. This emergency program was lifted in February 2002, after the rainy season refilled the reservoirs. This crisis strongly hit Brazil's economic performance, as well as causing a great deal of concern throughout its population.

Table 1 shows the generation capacity of the current and projected (operational in 2005) biomass- and fossil fuel-fired power plants. As verified in most countries with fossil fuel-based power generation matrices, a significant increase in the emissions of some trace elements to the atmosphere is expected. This study aims to estimate the thermal energy generation atmospheric emissions of trace elements of environmental significance, namely arsenic, cadmium, chromium, lead, mercury and nickel, taking

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into consideration this new scenario already becoming reality in the country.
In order to calculate the annual atmospheric releases of trace metals from this source, emission factors reviewed in the international and Brazilian literatures were used. Special attention was dedicated to the coal-burning-related emissions, considering the coal's higher trace elements' levels, and the characteristics of the Brazilian coals. Power plants emissions of some metals, though important, represent a small share of the total emissions at a country level (Lacerda et al. 1995a). That may not be the case with Hg, a metal presenting a high volatility, with nearly 100% of its concentration being released in the vapor phase (Pires et al. 1997). The relative participation of the new Brazilian energetic matrix in the total Hg and other trace metals emissions to the atmosphere will increase not only due to the increasing use of fossil fuel-fired power plants, but also due to the reduction of atmospheric Hg emissions from small-scale gold-mining operations, historically the main source of Hg emissions to the atmosphere in Brazil, and the strengthening of emission control policies applied to other industrial trace metals sources, such as the chlor-alkali sector for Hg.

Database construction

Distillate oil, natural gas, coal, sugarcane bagasse and others (in decreasing order of importance; see Table 1) are used as fuel for power generation in Brazil. The country's fossil fuel- and biomass-burning power plants have an overall generation capacity of nearly 11,019 MW. This figure will suffer a three-fold increase by the year 2005, due to new and expanded facilities, mainly natural gas- and coal-fired plants. Emission factors published in the international and Brazilian literatures for As, Cd, Cr, Hg, Ni and Pb for each particular fuel type were used in order to estimate the annual emissions from these sources, taking into consideration the local fuel characteristics and industrial processes. Since Brazilian coals differ in their characteristics from imported ones, different emission factors were used to calculate emission estimates.

Table 1
Brazil's current and planned thermal generation capacity (March 2002 and 2005), sorted by fuel type (excluding nuclear power plants). (Source: ANEEL 2002)

Fuel type	Number of plants		Installed capacity (kW)	
	2002	2005	2002	2005
Natural gas	36	97	3,292,736	22,549,647
Industrial gas	16	20	654,340	667,740
Distillate oil	372	409	3,911,034	5,480,001
Coal	7	11	1,461,000	4,170,500
Biomass	182	203	1,700,126	1,858,361
Total	613	740	11,019,236	34,726,249

Brazilian federal and state laws have established the compulsory use of emission control technologies for power plants to be licensed to operate, and they are indeed implemented. Thus, emission factors for controlled facilities were used to calculate annual emissions from fossil fuel burning. Biomass-burning plants, however, are hereon assumed not to have such emission control devices (Patrick et al. 1994).

Natural gas combustion

Data on trace elements concentrations and emission factors for natural gas combustion are scarce, though it is widely agreed that these are much lower than the other fuels'. Emission factors proposed by Chu and Porcella (1995) and USEPA (1995) for Hg and by USEPA (1995) for the other elements back this assumption, showing extremely low emission factors for the assessed metals after natural gas combustion. Nonetheless, these proposed emission factors must be considered cautiously, because of the limited number of sampling points supporting them, and in the case of Hg the high variability of this metal's concentration within a single gas field. The poor knowledge of emission factors from natural gas combustion, the huge amounts of natural gas burned in power plants and the seven-fold increase in natural gas burning expected to occur in the next 3 years suggest a conservative view of the estimated emissions. Industrial gas represents less than 1% of the total gas generation capacity (Table 1). Also there is no plan to increase its use in the future; therefore, our database included this type of gas under the same statistics used for natural gas.

Coal combustion

A four-fold increase in energy production from coal-burning plants is projected for 2005 (Table 1). The Brazilian coalfields are located in the country's southern region, with the states of Rio Grande do Sul and Santa Catarina accounting for 99% of the country's coal production (Da Silva 1993; Bizarro César 2000). Since coal transport is a major factor in the coal-based energy production costs, all the existing and planned coal-fired power plants are and will be located in that region, with the sole exception of one, to be constructed at the Sepetiba Harbor, Rio de Janeiro State, in the country's southeastern region. It is hereon assumed that all the coal to be used in the power plants in the southern region is of Brazilian origin. This assumption is based on the high influence of transport on the cost of the energy produced, the existing Brazilian coal reserves, the production capacity of the coal-mining operations, and the historical 100% Brazilian coal supply for the coal-based power generation industry (Ministério de Minas e Energia 2001). The Sepetiba Harbor power plant, however, will reportedly use imported coals, with almost twice the heating value of the Brazilian ones.

Furthermore, reports on metal contents of Brazilian coals show significant discrepancies (Martins and Zanella 1990; R. Finkelman, personal communication, 2002). This may be a consequence of the variability of the metals concentrations both among different coalfields and stratigraphy within a single deposit, and the number of collected samples (unknown and 39, respectively, in the cited studies).

Different emission factors were used to calculate the annual emissions from these two different coal sources. Emission factors for Brazilian coal-fired plants were calculated from the mass balance and metals concentrations reported by Martins and Zanella (1990), the study of Pires et al. (1997), and the metals concentrations reported by R. Finkelman (personal communication, 2002), the latter being very similar to those found in US coals. Emission factors from USEPA (1995) were also considered. These emission factors, based on US coals, were adjusted by a factor of 1.8, due to the lower heating value of the Brazilian coals, meaning that more coal should be burned in order to generate the same amount of electricity. Emission factors for imported coals were estimated from several studies (Billings and Matson 1972; Nriagu and Pacyna 1988; Chu and Porcella 1995; USEPA 1995; Pirrone et al. 1996; Sunderland and Chmura 2000). It must be taken into account that emission factors reported in the international literature are based on studies performed on coals from western countries (mainly the USA and Canada), while the origin of the imported coals to be used in Brazil is uncertain.

Brazilian coals have a low heating value, nearly 3,300 kcal kg^{-1}, and recent historical records, from January 2000 to August 2001, show a burning efficiency of 0.828 metric tons MWh^{-1} for the operating coal-fired power plants, implying an energy conversion rate of 31.5%, operating at a 60% working load (Eletrobrás 2002). A similar consumption rate was assumed for the Sepetiba Harbor power plant, its burning efficiency being expected to be 0.46 metric tons MWh^{-1} due to its coal's higher heating value, reportedly 6,000 kcal kg^{-1} (Itaguai Energia S/A corporate press release). When calculating the expected emissions for 2005, we have considered a working load of 60% for all the power plants.

Oil combustion

The oil-based energy generation capacity will be increased by 40% until 2005 (ANEEL 2002). Oils to be used for power generation in Brazil are assumed not to differ significantly from others, due to the impossibility of predicting the origin of oils used for energy generation in the country. Also, there is still a large participation of imported oils from diverse origins in the Brazilian oil-based energy generation industry. Therefore, emission factors applied to the different trace elements are those reported in the literature (Nriagu and Pacyna 1988; Chu and Porcella 1995; USEPA 1995). Due to the high number of oil-fired plants and their high size variability, it was impossible to generate an accurate historical average working load for them. A 60% working load, similar to that of coal-fired plants, was considered in order to calculate their expected emissions.

Biomass combustion

Several types of biomass are used in Brazil as fuel for energy generation. Brazil is the world's largest sugarcane producer, so sugarcane bagasse has naturally become the main biomass fuel. Other minor fuels used are wood, tall oil and rice hulls. Emission factors were estimated from several sources (Nriagu and Pacyna 1988; Patrick et al. 1994; Lacerda 1995a; USEPA 1995; Pirrone et al. 1996; Sunderland and Chmura 2000). It must be taken into account that most of these sources refer to biomass from temperate regions, while tropical plants may have a different concentration of the elements under study (Lacerda 1995).

Sugarcane bagasse accounted for 50% of the biomass-based energy generation (Ministério de Minas e Energia 2000) in 1999. In order to estimate the total biomass burned, the amount of biomass burned annually for energy generation in 1999 was assumed to be twice the amount of sugarcane bagasse burned, reportedly 3,924,000 metric tons, so it is hereon assumed the burned biomass for the year of 1999 to be 7,848,000 metric tons. A biomass burning increase for the year 2005 was assumed to be proportional to the increase in the biomass-fueled generation capacity, therefore reaching 8,577,800 metric tons $year^{-1}$. In order to evaluate the environmental significance of emissions from this source, the seasonal operation of these facilities should be considered, since sugarcane bagasse is burned mostly after the harvest.

Results and discussion

Table 2 summarizes the emission factors estimated for this study. Emission factors from coal burning are by far the highest, particularly for As, Hg and Pb. Oil burning, however, results in the largest emission factor for Ni. Lowest emission factors are from natural gas, followed by biomass burning. Emission factors from Brazilian coals are higher than from foreign coals for As and Hg, lower for Cd, Ni and Pb and similar for Cr. This is of particular environmental significance since As and Hg are the most toxic of the metals analyzed and present high residence times in the atmosphere. Also, other industrial sources of these two metals have been submitted to strong environmental legislation, restricting their emissions. Since Brazilian coal plants are located in a relatively small region in the country's south, local contamination risk may be significant.

Tables 3 and 4 show estimates of present and future annual heavy metal emissions from non-nuclear fuel-burning power generation plants. Emissions are mostly due to coal

Table 2
Emission factors for fossil fuels (μg MJ^{-1}) and biomass (g t^{-1}) fuel-burning power generation in Brazil. *Values in parentheses* express the lower and upper emission factor ranges. To convert μg MJ^{-1} into μg MWh^{-1}, values were multiplied by 3,600

Fuel	As	Cd	Cr	Hg	Ni	Pb
Natural gas	0.09[a]	0.49[a]	0.62[a]	0.05[b](0.00034–0.11)	0.93[a]	0.22[a]
Coal (Brazilian)	277.50[c] (47.14–572.0)	3.99[d] (2.11–5.87)	252.15[d] (29.88–222.27)	57.07[c] (17.18–127.00)	88.84[d] (32.2–154.5)	58.80[d] (48.29–69.31)
Coal (foreign)	41.84[e] (15–100)	9.1[e] (5–25)	218.3[e] (16.6–500)	8.1[f] (1.7–35.0)	136.5[e] (18–500)	100.9[e] (26.8–300)
Distilled oil	1.86[c] (1.00–5.00)	3.18[c] (0.10–6.17)	35.73[c] (13.97–100)	0.86[b] (0.20–1.53)	1,220[g] (60–2,500)	93.89[e] (18–300)
Biomass	0.2[e] (0.1–0.5)	0.11[e] (0.02–0.30)	0.11[h]	0.09[i] (0.018–0.500)	1.08[e] (0.17–3.00)	1.87[e] (0.25–5.00)

[a]After USEPA (1995). A burning efficiency of 0.01 MWH m^{-3} was assumed
[b]Mean of means of the emission factors reported by Chu and Porcella (1995) and USEPA (1995)
[c]Mean of means of the emission factors calculated from Martins and Zanella (1990), USEPA (1995), Pires et al. (1997) and Finkelman (personal communication, 2002)
[d]Mean of means of the emission factors calculated after Pires et al. (1997), USEPA (1995) and Finkelman (personal communication, 2002)
[e]Mean of means of the emission factors reported by Nriagu and Pacyna (1988) and USEPA (1995)
[f]Mean of means of the emission factors reported by Billings and Matson (1972), Nriaguand Pacyna (1988), USEPA (1995), Pirrone et al. (1996) and Sunderland and Chmura (2000)
[g]After Nriagu and Pacyna (1988)
[h]After USEPA (1995). A heating value of 5,200 Btu lb^{-1} was assumed to convert to g t^{-1}
[i] Mean of means of the emission factors reported by Nriagu and Pacyna (1988), Patrick et al. (1994), Lacerda (1995), USEPA (1995), Pirrone et al. (1996) and Sunderland and Chmura (2000)

Table 3
Estimated annual emissions (2002) for a working load of 60% (fossil fuels), and 7,848×10^3 metric tons of burned biomass (t $year^{-1}$). *Values in parentheses* represent the expected variation range. Imported coal is presently not used

Fuel	As	Cd	Cr	Hg	Ni	Pb
Brazilian coal	7.67 (1.30–15.81)	0.11 (0.06–0.16)	3.48 (0.83–6.14)	1.58 (0.47–3.51)	2.46 (0.89–4.27)	1.62 (1.33–1.92)
Distilled oil	0.14 (0.07–0.37)	0.24 (0.01–0.46)	2.64 (1.03–7.40)	0.06 (0.01–0.11)	90.28 (4.44–185.00)	6.95 (1.33–22.20)
Natural gas	0.01	0.03	0.04	0.01	0.06	0.01
Biomass	1.57 (0.78–3.92)	0.86 (0.16–2.35)	0.86	0.71 (0.14–3.92)	8.48 (1.33–23.54)	14.68 (1.96–39.24)
Total	9.39 (2.16–17.53)	1.24 (0.26–3.00)	7.02 (2.76–14.44)	2.36 (0.63–7.55)	101.28 (6.72–212.87)	23.26 (4.63–63.37)

Table 4
Estimated annual emissions (2005) for a working load of 60% (fossil fuels), and 8,578×10^3 metrictons of expected burned biomass (t $year^{-1}$). *Values in parentheses* represent the expected variation range

Fuel	As	Cd	Cr	Hg	Ni	Pb
Brazilian coal	14.67 (2.49–30.23)	0.21 (0.11–0.31)	6.65 (1.59–11.74)	3.02 (0.90–6.71)	4.70 (1.70–8.16)	3.10 (2.54–3.67)
Imported coal	1.09 (0.39–2.60)	0.24 (0.13–0.65)	5.69 (0.43–13.03)	0.21 (0.04–0.91)	3.56 (0.47–13.03)	2.63 (0.70–7.82)
Distilled oil	0.16 (0.09–0.43)	0.27 (0.01–0.53)	3.07 (1.20–8.60)	0.07 (0.02–0.13)	104.97 (5.16–215.00)	8.08 (1.55–25.81)
Natural gas	0.04	0.21	0.26	0.02	0.40	0.09
Biomass	1.72 (0.86–4.29)	0.94 (0.17–2.57)	0.94	0.77 (0.15–4.29)	9.26 (1.46–25.73)	16.04 (2.14–42.89)
Total	17.68 (3.87–37.59)	1.87 (0.63–4.27)	16.61 (4.42–34.57)	4.09 (1.13–12.06)	122.89 (9.19–262.32)	29.94 (7.02–80.28)

burning, particularly Brazilian coals, which result in the largest emissions of As, Cr and Hg, which can reach maximum emissions of about 37.6, 34.6 and 12.1 t $year^{-1}$, respectively. Major emissions for Cd, Ni and Pb are from distilled-oil- and biomass-burning plants, reaching maximum emissions of about 4.3, 262.3 and 80.3, respectively. The extremely high estimated emissions of Ni from distilled oil combustion should be used with care, since one of the emission factors available is too high (Nriagu and Pacyna 1988) and the other available factor from the USEPA (1995) gives undetectable Ni concentrations in distilled oil. Different relative importance of each fuel type results in different scenarios of heavy metals emissions increase in 2005 relative to the present. Whereas for As, Cr and Hg emissions will double due to the much higher emission factors of these elements from coal, the increase for Cd will reach 50% and for Ni and Pb about 20%, due to the smaller increase of distilled-oil- and biomass-based generation capacity, which have relatively higher emission factors for these elements. There are no trace elements emission inventories from anthropogenic sources at the country level, yet local inventories are available, showing much higher atmospheric emissions for most metals originated from activities other than energy generation. Thus, the contribution of the fuel matrix change to the total emissions will be small when compared to other major sources such as industry and mining. For example, emissions of Cd and Pb to the atmosphere at the Sepetiba Bay Basin, a fairly industrialized area in SE Brazil, reach about 10 and 61 t year^{-1}, respectively (Lacerda et al. 2002), higher than the total emissions from power generation for these two metals estimated in the present study for the entire country. Contrary to other heavy metals, however, estimated emissions for Hg from non-nuclear fuel power generation plants may reach a relatively significant level when compared to the other main sources. The relative participation of each source in the total inputs of these pollutants to the atmosphere should be considered in the allocation of resources for control and monitoring programs. However, their environmental significance will be shown by the total amounts of each substance that are actually released into the environment.

Fossil fuel combustion is presently the principal source of Hg to the atmosphere on a global scale. In North America, for example, this source contributes about 100 t year^{-1}, about eight times higher than the estimates for 2005 in Brazil (Pirrone et al. 1998), while in Asia it reached 420 t in 1992 (Pirrone et al. 1996). At the regional level, however, the increase in Brazilian emissions is significant. The estimated Hg emission to the atmosphere in Central and South America, including Brazil, from coal burning, for example, reached 6.2 tons year^{-1} in 1992, with a projected increase of 3% per year (Pirrone et al. 1996); therefore the projected maximum emission from coal burning in 2005 (7.6 tons year^{-1}) in Brazil could equal that number.

Notwithstanding the relatively small emissions when compared to more industrialized countries, the proposed energy matrix change in Brazil will significantly influence the relative importance of the different Hg sources to the atmosphere. One major reason is the continuous reduction of Hg emissions from other industrial sources, which has been more significant than for other metals. The chlor-alkali industry (mercury electrolytic cells users), for example, consumed 60% of the country's total mercury demand in 1979, though it accounted for only 7.4% of the atmospheric Hg emissions 10 years later (Lacerda 1997). Today, it is still one of the major sources of atmospheric mercury emission in Brazil, although total banning of this technology is expected to occur within the next decade. Using the parameters given by Moreira. and Pivetta (1997) and ABICLOR (2001), we estimate these emissions to be today in the range of 14–20 tons year^{-1} (Table 5).

Small-scale gold mining operations were responsible for nearly 84% of the total Hg emissions to the atmosphere in Brazil in 1991 (about 136 t year^{-1}) (Lacerda et al. 1995b), although it has shown a marked decrease in the past few years. Presently, small-scale gold mining is responsible for the release of 15–30 metric tons to the atmosphere (Lacerda 2003) or about 12 t year^{-1} if official gold production numbers are used for estimating Hg emission (Maron 2000). This decrease is due to a drastic reduction in gold mining operations in the Amazon and is expected to fall further in the next few years.

Table 5
Estimated Hg emissions to the atmosphere from major sources in Brazil during the peak of gold mining between 1986 and 1990, today and projected emissions for 2005 (t year^{-1}). Emissions were estimated based on emission factors and consumption parameters for major sources after Pfeiffer and Lacerda (1988), Bezerra (1990), Ferreira and Appel (1991), Lacerda et al. (1995b), Lacerda (1997), Lacerda and Marins (1997), Moreira and Pivetta (1997), Veiga (1997) and ABICLOR (2001)

Source	1986–1990	1998–2002	2005[a]
Energy generation	<1.0	0.5–3.5	2–12
Chlor-alkali industry	8–20	14–20	Stable[b]
Gold mining	100–170	11–30	Decreasing[c]
Others[d]	<1.0	<1.0	Decreasing[e]
Total	110–190	26–54	–

[a]Estimates for most other mercury sources are difficult to quantify due to dependency on the country's economic growth. However, a tendency determination is possible due to present environmental policies regulating the industry
[b]Although an increase in alkali production is expected, this will be solely based on non-Hg cells technology
[c]Exhaustion of easily mined deposits and stable international gold prices
[d]Others include electro-electronics, dental and pharmacy, paints and chemistry, from which major emissions are to soils and waters and which contribute less than 1.0 t year^{-1} to the atmosphere
[e]Recycling of batteries and lamps is expected to reduce emissions to less than the estimates for previous periods, as well as substitution of Hg in various industrial chemical processes

Other Hg sources to the atmosphere in Brazil, such as the chemical and electro-electronics industries, have remained relatively constant over the last 10 years and no significant decrease or increase is expected to occur in the near future. More recently, recycling of the Hg in fluorescent bulbs and special disposal of batteries have become common practices in the country, increasing the reduction in Hg emissions.

The relative atmospheric Hg contribution of the power generation industry will, therefore, significantly increase in the coming years and may reach 15% of the total Hg emission to the atmosphere by 2005. However, higher proportions can be attained if a faster decrease in small-scale gold mining occurs, a possible scenario due to improving social–economic conditions of the country and the near exhaustion of easily mined deposits (Maron 2000). Also, most emission control measures will certainly be more effective when applied to other industrial sources, whereas there is an enormous difficulty in further reducing the Hg emissions from power-generating plants (Pires et al. 1997).

Conclusions

Though not yet reaching the level of participation in overall power generation it has in most developed countries, thermoelectric generation in Brazil is expected

to keep increasing in the coming years. The resultant heavy metals emissions will significantly rise, and they must be considered at the regional and local levels in order to evaluate both their environmental and public health significance over the affected areas and populations. Coal-fired power plants represent the lion's share of heavy metals emissions. Since these plants are located in a clearly defined region of the country, their emissions' fate cannot be analyzed at the country level, but must be considered within a regional framework. Among the different heavy metals, Hg is of particular significance, since major changes in other Hg sources to the atmosphere in Brazil may relatively increase the importance of thermoelectric energy generation, in a manner similar to the present situation in Europe and North America.
Finally, no upstream emissions, such as those caused by mining operations, distilleries, transport, etc., were considered in this inventory. Such emissions, though, must be taken into account when monitoring the overall emissions of a particular facility.

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References

ABICLOR (2001) Anuário estatístico 2000. Associação Brasileira da Indústria de Álcalis e Cloro-derivados, São Paulo, pp 24
ANEEL (2002) Banco de Informações de Geração. Agência Nacional de Energia Elétrica, Brasil. www.aneel.gov.br
Bezerra JFM (1990) Estimativas de cargas de mercúrio liberadas para o meio ambiente por atividades industriais caracterização de fontes. In: Hacon S, Lacerda LD, Pfeiffer WC, Carvalho D (eds) Riscos e Consequências do uso do Mercúrio. FINEP/UFRJ Ed, Rio de Janeiro. pp 91–109
Billings CE, Matson WR (1972) Mercury emissions from coal combustion. Science 176:1232–1233
Bizarro César S (2000). Carvão mineral. In: Sumário Mineral 1999. Departamento Nacional de Produção Mineral, Ministério de Minas e Energia, Distrito Federal, pp 30–31
Chu P, Porcella DB (1995) Mercury stack emissions from US electric utility power plants. Water Air Soil Pollut 80:135–144
Da Silva ZCC (1993) Candiota coalfield – a world-class Brazilian coal deposit. J Coal Geol 23:103–116
Eletrobrás (2002) Conta Consumo de Combustíveis. www.eletrobras.gov.br
Ferreira RH, Appel LE (1991) Mercury: sources and uses in Brazil. In: Proc Int Symp on Environmental Studies on Tropical Rain Forests, Manaus, 8–11 Nov, pp 207–216
Lacerda LD (1995) Amazon mercury emissions. Nature 374:21–22
Lacerda LD (1997) Evolution of mercury contamination in Brazil. Water Air Soil Pollut 97:247–255
Lacerda LD (2003) Updating global Hg emissions from small-scale mining and assessing its environmental impacts. Environ Geol (in press)
Lacerda LD, Marins RV (1997) Anthropogenic mercury emissions to the atmosphere in Brazil: the impact of gold mining. J Geochem Explor 58:223–229
Lacerda LD, Guerra T, Castilhos ZC, Hatje V, Canesin FP, Cunha LC (1995a) Heavy metals atmospheric inputs from energy generation in Brazil. In: Proc 10th Conf on Heavy Metals in the Environment, Hamburg, Publ 1, pp 81–83
Lacerda LD, Prieto RG, Marins RV, Azevedo SLN, Pereira MC (1995b) Anthropogenic mercury emissions to the atmosphere in Brazil. In: Proc 10th Conf on Heavy Metals in the Environment, Hamburg, Publ 1, pp 379–382
Lacerda LD, Marins RV, Barcellos C (2002) Anthropogenic fluxes of sediments and trace metals of environmental significance to Sepetiba Bay, SE Brazil. In: Lacerda LD, Kremer H, Kjerfve B, Salomons W, Marshall Crossland JI, Crossland JC (eds) South American basins: LOICZ global change assessment and synthesis of river catchment – coastal sea interaction and human dimensions. LOICZ Reports and Studies no 21. LOICZ, Texel, pp 212
Maron A (2000) Ouro. In: Sumário Mineral 1999. Departamento Nacional de Produção Mineral, Ministério de Minas e Energia, Distrito Federal, pp 78–79
Martins AF, Zanella R (1990) Estudo analítico-ambiental na região carboenergética de Candiota, Bagé (RS). Ciência e Cultura 42(3–4):264–270
Ministério de Minas e Energia (2000) Balanço Energético Nacional 1999. Ministério de Minas e Energia, Distrito Federal, pp154
Ministério de Minas e Energia (2001) Anuário Mineral Brasileiro 2001 – Carvão. Ministério de Minas e Energia, DF, pp 157
Moreira JC, Pivetta F (1997) Human and environmental contamination by mercury from industrial uses in Brazil. Water Air Soil Pollut 97:241–246
Nriagu JO, Pacyna JM (1988) Quantitative assessment of worldwide contamination of air, water and soils by trace metals. Nature 333:134–139
Patrick Jr WH, Gambrell RP, Parkpian P, Tan F (1994) Mercury in soils and plants in the Florida Everglades sugarcane area. In: Watras CJ, Huckabee JW (eds) Mercury pollution – integration and synthesis. Lewis, Boca Raton, pp 609–614.
Pfeiffer WC, Lacerda LD (1988) Mercury inputs into the Amazon region, Brazil. Environ Tech Lett 9:325–330
Pires M, Fiedler H, Teixeira EC (1997) Geochemical distribution of trace elements in coal: modelling and environmental aspects. Fuel 76(14–15):1425–1437
Pirrone N, Keeler GJ, Nriagu JO (1996) Regional differences in worldwide emissions of mercury to the atmosphere. Atmos Environ 30(17):2981–2987
Pirrone N, Allegrini I, Keeler GJ, Nriagu JO, Rossmann R, Robbins JA (1998) Historical atmospheric mercury emissions and deposition in North America compared to mercury accumulation in sedimentary records. Atmos Environ 32:929–940
Sunderland EM, Chmura GL (2000) The history of mercury emissions from fuel combustion in maritime Canada. Environ Pollut 110:297–306
USEPA (1995) Compilation of air pollutants emission factors – AP-42, 5th edn, vol I. Stationary point and area sources. www.epa.gov/ttn/chief/ap42/index.html
Veiga MM (1997) Introducing new technologies for abatement of global mercury pollution in Latin America. UNIDO/UBC/CETEM-CNPq, Rio de Janeiro, pp 94