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Sulfur dioxide abatement costs and compliance with health-based standards: the case of copper smelters

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Abstract

This paper estimates the cost of the abatement of sulfur dioxide (SO_2) for three copper smelters operating in Chile. It analyses compliance with emission goals and with the atmospheric health-based SO_2 and breathable particle standards. The smelters are Chuquicamata, belonging to the State-owned company, Codelco; and Hernán Videla Lira and Ventanas belonging to ENAMI, the national mining company, also owned by the State. The marginal investment for abating 1 ton of sulfur in 1999 was estimated to be US$186 (1998) for Ventanas, and US$181 for Paipote. The average investment for abating 1 ton of sulfur to fully comply with the annual standard measured on average in these smelters, was estimated to be US$220 and US$170 for the Ventanas and Paipote smelters, respectively. These values are not far from the market value for SO_2 transactions from stationary sources in the USA.

Keywords: Sulfur dioxide; Costs; Abatement; Copper smelters

Introduction

This paper estimates the cost of the decontamination plans (DP), for three copper smelters operating in Chile. It analyses the smelters' compliance with emission goals and with the atmospheric health-based sulfur dioxide (SO_2) and particle standards. The smelters are Chuquicamata, located near the Chuquicamata mine belonging to the State company Codelco; Hernán Videla Lira, also known as Paipote, located near the city of Copiapó; and Ventanas, located on the coast, in the central part of Chile. Fig. 1 shows a map with the location of the copper smelters that operate in Chile. The smelters of Paipote and Ventanas belong to the Empresa Nacional de Minería, ENAMI, the national mining company owned by the State. The Chuquicamata, Paipote and Ventanas smelters produced 640 000 tons of smelted copper in 1998, which represented, 32.5, 5.0 and 8.1%, respectively, of Chile's smelted copper output.

Decontamination plans were issued in 1992 by Supreme Decree 185 (DS 185/92) in order to bring emissions from stationary sources into compliance with health-based atmospheric pollutant quality standards. DS 185 defined saturated areas for SO_2 and particulate matter (under 10 μm in diameter), PM10, in those areas that exceeded the standards for those pollutants. DS 185 considered that the standards should be applied at points of maximum impact, that is, maximum concentration. This was subsequently changed by the regulation for preparing quality and emission standards (DS 93/95), whose article 27, title III, defines that "compliance with the health-based standard shall be checked by carrying out measurements in all those places where there are human settlements or when such emissions directly or indirectly affect the population's health". If a specific area of the country is declared to be saturated with respect to one or more atmospheric pollutants, it implies that a DP should be created for that area. A DP must include at least a program for reducing the emission of the pollutants exceeding the standard, to ensure that when the program of emission reduction is completed, the quality standards shall be complied with.

The benefits of meeting the SO_2 standard are: to prevent respiratory illnesses in humans, especially by asthmatic and sensitive populations, to reduce acid rain in

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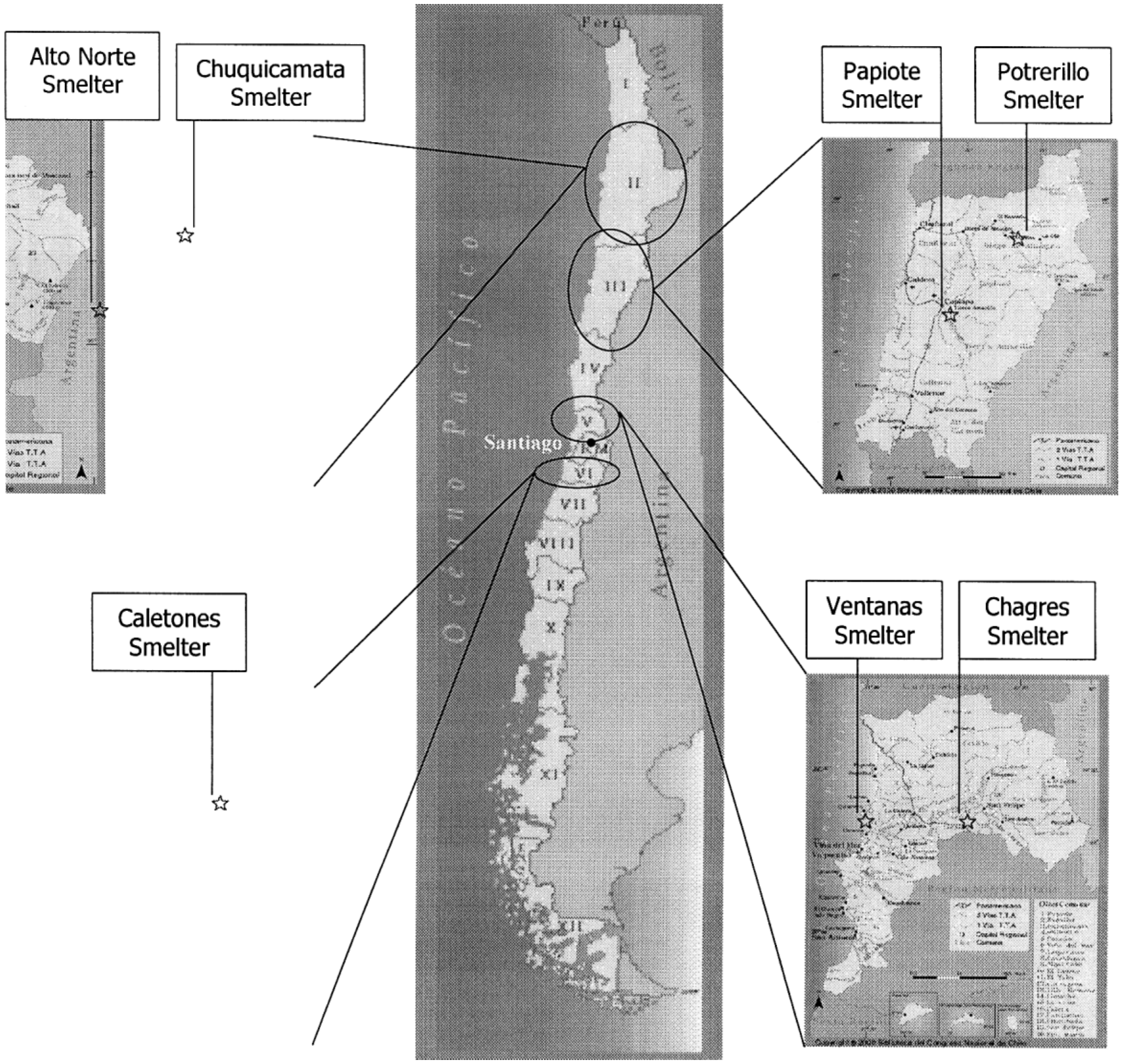

Fig. 1. Map of Chile showing location of the seven copper smelters.

those cases where this occurs, and to prevent foliage damage and respiratory illnesses to fauna. The benefits of meeting the particulate matter standards are: to prevent respiratory illnesses and allergies by humans, to avoid deposition on plants and foliage therefore reducing their growth, and to avoid transport and deposition or inhalation of toxic substances and elements.

The DP for Ventanas, Chuquicamata, and Paipote were prepared and approved in 1992 (DS 252/93), 1993 (DS 132/93) and 1994 (DS 180/95), respectively. The deadlines for completing the plans related to emissions and quality goals were 31 December 1999 for the Chuquicamata and Paipote smelters, and 30 June 1999 for the Ventanas Smelter.

The DPs in the other four copper smelters operating in Chile are in other development stages. The Caletones and Potrerillos smelters, both of which belong to CODELCO, are near the El Teniente mine, and El Salvador mine, respectively. The DPs for these smelters were not analyzed in this paper since they have been recently approved (DS 81/98; DS 179/99) and there is not sufficient data available to assess the reduction of their emissions. The Chagres smelter (Compañia Minera Disputada de las Condes) was not subjected to a DP since this was the only copper smelter in Chile that fulfilled the standard defined in Resolution 1215 of 1978 of the Ministry of Health (Resolution 1215/78), which preceded DS 185. Finally, the Refimet smelter, called today Altonorte, located near Antofagasta, belonging to Noranda, began operating in 1993 and carried out an Environmental Impact Assessment which assured that the standard set by DS 185 would be complied with.

The technology used in these smelters before the implementation of the DPs was mainly made up of reverberatory furnaces followed by Peirce Smith or Hoboken converters. The technology used at the end of the DPs consisted mainly of Teniente Modified Converters, a type of autogenous smelting reactor, followed by Peirce Smith or Hoboken Converters, and, of course, acid plants and electrostatic precipitators. Emission reduction was achieved mainly by transforming SO_2 into sulfuric acid, and in the case of emissions of particulate matter, by precipitation and liquid–solid separation. In the Chuquicamata smelter, an Outokumpu Flash Furnace was installed in addition to the Teniente Converters. At least one electric furnace was built in one of the smelters in order to recover copper from slag. The introduction of autogenous reactors to smelt sulfide ores resulted in a more efficient use of energy, although this is not considered in the cost estimate.

Methodological considerations

The analysis of the DPs was carried out with data provided by the Chilean National Environmental Protection Agency, Conama, on SO_2 and breathable particulate matter (PM10) emissions and concentrations measured in the smelters and in their monitoring stations (Conama, 1999). The number of times the standard was exceeded was also reported. These data were available for the years 1993–1999. Conama's role is managing and enforcing the Environmental impact Assessments System and Decontamination Plans, as well as coordinating all relevant Ministries towards passing new decrees, regulations and laws. The enforcement of health and environmental standards, as well as other environmental regulations, is the responsibility of the respective Ministries.

A sulfur balance was carried out for each year for each smelter. It considers that the captured sulfur is given by the content in the sulfuric acid produced, data that was obtained from two companies, Codelco and Enami, and that 3% was contained in solids, 2% in slag and 1% in the smelter powders. The total sulfur fed into the smelter is equal to the captured sulfur plus the emitted sulfur. Also, the total sulfur should equal the dry concentrate weight fed into the smelter times the concentrate sulfur grade. This data made it possible to estimate the percentage of sulfur captured as a fraction of the total sulfur fed into the smelters. The analysis was carried out from 1985 to 1999 since the capture of sulfur began in Chuquicamata and Paipote in the mid 1980s, before the implementation of the DPs. The data regarding production of blister copper, anodes, fire refined copper, concentrate, the copper and sulfur grade of the concentrates, production of sulfuric acid, and other data for each smelter, was obtained from the database of the Mining Center of the Catholic University of Chile or directly from Codelco and Enami. The price considered for acid was that in the place of shipment of each smelter, thus, it does not include transport costs. The average price for acid was obtained from the monthly Bulletins of the Sociedad Nacional de Minería, Sonami (Boletines Sonami, 1993–1999) and directly from the companies.

The above information was confirmed with publications of the Comisión Chilena del Cobre, Cochilco, (Cochilco, 1998), Solari and Lagos (1991), Lagos (1997), Enami (1999), and information from the Compañia Minera Escondida (Gonzalez, 1999).

The results of the DPs were compared with the emission goals of each plan (see Table 1), and with the SO_2 and PM10 health-based atmospheric standards (DS 93/95) (see Table 2). The method used to derive quality standards from emission data is by using an atmospheric dispersion model.

The cost of compliance for each smelter considered capital costs of modernizing the smelter's gas capture systems, and the resulting additional operating costs. The capital costs associated with the environmental investments in equipment and infrastructure are those linked with some of the environmental ordinances, decrees or regulations. In the cases of the Paipote and Ventanas smelters, other investments associated with emission reductions were considered. Capital costs were spread for a period of 15 years in the case of the Chuquicamata and Paipote smelters and were high some years due to acquisition of equipment such as new reactors. Other years, when no large machinery was being acquired, capital costs decreased. Investment for the three smelters was annualized considering a horizon of 15 years and a discount rate of 12%, the value used normally by Codelco and other State owned companies.

Operating costs exclude depreciation and financial costs and include the operating costs of the environmental equipment and infrastructure, for example, acid plants, electrostatic precipitators, etc. They also include the revenue obtained from the sale of the sulfuric acid.

This information was provided by Codelco and Enami. Complementary information was obtained from the series of annual reports of both companies (Codelco, 1990; Annual memoirs Enami, 1993–1998; Annual memoirs Codelco, 1990–1998).

Table 3 shows environmental investment in the three smelters and the environmental operating costs of environmental equipment. We can see that the weight of these costs is negligible during the first years compared to investment. During the late 1990s the operating costs of these equipment were negative due to the high price of sulfuric acid. This situation, which may be temporary, can be considered as an added bonus, and it is not the reason for justifying the original installation of the environmental equipment.

Investments on a specific year do not necessarily have an immediate effect on emissions or on operational costs. For instance, the lag between the installation of major equipment, such as an acid plant, and its commissioning may be a few years.

Table 1
Emission goals in the DPs[a]

Year	Chuquicamata's smelter		Paipote's smelter		Ventanas smelter	
	Sulfur (Ton/year)	PM_{10} (Ton/year)	Sulfur (Ton/year)	PM_{10} (Ton/year)	Sulfur (Ton/year)	PM_{10} (Ton/year)
1993	252 000	9720			62 000	3400
1994	234 000	8280			62 000	3400
1995	198 000	3240	39 900	1500	62 000	3400
1996	198 000	3240	39 900	1500	62 000	3400
1997	198 000	3240	39 900	1500	62 000	3400
1998	162 000	3240	30 000	1000	45 000	2000
1999	Compliance with health-based standards	Compliance with health-based standards	20 000	600	Compliance with health-based standards	1000
2000			Compliance with health-based standards	Compliance with health-based standards		

[a] Source: DPs for Chuquicamata, Ventanas and Paipote.

Table 2
Health-based standard for the SO_2 and PM_{10}[a]

Type of standard	Value limit (μg/Nm^3)	Observations
Health-based standard of SO_2	80	Yearly mean
	365	Daily mean
Particulate breathable material (PM_{10})	150	Daily mean

[a] Source: DS 185/92.

Analysis of the decontamination plans

Fig. 2 shows the sulfur input, emissions, and capture, for the three smelters, and compares them with the DPs goals. It is observed that in 1999 the Chuquicamata, Paipote, and Ventanas smelters improved on the emission goals by 24, 48, and 53.4%, respectively.

The reduction of sulfur fed into Chuquicamata in 1998 was due to a strike which reduced overall smelter production. The increase of sulfur fed into Paipote in 1998 and 1999 did not result from the net increase in copper production but rather to an increase in the sulfur grade of concentrate caused by a reduced supply from small mines. The Ventanas smelter reduced anodic copper production from 127 000 tons in 1993 to 105 000 tons in 1999, as part of the DP. The sulfur concentrate grade also increased in Ventanas, from about 26% in the first half of the 199Os, to over 30% in the last 2 years considered.

Fig. 3 shows four indicators of compliance with the SO_2 standard. The first is the average annual SO_2 concentrations measured in all monitoring stations of each smelter from 1994 to 1999. The second indicator is the annual SO_2 concentrations measured at the stations with the maximum reading. The third indicator is the number of readings exceeding the SO_2 daily standard in any monitoring station in each smelter. The fourth indicator is the number of critical episodes recorded in each smelter. A critical episode is an event defined in article 19 of Supreme Decree 185, where the SO_2 concentration exceeds 0.75 parts per million at any monitoring station. After such event, the company operating the smelter is required to notify the local health authorities. Educational facilities and hospitals should be notified of this event and when the concentration reaches higher levels, different steps are taken, such as sending students home (DS 185/92).

Fig. 3 shows that the Chuquicamata smelter did not comply with indicators one and two, despite the fact it complied with emission goals. All three monitoring stations are located within the premises of the Chuquicamata mining company. In 1998 when the smelter reached the minimum SO_2 emission level, the annual average of SO_2 concentration in the three monitoring stations was 114 μg/Nm^3, and the annual average of SO_2 concentration in the station with the highest reading was 142 μg/Nm^3. This represents values 42.5 and 77.5% higher, respectively, than the annual standard. Also in 1998, the daily health-based standard for SO_2 was surpassed 14 days in one station and slightly less in the other two monitoring points. The situation in 1999 was even worse, since sulfur emissions increased, reaching up to 35 days that the daily standard was exceeded. The number of critical episodes also increased in 1999 with

Table 3
Investments and costs associated to the DP of the three smelters (millions of US$ of 1998); investment for Paipote smelter in 1986 was estimated

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	Total
Chuquicamata															
Annual environmental investment (million US$98)	37.11	51.71	19.12	13.46	3.51	13.53	46.57	40.04	17.18	31.07	29.56	13.49	20.10	8.70	345.15
Annual operating cost (million US$98)	0.22	0.32	0.41	0.66	0.65	0.72	0.77	0.42	0.09	1.09	0.59	−28.31	−35.54	−27.98	−85.90
Total cost (million US$ 98)	37.33	52.03	19.53	14.12	4.16	14.25	47.34	40.46	17.27	32.16	30.15	−14.82	−15.44	−19.28	259.25
Paipote															
Annual environmental investment (million US$98)	19.08						3.27	0.97	1.56	7.14	12.84	29.85	23.78	5.75	104.24
Annual operating cost (million US$98)	0.05	0.05	0.06	0.05	0.04	0.05	0.05	0.02	0.01	0.08	0.04	−2.67	−4.19	−3.81	−10.22
Total cost (million US$98)	19.13	0.05	0.06	0.05	0.04	0.05	3.32	0.99	1.57	7.22	12.88	27.18	19.59	1.94	94.02
Ventanas															
Annual environmental investment (million US$98)			2.39	46.12	23.10	2.92	3.27	0.97	1.55	8.34	19.13	21.86	4.65	2.68	136.98
Annual operating cost (million US$98)					0.04	0.11	0.14	0.08	0.01	0.09	0.07	−2.94	−5.80	−5.22	−13.42
Total cost (million US$98)			2.39	46.12	23.14	3.03	3.41	1.05	1.56	8.43	19.20	18.92	−1.15	−2.53	123.57

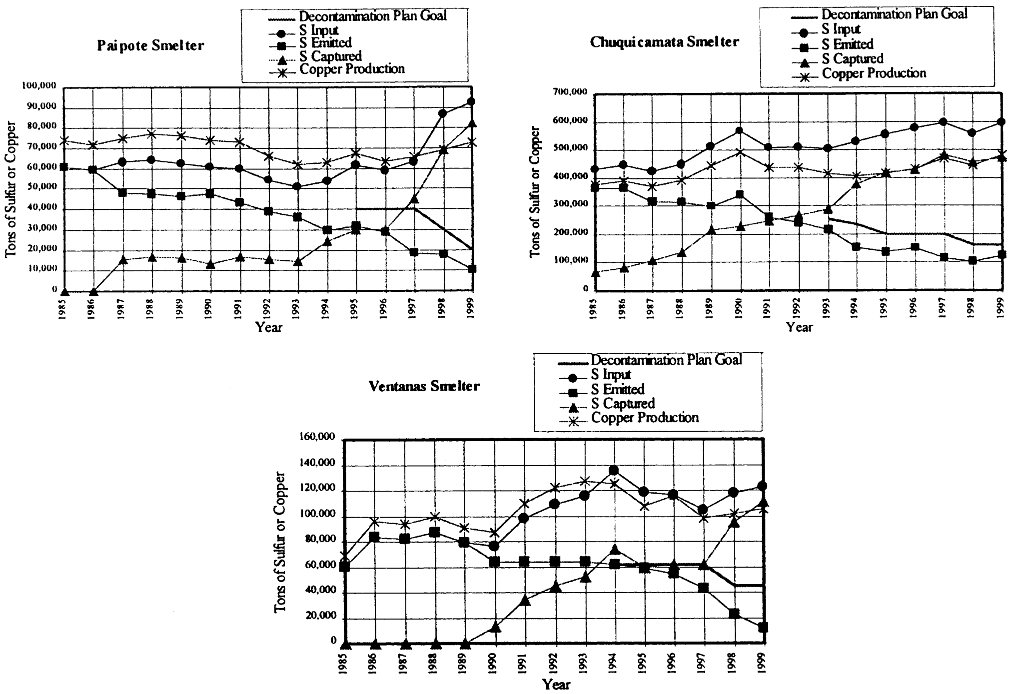

Fig. 2. Sulfur balance of Chuquicamata, Paipote and Ventanas smelters.

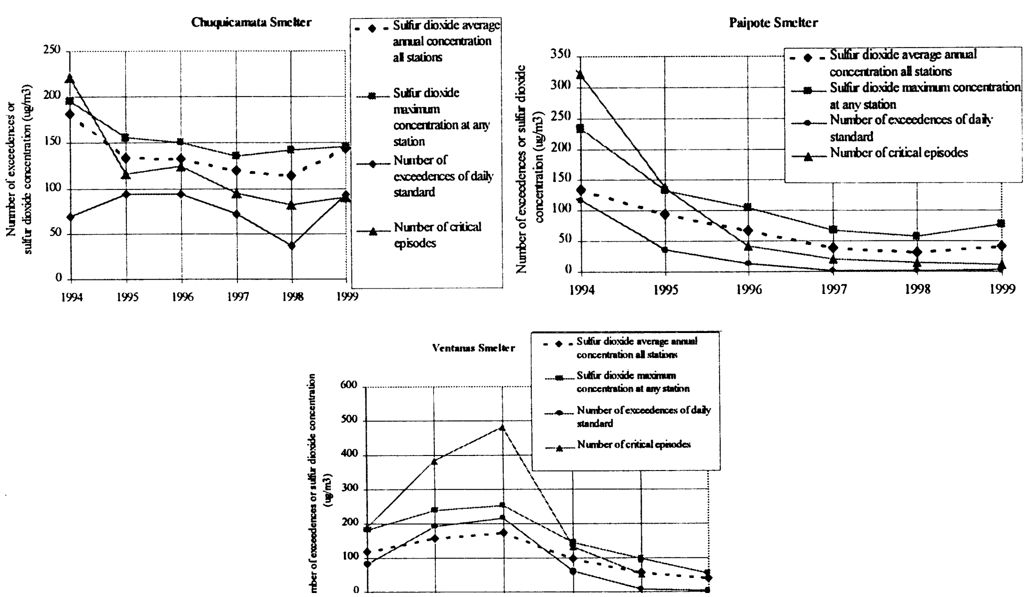

Fig. 3. Four indicators related with SO_2 concentration at the Chuquicamata, Paipote and Ventanas smelters.

respect to the previous year. The overall correlation between emissions and health-based standards shows that the dispersion model used at the beginning of the 1990s to predict the concentration of SO_2 overestimated the emissions that would comply with the standards. In 1999 the Chuquicamata smelter requested the Ministry of Health that the DP be extended for two additional years, since during this period the health standards for SO_2 could be complied with as a result of the required abatement of arsenic emissions (DS 165/98) forecast to be achieved in the same period.

As for the Paipote smelter, Fig. 3 shows that since 1997 the annual mean SO_2 concentration measured in the monitoring stations was below the standard (80 $\mu g/Nm^3$) and that this value was not exceeded in any of the stations. The daily standard for SO_2 was exceeded twice in the Paipote station in 1998, and three times in 1999. This station is located in a densely populated area.

The number of critical episodes were 14 and 11 times in 1998 and 1999, respectively, and almost all of these episodes occurred in the Tierra Amarilla monitoring station, different from the point where the daily standard was exceeded most times. Tierra Amarilla is a small village located about 5 km south of the smelter, and it is apparent that critical episodes are likely to occur here, whereas the average daily SO_2 health-based standard is usually complied with. Sulfur emissions are expected to be reduced further in 2000, when a new electric furnace, rather than a reverberatory furnace, will recover copper from slag.

The Ventanas smelter fully complied with the annual health-based SO_2 standard in 1999, when the daily standard was exceeded 2 days in two monitoring stations. There was no information regarding critical episodes for 1999. The DP was completed on 30 June 1999. It should be added that in the area where the Ventanas smelter is located there is also a Thermoelectric Power Station, whose contribution to sulfur and particulate concentrations was not known to this study.

The PM10 in the facilities of the Chuquicamata mine and plants was exceeded four times (January–September 1999), and the emission goal has been fulfilled since 1993. Exceeding the health standard for particulate matter is due fundamentally to the particle emissions from the mine, and not from the smelter, since this captures a high fraction of the particles generated. PM10 was fully complied with in 1998. In the case of Paipote, the emission goal was complied with since this information was reported to the Regional Health Service in 1997. In the case of Ventanas, the emission goal was complied with in the 1994–1998 period, but the health-based standard was exceeded 10 times in 1998, six times in 1997 and a similar number of times in the previous years. It should be added that this information is based on a few measurements per year, and no information was available regarding the level of production of the smelters at the times when monitoring was carried out for PM10.

Cost analysis of the decontamination plans

Table 4 shows the annualized investment or marginal investment to abate 1 ton of sulfur in 1999.

Larger marginal costs, calculated as indicated in Table 4, for sulfur abatement at the Ventanas and Paipote smelter are due partly to the fact that these smelters consider all those costs that lead to the reduction of sulfur emissions as environmental investment, while Chuquicamata considers only those which result from a regulation or those which do not lead to profits. Paipote and Ventanas, for instance, considered that the replacement of reverberatory furnaces by autogenous reactors was an environmental investment, while Chuquicamata considered that it was not. As a result, the ratio between the environmental investment and the total investment in the three smelters differs substantially, being 50% for Chuquicamata, 63.6% for Ventanas and 75.6% for Paipote in the periods indicated in Table 4. Another factor that may influence this ratio is the scale of each operation, therefore the correction of the marginal cost of abatement of SO_2 to fit a unique criteria is not straight forward. It can be considered, nevertheless, that the cost of abating SO_2 should include all costs leading to this goal, therefore, Chuquicamata's marginal abatement costs must be an underestimation of the real costs.

The investment associated with sulfur abatement required for producing 1 ton of copper is shown in Table 4. These values are relevant for the calculation of the Extended Domestic Resource Cost (EDRC). We can see that the difference between marginal and average costs is quite substantial, suggesting that a range of values should be used in the EDRC calculation.

Fig. 4 shows the marginal investment for abating SO_2 as a function of abated sulfur.

The average cost of SO_2 abatement is plotted in Fig. 5 versus the degree of compliance (standard concentration [80 μg/Nm^3] measured annual concentration) with the annual health-based SO_2 standard, measured in all monitoring stations. The average cost is equal to the ratio between the total cumulative annualized environmental cost (in 1998 US$) and the cumulative sulfur abated (in tons).

It is important to stress that when compliance costs are compared, the base for comparison should be the year or years when compliance with 100% of a standard was achieved. If many monitoring stations are involved, a further base for comparison is that the standard cannot be exceeded at any of them. In 1996 Paipote complied with the annual standard measured as an average in all stations, but in one monitoring station it exceeded the standard. Paipote complied with the annual standard in all stations for the first year in 1997, and the average concentration of SO_2 in all stations was 209% smaller than the standard. The comparable year for Ventanas was 1999. The Chuquicamata smelter is not eligible for this comparison because it has not achieved compliance.

Fig. 5 shows that in 1999 (points further to the right) compliance with the annual standard reached up to 225% in Ventanas and up to 300% in the Paipote smelter, yet that year none of these smelters fully complied with daily standard and critical episode criteria. Therefore, no significant correlation was found in any of the smelters between compliance with the daily SO_2 standard, measured as the number of times the standard was exceeded per year, and sulfur abatement. This shows that other factors, like meteorological conditions, have a greater weight in triggering these events than the amount of sulfur emitted. Also, measuring compliance as the number of times that a daily standard is fulfilled or a critical episode criteria is overcome is not directly related to the

Table 4
Marginal investment per ton of abated sulfur and per ton of copper produced, and abatement in three smelters

	Marginal investment[a] (US$ 1998) of abating 1 ton of sulfur in 1999	Period of investment considered	Sulfur abated in 1999 (ktons)	Total investment in period considered (million US$ 1998)	Annualized investment[b] (US$ 1998)/ton of copper produced in 1999	Cumulative annualized investment[c] (US$ 98)/cumulative tons of copper produced	Percentage of total sulfur abated in last year of period w/r to total input sulfur to the smelter
Chuquicamata	107	1985-1999	472.7	345.19	105.4	65.3	80
Paipote	186	1986-1999	82.4	104.2	220.4	81.1	90
Ventanas	181	1988-1999	110.9	135.9	191.2	117.3	90

[a] Marginal investment=annualized investment in 1999 divided by sulfur abatement in the same year.
[b] Annualized investment associated with sulfur abatement in 1999 divided by copper produced in the same year.
[c] Cumulative annualized investment associated with sulfur abatement divided by total production of copper in the periods indicated in the table. This is the average cost of abatement of SO_2.

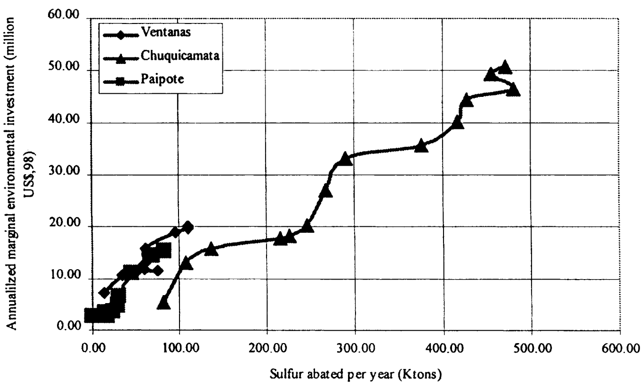

Fig. 4. Annualized marginal investment versus sulfur abated each year for the three smelters.

health risk. If the concentration is high enough, one acute event may be sufficient to cause very serious health effects. On the other hand, if the degree that the standard is exceeded is small, it is likely that many events will not lead to any significant short term effects.

This figure also suggests that once all the abatement equipment is installed and no more investments are required, the costs of abatement tend to diminish slightly with time, as it occurs in fact. Fig. 5b is the same as Fig. 5a but it includes the environmental operating costs. We can see that environmental operating costs do not have much influence on total abatement costs.

Compliance with the annual SO_2 standard, expressed as the average measured in all monitoring stations in each smelter, occurs at US$220/ton of abated sulfur for Ventanas, and at US$170 for Paipote. Expressed in terms of SO_2, these values become US$110 and US$85, respectively. It is important to note that the market price of a ton of abated SO_2 in the USA was US$100 in 1999 (Ellerman et al., 1997).

Conclusions

The compliance of the Chuquicamata, Paipote and Ventanas smelters with health-based standards for SO_2 was analyzed. None of the three smelters had fully complied with the various levels of this standard.

The three smelters analyzed are State owned, nevertheless, they abide by the same health and environmental standards as other smelters operating in the country. From this perspective abatement costs should be the

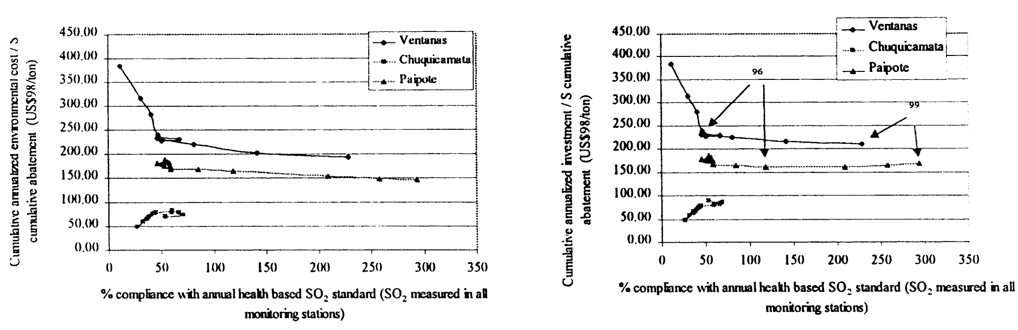

Fig. 5. (a) Relationship between the ratio of cumulative annualized environmental cost and cumulative sulfur abatement versus degree of compliance with the annual health based SO_2 standard. (b) Relationship between the ratio of cumulative annualized environmental investment and cumulative sulfur abatement versus degree of compliance with the annual health based SO_2 standard.

same as those of privately owned smelters. In spite of this, it can be argued that the period granted by these DPs to fulfill the standards could have been shorter. Had this been the case, the total cost of abatement should have been higher.

The Paipote and Ventanas smelters had complied 100% with the annual standard, but had not fully complied with the daily standard and the critical episode criteria, although they came close to achieving this goal. The Chuquicamata smelter had an average annual SO_2 concentration which exceeded the standard by 42% in 1998 and by 80% in 1999. That year Chuquicamata requested an extension of its DP for a further 2 years, so that it could comply with the recently defined arsenic standards, and as a by-product of the arsenic abatement, the smelter should comply with SO_2 and other atmospheric pollutants standards. Ventanas and Paipote should be able to fully comply without further investment if they use a meteorological forecasting program which allows the operators of the smelters to reduce production under adverse conditions.

The marginal investment for abating one ton of sulfur in 1999 was US$186 (1998) for Ventanas, and US$181 for Paipote. The average investment for abating one ton of sulfur, fully complying with the annual standard and measured as an average in these smelters, were US$220 and US$170 (US$ 1998) for the Ventanas and Paipote smelters, respectively. These values are not far from the market value (US$100) for SO_2 transactions from stationary sources in the USA. It becomes evident that a separate calculation in order to estimate the cost of abating one specific pollutant, for instance arsenic, is quite difficult, if not impossible.

Finally, the Chuquicamata, Paipote and Ventanas smelters captured about 80, 90, and 90%, respectively (in 1999) of the input sulfur. Further efforts should be carried out in order to comply with the daily and critical episode standards in the three smelters. This is also true for compliance with the environmental standard. The percentage sulfur captured in these smelters is considerably lower than that captured by smelters with technology based standards, such as 99.92% (for 1999) by the Kennecott smelter at Bingham Canyon. From Chile's perspective, nevertheless, the goal is to protect human health and the environment, and this is achieved by complying with air quality standards. Chile's SO_2 standards were defined on the basis of the standard of the United States Environmental Protection Agency, EPA, in the early 1990s, which have remained unchanged.

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