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Industrial Metabolism

A Case Study of the Economics of Cadmium Control

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Preface

This study of the control of cadmium is the result of the Institute's participation in a research project funded by the European Science Foundation on waste management in the North Sea. In order to identify options for reducing the inflow of toxic materials into the North Sea, which subsequently accumulate in the seabed and in living organisms, one needs to determine the complex channels through which these materials enter the economy, are used in production processes, and eventually are emitted and transported to their final deposition. Cadmium was chosen for this case study because it is one of the most dangerous heavy metals and, at the same time, occurs in many economic activities, thus requiring a detailed account of its flows before a scenario for its efficient control can be developed.

The authors first examine cadmium flows and discharge sources in West Germany. They then identify the technologies for controlling cadmium discharges and assess the diffusion of these abatement techniques and estimate their costs. There exist essentially three options for controlling cadmium discharges: (i) substituting other materials for cadmium and cadmium-containing materials; (ii) removing cadmium from wastewater or exhaust air using so-called end-of-pipe measures, i.e., different types of filters and other forms of treatment; and (iii) removing cadmium using new integrated or "clean" technologies, which reduce the flow of cadmium in the production processes, thus making end-of-pipe treatment of discharges less necessary.

The discharging of cadmium into water and into the air has been controlled quite successfully in the last two decades. Yet, there still exist regions where cadmium concentrations are high and where cadmium should not be allowed to continue to accumulate. Unfortunately, the cadmium pollution originates predominantly from diffuse sources; thus controlling cadmium is difficult and quite expensive.

The authors are grateful for the help of a large number of specialists in the various fields covered in this study. Without their expertise and their generous help in supplying often confidential information, many of the results could not have been produced. Special thanks go to Dr. Frankenfeld at the Chemische Fabrik Budenheim, to Mr. Gabrisch at the Gesamtverband Buntmetallindustrie, to Dr. Stigliani and his colleagues at the IIASA, and to Mr. Spies at the Statistische Bundesamt. Ilse Büxenstein-Gaspar, Kerstin Stark, Regine Treutler, and Korinna Werner patiently helped to transform the manuscript into a readable monography. They deserve the thanks for eliminating many errors and inconsistencies; for the remaining ones, the authors claim responsibility.

Kiel, February 1995 Horst Siebert

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A. Introduction

Cadmium (Cd), being a toxic material and as such a threat to human health and the environment, has become well known because of the so-called Itai-Itai disease, which occurred in Japan in the sixties. It was caused by heavy cadmium contamination of rivers used to irrigate rice paddies. Since then many toxicological studies have revealed that cadmium is one of the most toxic heavy metals and that it is particularly dangerous for living organisms, since it accumulates slowly in the body, manifesting its toxic effect only after a long time lag.

Cadmium develops its toxicity only in concentrated forms. Whereas it can be found in the earth's crust only in low concentrations and thus poses no danger, the world production and use of cadmium increased drastically during this century from about 100 tons per year (t/yr) in the twenties to about 20,000 t in the seventies and eighties (see Ewers 1990). The production and use of such large amounts lead to considerable health hazards, especially since the increasing stock of cadmium in soils and sediments does not quickly disappear from the human environment.

This increasing health hazard has led the German *Sachverständigenrat für Umweltfragen* (Environmental Advisory Board) to demand a reduction in the use of cadmium and in the exposure of humans to cadmium through air, water and food (see Sachverständigenrat für Umweltfragen 1987). Similarly, the *Third International Conference on the Protection of the North Sea* demands the reduction of inputs of cadmium into the North Sea (among other substances) between 1985 and 1995 by at least 70 percent (see Third International Conference on the Protection of the North Sea 1990). These demands raise a number of questions:

- What is the quantitative flow of cadmium in the economy?
- How does it interact with the existing stock of cadmium?
- Which sectors contribute to the accumulation of the stock of cadmium in the economy and in the environment?
- Which sectors discharge cadmium in the different environmental media?
- How did these cadmium emissions[1] evolve over time and what is their likely future path?
- What is the potential for reducing the flow of cadmium in the economy?

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[1] For the sake of simplicity, the term "emissions" will henceforth be used to mean "emissions" as well as "effluents".

- What is the technological potential for reducing cadmium pollution of media that impose health hazards, directly or through the food chain?
- What are the economic costs of achieving such reductions in cadmium emissions?

This list of questions already suggests that the road from collecting the facts to finding policy conclusions as to how to control the use of a toxic substance like cadmium is not straightforward. The complexity of controlling the environmental problems of many substances becomes obvious when it is recognized that "reactive policies" only relocate these substances. In doing so, they may improve the quality of one environmental media at the cost of deteriorating that one in which the substance is rerouted. In light of these difficulties a new concept has been introduced that is designed to explicitly take into account the complexity of environmental and economic interaction referred to as "industrial metabolism".[2]

Industrial metabolism "*embodies a systems approach to minimizing emissions of toxic chemicals by considering all sources of the chemicals, the pathways by which they flow through the industrial economy, and mechanisms by which they are transformed into outputs that must be absorbed and processed by the environment*" (Stigliani and Jaffe 1992, p. 11). This approach is far removed from the traditional approaches, which control one environmental medium (e.g., air or water) or one industrial sector in that it analyzes all environmental media and all economic activities. The interdisciplinarity and the complexity of the industrial metabolism approach requires confinement to specific issues. The only major study conducted so far is the IIASA's (International Institute for Applied System Analysis) Rhine Basin Study on seven chemicals in the Rhine River Basin (see, e.g., Stigliani and Anderberg 1992). The present study has been inspired by Stigliani's work, but it differs from his work by explicitly focusing the whole analysis on economic issues such that desirable environmental policies can be adequately addressed. Although the available data have not permitted to derive exact cost functions, a striking hierarchy of policy options in the various sectors has emerged.

In Chapter B, we examine cadmium flows and emission sources in West Germany. In Section B.I, we present estimates of the yearly addition of cadmium to the existing stock and of the flow of cadmium through economic channels. Further, we assess the amount of cadmium that remains in the economy in the form of cadmium-containing products. The production, consumption and disposal of these products lead to cadmium emissions into

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[2] See, e.g., Ayres et al. (1989), Ayres and Simonis (1993), or Stigliani and Jaffe (1992).

various environmental media. In Sections B.II and B.III, we discuss recent estimates of cadmium emissions into the air and the water on a sectoral level. The final media in which cadmium ends are the soils. Consequently, in Section B.IV, we present some estimates on the total deposition of cadmium, and we discuss the cadmium dynamics in the soil.

Chapter C deals with the control of cadmium. In Sections C.I and C.II, we discuss various options for reducing cadmium emissions into the air and into the water (end-of-pipe measures, input substitution, clean technologies). We estimate the likely potential for further reductions, and we compare the costs of alternative measures as far as this is possible in light of a very limited data base. In Chapter D, we summarize our main results and derive some policy conclusions on how to implement efficient strategies for reducing the threat of cadmium for human beings and the environment in general.

We have derived and estimated the information and data in this report predominantly from secondary sources. We have collected very little primary data ourselves. Instead, we have compiled statistical data, engineering information, and other sources from the gray and not so gray literature to draw a reasonably consistent picture of the use and the fate of cadmium in West Germany since the eighties to the present.

B. Cadmium Flows and Emission Sources

I. Cadmium Flows in Germany: An Overview

Cadmium is a relatively rare element that occurs in the earth in low concentrations, thus rendering its exclusive mining unprofitable. Instead, cadmium is produced as a by-product during the processing of zinc (Zn) concentrates, which normally contain 0.1–0.3 percent of cadmium; in some instances the concentration can be as high as 1 percent (see Suess et al. 1985). In addition to the intentional production of cadmium as a raw material, it also enters the environment and the economy unintentionally as a contamination of fuels, iron ore and other materials.

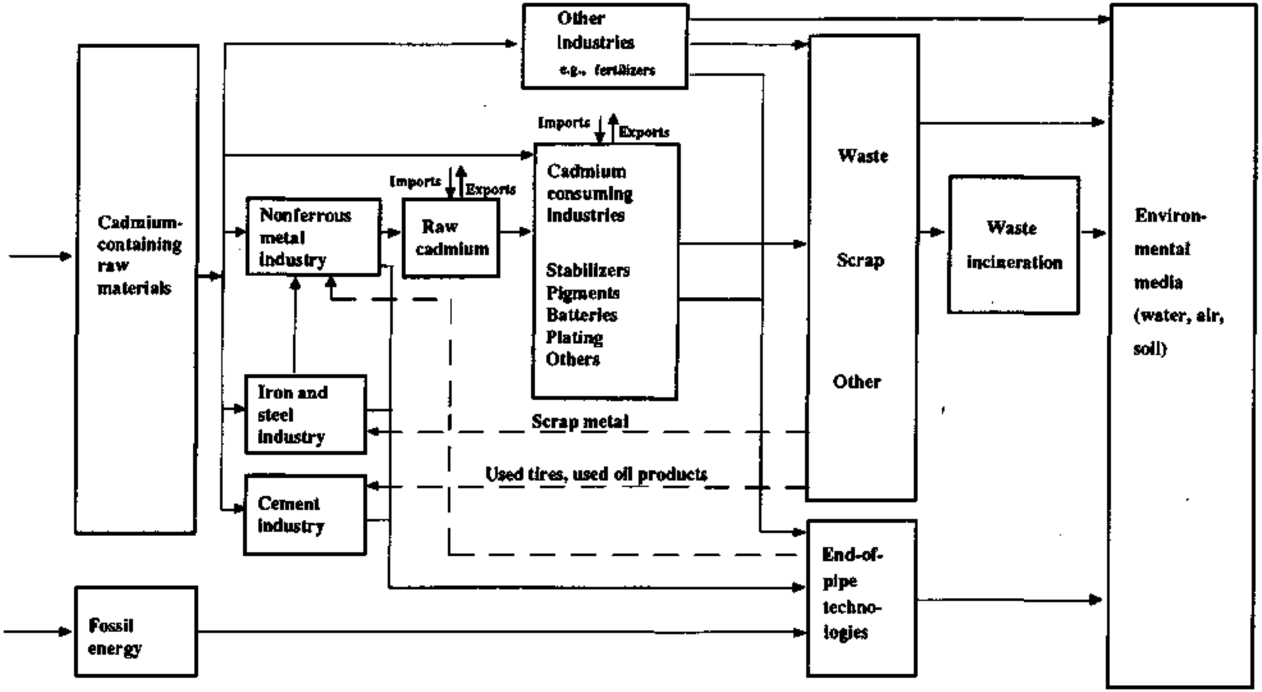
The main problem with cadmium is its ability to accumulate in living organisms and thus to create health risks in the long run. Therefore, it would be desirable to illustrate the development of the stock of cadmium in specific environmental media and in products. Unfortunately, such a cadmium balance is impossible to construct given the information that is available at the moment. The only feasible approach consists of a detailed enumeration of sectoral flows of cadmium. Because of missing legal requirements for data collection on the use and on emissions of cadmium, even this approach is highly speculative.

Figure 1 illustrates the most important flows of cadmium. The arrows do not contain numbers about the volume of cadmium flows for several reasons: some arrows cannot be quantitatively assessed because of a lack of data, and others are subject to such large errors that we prefer to discuss these numbers in the following chapters.

The accumulation of cadmium in the human environment occurs in two different ways: intentionally, by the nonferrous metal industry, which produces raw cadmium for later use in the manufacturing industry (mainly for stabilizers, pigments, batteries and plating); and unintentionally, through the use of contaminated inputs by the iron and steel and the cement industry, through the burning of cadmium-containing fossil fuels (mostly hard and brown coal) and through the production and use of cadmium-containing phosphate fertilizers, all of which result in cadmium wastes that pollute air, water or soil.

Figure 1 illustrates processes with widely different time frames. This imposes problems in defining a cadmium flow per period, and it also makes it difficult to determine the stock of cadmium in the human environment. The stock problem is due to the fact that cadmium in products is added to the existing stock and remains in this form for, possibly, decades — an example is

Figure 1 — Cadmium Flows in Germany



plastic window frames. Hence, the transformation of goods into waste and the emission into environmental media may take place many periods after the production of cadmium, but cadmium may also be emitted immediately after use — as in the case of fossil fuels. Therefore, for a quantitative assessment of the emissions of cadmium into the environment, the input of new cadmium into the economic system within a specific period may not be very important in determining the emissions within this period. Beyond that, even if there were no new cadmium coming into the system, the existing stocks would for quite some time *still* induce important flows and emissions.

The influence of the already existing stock of cadmium on flows is manifold. An important controlled flow goes from filters of smelting processes back to the nonferrous metal industry where some of the dust is recycled. Uncontrolled additions to the flow of cadmium experience the iron and steel industry, through contamination of scrap metal with cadmium, and the cement industry. Another important addition to flows that is not shown in Figure 1 is the contamination of soil that enters the food chain.

1. Production of Cadmium

Cadmium is produced as an intentional product when processing zinc ore, in which it is a trace element. Almost all cadmium is extracted from zinc ore, and more than 98 percent of the extracted material is used as an input in production, whereas the rest is waste. About 3.2 kg Cd/t Zn can be produced (see Brahms et al. 1989, p. 148).

Table 1 summarizes the production of cadmium in West Germany. Primary production from the processing of zinc ore dominates the production of secondary processing from used metals. The total cadmium production remained approximately constant in the first half of the eighties.

Table 1 — Cadmium Production in West Germany, 1981–1986 (t/yr)

	1981	1982	1983	1984	1985	1986
Primary production	1,323	1,293	1,911	1,242	1,305	1,359
Secondary production	231	141	71	226	185	202
Total	1,554	1,434	1,262	1,468	1,590	1,561

Source: Böhm and Schäfers (1990).

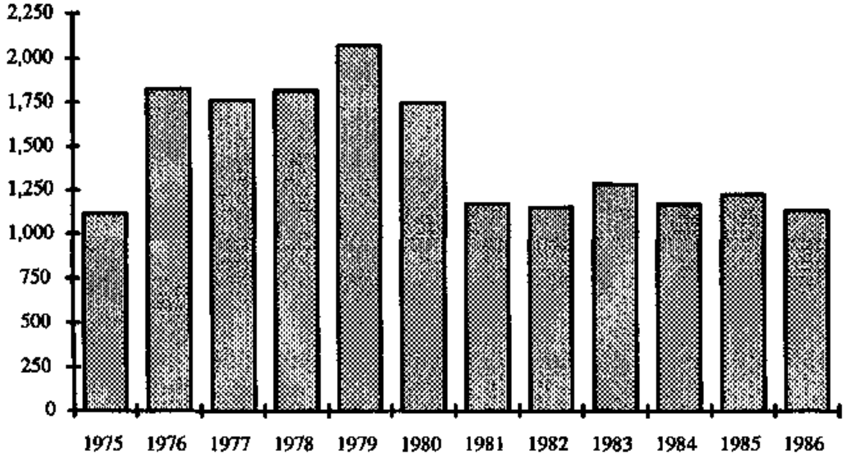
For an assessment of the cadmium flows in Germany, not only the production of cadmium but also the in- and outflow of cadmium through international trade must be taken into account. Balzer and Rauhut (1987) estimate these relations in a "cadmium balance." On the one hand, it incorporates all imports of cadmium from abroad in the form of raw materials (e.g., zinc), of raw cadmium, or of cadmium contained in products. On the other hand, exports of cadmium and cadmium-containing products are also taken into account. For 1986, 531 t of cadmium metals have been imported and 438 t exported resulting in 93 t net imports. In the same year, 985 t of cadmium contained in products were imported compared with 1,314 t of exported cadmium, thus resulting in a net outflow of cadmium in products of 329 t. The overall trade effect is a net outflow of cadmium of 236 t in 1986. Hence of the cadmium production amounting to 1,561 t about 1,325 t did remain in Germany.

2. Intentional Input of Cadmium

The flow of cadmium in one time period ends in essentially three possible states: first, cadmium can be exported to other countries, either directly or incorporated in products; secondly, it can be converted into products that remain in Germany; and thirdly, it can be emitted into the environment during the production or consumption of products. The incorporation of cadmium into products thus only extends the time lag until cadmium becomes a potential source of pollution. Whereas the actual pollution of water and air are discussed in Sections B.II and B.III, the conversion of cadmium into products is discussed here. The amount of cadmium in products is an important determinant of cadmium flows in the future, when these products are once again utilized in the production processes as a result of recycling or are disposed of through waste incineration or dumping.

Figure 2 shows the trend of cadmium use in products that have entered German markets between 1974 and 1986. The level of about 1,700–1,800 t/yr in the seventies has dropped to between 1,100–1,200 t in the eighties, however, without a continuing falling trend in the latest years for which data are available. A look at the development by product groups reveals that there are various trends at work that accidentally level out the overall consumption in the eighties (see Table 2). The most important developments can be observed for batteries and plating. In the market for batteries the nickel-cadmium batteries achieve increasing market shares. Consequently the amount of cadmium contained in batteries doubled between the mid-seventies and mid-eighties from 150 to about 300 t/yr. Some authors guess that the number may be as high as 400 t because of insufficient accounting of battery imports (see Böhm and Tötsch 1989, p. 89). Since the importance of nickel-cadmium batteries is still

Figure 2 — Cadmium Content of Products in West Germany, 1975–1986 (t/yr)



Source: Böhm and Schäfers (1990).

Table 2 — Cadmium in Products, 1974–1986 (t/yr)

	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Stabilizers	248	207	349	366	384	522	490	368	328	317	278	296	289
Pigments	771	424	664	572	619	753	548	291	317	293	364	434	363
Batteries	150	150	253	238	192	213	238	280	255	357	300	310	308
Plating	354	196	420	397	382	319	266	160	180	200	167	118	122
Cadmium compounds	25	13	27	91	108	142	126	20	20	37	33	39	19
Alloys	87	75	52	47	63	44	31	31	29	28	22	21	23
Glass	22	13	12	15	13	15	14	12	10	11	4	4	6
Rectifiers	24	16	19	6	6	21	8	3	1	1	na	na	na
Others	28	22	30	30	51	40	26	8	11	39	na	na	na

na = not available.

Source: Böhm and Schäfers (1990).

rising, they will become the most important medium in which the stock of cadmium is stored.

The opposite trend can be observed in plating. The use of cadmium has dropped from 420 t in 1976 to around 120 t in 1985/86. This process is mostly due to the reduction of cadmium-galvanized steels in the automobile industry. Further reductions may be possible if similar changes in technology will be introduced in the aerospace and defense industry, which consume a large part of such metals (see Böhm and Schäfers 1990, p. 38–39).

There is no uniform trend in the other product categories. Pigments, which usually make up for almost half of all cadmium in products, have fallen to around 30 percent. After a considerable reduction, there was an increase in the last few years, which may be caused by increased production of plastic. Also for stabilizers a falling trend cannot be clearly identified.

3. Inadvertant Input of Cadmium

In addition to the intentional use of cadmium in production processes, cadmium also enters the environment as a trace element in other economic activities. Especially the burning of fossil fuels, the manufacturing of iron and steel, and cement production are the main contributors. Cadmium is a trace element in coal and oil with widely varying contents — between 0.01 and 10.0 parts per million (ppm) (for details see Table 3 in Section B.II). Since large amounts of fossil fuels are burned, a considerable input of cadmium into the environment can take place even though the cadmium concentration in the fuels is very low. Böhm and Schäfers (1990, p. 9) report that the German *Umweltbundesamt* (Environmental Protection Agency) estimates the cadmium inflow, given fossil fuel use, to be from hard coal 98 t, from brown coal 11 t, and from oil about 1 t.

The cadmium inflow of the iron and steel industry comes to a small extent from trace elements in iron ore. The more important input, however, is the cadmium content of scrap metals that are recycled in the production of iron and steel. In this case, it becomes very difficult to determine the flow of cadmium, since this flow depends on the stock of cadmium in scrap metal that was produced in earlier decades (see Sachverständigenrat für Umweltfragen 1990). The situation is further complicated because the iron and steel industry gives filter dust and sewage sludge with high heavy metal contents to the nonferrous metal industry for recycling. Nonrecyclable parts are often returned into the smelters. It is likely that more than 100 t Cd that belong to the already existing stock are again processed.

The cadmium load of the cement industry also is due to the already existing stock of cadmium. In this industry, a considerable part of the energy input is taken from used tires[3] and used oil products, having high cadmium contents. A

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[3] In 1987, the German cement industry did burn about 157,000 t of used tires amounting to 39 percent of all used tires (see Sachverständigenrat für Umweltfragen 1990, p. 190).

similar source of cadmium is the incineration of waste, for which cadmium inputs are unknown, however. Although these processes do not add to the existing stock of cadmium in the environment, they reactivate stored cadmium and turn it into a potential source of emissions into air and water.

It is practically impossible to quantify and combine all sources of cadmium flows. Thus a couple of rough estimates will have to suffice. The number of cadmium flows that are added to the already existing stock every year in the form of cadmium-containing products or in the form of emissions is around 1,300 t/yr. In terms of environmental effects, however, it is not the net addition to the stock but the gross flow of cadmium in production or consumption processes that is relevant, since this provides the potential for emissions into the environment. Rauhut (1990) estimates a throughput of 3,077 t for 1986 in the West German economy, which exceeds the addition to the stock by a factor of more than two. It should be emphasized, however, that these numbers are highly speculative.

II. Airborne Cadmium Emissions

Cadmium emissions can be grouped into point-source emissions and nonpoint emissions. Nonpoint emissions, however, are only of minor relevance in the case of airborne emissions.[4] The only known sources of nonpoint cadmium emissions to the air belong to activities related to the storage, handling and transport of dust-spreading goods with high cadmium content like zinc ore concentrate (see Table 3). As Böhm and Schäfers (1990, p. 4) note, information is not available on the quantitative magnitude of these emissions. However, in view of the figures to be discussed below, it seems reasonable to assume that airborne cadmium emissions from nonpoint sources are quantitatively almost insignificant compared with the emissions from point sources.[5]

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[4] It will be discussed in Section B.III that this is quite different in the case of aqueous emissions.

[5] This view is also supported by the existence of strict legal regulations concerning diffuse emissions of cadmium and other heavy metals. According to the Technical Directive on Air Pollution (*Technische Anleitung zur Reinhaltung der Luft — TA-Luft*) from 27 February 1986, emissions caused by storage, handling and transport of dust-spreading goods with a cadmium content of more than 50 ppm have to be minimized by employing the so-called most effective measures (*wirksamste Maßnahmen*); see TA-Luft (1986, § 3.1.5.5).

Table 3 — Cadmium Content of Fossil Fuels and Selected Raw Materials (ppm)

Fossil fuels	Cadmium content	Raw materials	Cadmium content
Hard coal	0.50–10.00	Iron ore	0.12–0.30
Brown coal	0.01–3.00	Limestone	0.01–0.70
Heavy oil	0.01–0.10	Sand, clay	0.03–3.00
Natural gas	negligible	Zinc ore concentrate	1,000–12,000
		Lead ore concentrate	3–500
		Copper ore concentrate	30–1,200

Source: Böhm and Schäfers (1990).

Table 4 summarizes the information on airborne cadmium emissions by sectors in West Germany. However, the data from several studies compiled in this table are not as informative as it may seem at first glance. Except for the ERL Report (1990)[6] all estimates presented in Table 4 are published in a rather sketchy way that does not facilitate a reexamination of the obtained results. In particular, information about the employed methodology and the underlying emission coefficients is not provided. Hence, a cross-checking between the results of the various estimates is hardly possible and the quality of the data cannot be judged. But, despite all differences, the estimates presented in Table 4 clearly indicate that there are basically five activities that are responsible for approximately 85–95 percent of total airborne cadmium emissions in West Germany:

- the combustion of fossil fuels (i.e., coal, oil) by power plants, industrial furnaces and private households,
- the production of iron and steel,
- the production of nonferrous metals (zinc, lead, and copper),
- the manufacturing of glass and ceramics, and
- the incineration of solid waste.

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[6] The report was undertaken during 1989 by Environmental Resource Limited (London) on behalf of the Commission of the European Communities (Directorate General for Environment, Consumer Protection and Nuclear Safety — DG XI). The aim of this study was the quantification of cadmium emissions to air, water and land on a source-by-source, country-by-country basis for each of the 12 Member States.

Table 4 — Estimates of Airborne Cadmium Emissions in West Germany by Activities, 1980–1989 (t/yr)

	1980–1982[a]	1982[b]	1985–1989[c]	1985–1986[d]	1986[e]
Power plants and industrial furnaces					
Coal combustion	2.2	1.4–5.6	6.4	1.3	2.3–3.3
Oil combustion	0.5	0.2	3.9	0.1	0.2–1.0
Small-scale consumers of fossil fuels					
Coal combustion	1.3	0.3	1.8	1.3	0.5
Oil combustion		< 0.01	1.0		
Zinc refining	5.0–7.0	14–24	8.4	2.4	12–20
Lead refining		1.2–1.8	0.9		
Copper refining		0.35–1.04	1.7		
Iron and steel	5.0	2.2–14.3	6.0	< 3.0	4.85–12.1
Nonferrous mining	.	.	0.05	.	.
Battery manufacturing	0.31	.	3.9	0.03	.
Alloy manufacturing	0.5	.	0.18	1.4	.
Cement manufacturing	0.3	0.09–0.36	1.1	< 0.2	0.2–1.4
Glass manufacturing	3.0	0.25–1.00	.	.	1.1–2.6
Ceramic manufacturing	.	4	.	.	0.3–0.6
Pigment manufacturing	0.17	0.1–0.3	.	0.01	.
PVC manufacturing	.	0.06	.	.	.
Waste incineration					
Household waste	2.9–3.8	1.1–5.3	7.20	< 2.0	3.3–6.0
Industrial waste	.	.	.	.	0.5–1.4
Sewage sludge	0.1	.	.	0.1	< 0.05
Motor traffic	.	0.6	1.75	.	.
Total	21.3–24.2	25.9–58.9	44.90	< 11.8	25.3–49.0

[a] Bundesverband der Deutschen Industrie (1982). — [b] Umweltbundesamt (1991). — [c] ERL Report (1990). — [d] Bund-Länder-Ausschuß Umweltchemikalien (1988). — [e] Bund-Länder-Ausschuß Umweltchemikalien (1989).

Source: See notes a–e.

Airborne cadmium emissions caused by the other activities mentioned in Table 4 (i.e., nonferrous mining, motor traffic, manufacturing of batteries, alloy, cement, pigments and PVC) contribute only very little to the total emissions.

1. Combustion of Fossil Fuels by Power Plants and Industrial Furnaces

Hard coal, brown coal, and oil contain a certain amount of cadmium (see Table 3), which is partly released in form of cadmium contaminated flue dust during the process of combustion. The published numbers of annual airborne cadmium emissions caused by power plants and industrial furnaces range from 1.3–6.4 t resulting from the combustion of coal and from 0.1–3.9 t resulting from the combustion of oil (see Table 4). The wide span between the various estimates indicates that there is considerable uncertainty concerning the magnitude of emissions. However, in both cases the upper limits are claimed by the ERL Report (1990), and it seems that these figures overestimate emissions.

This is particularly obvious in the case of oil combustion: The emission coefficients used in the ERL Report (1990) are 0.25 g Cd/t oil consumed by power plants and 0.145 g Cd/t oil consumed by industrial furnaces. These coefficients can be checked against the cadmium content of fuel. Since oil-fired plants are usually not equipped with dust filters (see Umweltbundesamt 1989, p. 519), it may be possible that the emission coefficient equals the cadmium content, but it is not possible that the former figure exceeds the latter. According to estimates of the German *Umweltbundesamt*, published by Böhm and Schäfers (1990), the cadmium content of heavy oil (*Heizöl S*) amounts only to 0.01–0.1 g/t (see Table 4). Hence, the emission coefficients employed by the authors of the ERL Report (1990) seem too high, and a recalculation of their results using an average coefficient of 0.04 g Cd/t oil leads to an estimate of approximately 0.8 t airborne cadmium emissions caused by the combustion of oil in power plants and industrial furnaces. This magnitude is roughly in line with the figures published by the other studies (see Table 4).

According to legal regulations concerning air pollution, coal-fired power plants and industrial furnaces are usually equipped with dust-arresters in Germany. Since the amount of cadmium that is released during the combustion process condenses onto the fly ash particles, the respective cadmium emissions depend not only on the coal's cadmium content but also on the removal factor of the employed filter systems. While the cadmium content used in the ERL Report (1990) is roughly in line with the estimates presented in Table 3, there is a considerable inconsistency concerning the removal factors: The ERL Report (1990) uniformly assumes for all EC member states that 9 percent of the coal's cadmium content is finally emitted to the air. In contrast to this, the removal factors of filter systems used by coal-fired plants in Germany usually amount to 98 percent and more (Böhm and Schäfers 1990, p. 9). Hence, it has to be suspected that cadmium emissions are much lower than claimed in the ERL Report (1990).

From the above discussion and from the figures presented in Table 4, it seems reasonable to conclude that annual airborne cadmium emissions caused by power plants and industrial furnaces amounted to approximately 2–5 t in the period of 1982–1986. This magnitude, however, cannot be applied to the current situation, since the legal restrictions concerning air pollution by power plants and major industrial furnaces changed in June 1983, when the so-called Ordinance on Large Combustion Facilities (*Großfeuerungsanlagenverordnung*) was introduced. According to this regulation, new plants are required to meet very strict emission standards concerning SO_2, NO_x, suspended matter (dust) and other pollutants, and already existing plants have to be improved within specific transition periods. According to the Umweltbundesamt (1989) this regulation would lead to a 60 percent reduction in emissions of suspended matter from large combustion plants between 1983 and 1993 (see Table 5). As a consequence, airborne cadmium emissions caused by these sources would also decrease considerably. This reduction would probably be somewhat smaller than the 60 percent reduction in suspended matter emissions, because cadmium, which is volatilized during combustion processes, preferably condenses onto fly ash particles smaller than 5 µm, which can only partially be removed even by modern filter technologies (see Ewers 1990, p. 1).

Table 5 — Estimated Annual Emissions of Power Plants and Industrial Furnaces Regulated by the Ordinance on Large Combustion Facilities from 1983, 1988, and 1993 (1,000 t)

	1983	1988	1993
Sulphur dioxide (SO_2)	1,940	700	400
Nitrous oxides (NO_x)	960	590	250
Suspended matter	100	60	40

Source: Umweltbundesamt (1989, p. 519).

2. Combustion of Fossil Fuels by Small-Scale Consumers

In the case of fossil fuel combustion by households and other small-scale consumers, the large differences between the estimates of the ERL Report (1990) and the other studies cannot be explained using the published data and material. However, in view of the growing diffusion of district heating systems (*Fernwärme*) and in view of ongoing substitution processes in favour of cadmium-free natural gas (see Umweltbundesamt 1989, pp. 559–560), it may be concluded that the amount of airborne cadmium emissions from the combustion of fossil fuels by households and small-scale consumers is likely to become negligible in the medium term.

This trend will also be supported by the so-called Ordinance on Small Combustion Facilities (*Kleinfeuerungsanlagenverordnung*) enacted in July 1988. According to this ordinance, coal-fired small-scale facilities with a nominal heat capacity (*Nennwärmeleistung*) of more than 15 kilowatts (kw) and oil-fired small-scale facilities with a nominal heat capacity of more than 28 kw must meet certain emission standards with respect to suspended matter.

3. Production of Iron and Steel

Cadmium enters the process of iron and steel making in two ways: as an undesired trace element of natural iron ore (see Table 3) and as a contamination of scrap metals that results from the intentional use of cadmium in surface plating. According to Böhm and Schäfers (1990, p. 7), the cadmium input caused by the use of natural iron ore is negligible compared with the huge amounts of cadmium that enter the process via scrap metals. However, the scrap metals' cadmium content varies widely and, therefore, suitable coefficients describing airborne cadmium emissions from iron and steel making can hardly be determined. This problem leads to considerable uncertainty, about the actual magnitude of emissions. In particular, the estimates of the Umweltbundesamt exhibit an extremely wide span of uncertainty which ranges from a lower bound of 2.2 t/yr to an upper bound of 14.3 t/yr (see Table 4). However, the Umweltbundesamt (1991) additionally provides a mean value of 6.9 t, which is roughly in line with the other estimates shown in Table 4.

The data discussed above suggest that a magnitude of 5–7 t may be viewed as a rough guess of annual airborne cadmium emissions from iron and steel making in the period of 1982–1986. There are two reasons to believe that the current emissions from iron and steel making are considerably lower. The first reason is related to a change in the legal requirements concerning air pollution by iron and steel making that are laid down in the so-called Technical Directive on Air Pollution (*Technische Anleitung zur Reinhaltung der Luft — TA-Luft*). This regulation, originally introduced in 1974, was tightened considerably in 1986 (see Table 6). In particular, the emission standard concerning the permissible amount of suspended matter per m^3 of exhaust air caused by the electric arc process has been reduced from 150 to 20 mg. This requirement is of particular importance for airborne cadmium emissions because scrap metals are usually recycled through the electric arc process (see Elgersma et al. 1991, p. 77). Hence, one can expect that the tightened emission standards that are to be met by each plant by the year 1996 will lead to a significant reduction in airborne cadmium emissions compared with the period 1982–1986.

Table 6 — Changes in the Technical Directive on Air Pollution (*TA-Luft*) That Are Important with Respect to Cadmium Emissions, 1974 and 1986

	1974	1986
	Concentration of suspended matter in exhaust air of regulated sources	
General standards	150–500 mg/m^3	50–150 mg/m^3
Special standards		
Iron and steel production		
Electric arc process	150 mg/m^3	20 mg/m^3
Basic oxygen process	No special standard	20–50 mg/m^3
Lead refining	20 mg/m^3	10 mg/m^3
Zinc and copper refining	No special standard	20 mg/m^3
	Concentration of heavy metals in exhaust air of "highly polluting sources"	
Scope of application	Sources that emit more than 0.5 kg/h of heavy metals	Sources that emit more than 1 g/h of cadmium, mercury and thallium
Emission standard	Total concentration of heavy metals in exhaust air is not allowed to exceed 20 mg/m^3	Total concentration of cadmium, mercury and thallium in exhaust air is not allowed to exceed 0.2 mg/m^3

Source: TA-Luft (1974, 1986).

The second reason is related to the fact that the cadmium content of scrap metals can mainly be attributed to the use of cadmium in plating activities. Consequently, the extent of cadmium plating determines the supply of cadmium in scrap metal with a specific time lag. According to Böhm and Schäfers (1990, p. 8) the average lifetime of plated metal parts ranges from 15 to 25 years. Hence, it seems reasonable to assume that the cadmium input to the production of iron and steel is mainly determined by the amount of cadmium used in plating with an average time lag of approximately 20 years. As one can see from Table 2, the amount of cadmium employed in these activities has been decreasing continuously since 1976.[7] This implies that the cadmium input through scrap metal will probably begin to decline in the middle of this decade. The figures presented in Table 2 suggest that this process will lead to a decrease of cadmium inputs by a factor of more than 3 within the next 15 years. This lagged effect, accompanied by the tightened emission standards, will induce a drastic reduction in airborne cadmium emissions of the iron and steel industry.

4. Production of Nonferrous Metals

Raw zinc ores, lead ores and copper ores contain a certain amount of cadmium (see Table 3) that is partly volatilized and released to the exhaust air during the process of refining. According to the particularly high cadmium content of zinc ores — the respective estimates range from 1–12 kg Cd/t (see Table 3) — zinc refining has to be viewed as one of the most important sources of airborne cadmium emissions (see Table 4). The specific amount of cadmium emitted to the air strongly depends on the type of refining process that is applied. Significant differences in airborne cadmium emissions exist between the high-polluting thermal process (imperial smelting) and the low-polluting electrolytic process. According to the ERL Report (1990), the emission coefficient of thermal zinc refining as operated in West Germany amounts to 58 g Cd/t Zn produced, while the respective coefficient for the electrolytic process is only 0.2 g Cd/t. As a consequence, the major part of airborne cadmium emissions caused by zinc refining can be traced back to the use of the thermal process. With respect to West Germany, it is estimated that in 1985 the thermal processes' share on total airborne cadmium emissions caused by zinc refining amounted to more than 99.4 percent (see ERL Report 1990). However, since the mid-eighties the thermal process has been reduced in capacity by a factor of almost 15. By now, in West Germany only one minor plant is still under operation. Hence, the emission data presented in Table 4 cannot be applied to the current situation. In view of the technological development, it seems justified to claim that the remaining airborne cadmium emission from primary zinc refining in West Germany may be almost negligible by now.

Concerning primary production of lead and copper, the published material does not allow to check if the emission data presented in Table 4 are still valid. However, since primary zinc and lead winning is sometimes linked within the

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[7] This decrease is in part due to substitution processes in the automobile industry. According to the German *Sachverständigenrat für Umweltfragen* one of the major German producers succeeded in reducing the cadmium content per car from 500 g to 1 g (see Sachverständigenrat für Umweltfragen 1990, p. 230).

same plant (see Elgersma et al. 1991, p. 38) it may be reasonable to assume that the current emissions caused by primary lead production also will be smaller than indicated by Table 4.

The secondary production of nonferrous metals by utilizing scrap materials constitutes a further significant source of airborne cadmium emissions. The production data in Table 7 show that secondary production is of particular importance in the cases of lead and copper winning. It is estimated for West Germany that in 1985 the secondary production of lead contributed 66 percent of the total airborne cadmium emissions caused by the production of lead, and the respective share for copper amounts to 50 percent (see ERL Report 1990). However, it cannot be judged whether these figures still can be applied to the current situation because of a lack of more recent data.

Table 7 — Primary and Secondary Production of Nonferrous Metals in West Germany, 1980–1988 (1,000 t)

	1980	1982	1984	1986	1988
Zinc					
Primary production	365.2	333.6	356.3	370.9	352.4
Secondary production	27.8	31.5	30.8	26.6	42.5
Lead					
Primary production	191.1	201.6	191.9	182.1	176.6
Secondary production	159.2	148.9	165.3	184.5	168.5
Copper					
Primary production	153.9	161.8	148.8	161.9	162.5
Secondary production	219.9	231.8	230.0	260.0	263.9

Source: Metallgesellschaft AG (1989).

Finally, it should be noted that both primary and secondary production processes have recently become subject to considerably tightened regulations that are laid down in the amended version of the Technical Directive on Air Pollution from 1986 (see Table 6): The standards concerning the general emission of suspended matter from nonferrous metal industries have been reduced to 10 mg/m^3 for lead refining and 20 mg/m^3 for zinc and copper refining respectively, and the permissible total concentration of cadmium, mercury and thallium in exhaust air of high polluting sources has been reduced to 0.2 mg/m^3. According to the German *Sachverständigenrat für Umweltfragen*, this tightening of regulations will — at least in the case of high-polluting sources — induce considerable reductions in cadmium emissions. The total decrease is expected to reach the order of 30–40 percent (Sachverständigenrat für Umweltfragen 1990, p. 231).

5. Manufacturing of Glass and Ceramics

Cadmium enters the process of glass and ceramic manufacturing in two ways: as an undesired trace element of raw materials like clay, sand, limestone, and dolomite (see Table 3), and as an ingredient of pigments used for coloring. According to Böhm and Schäfers (1990, pp. 8–9), the first route of cadmium input dominates in the manufacturing of heavy ceramics (e.g., bricks, potteries) and commodity glasses (e.g., plate glass), and the second route dominates in the manufacturing of fine ceramics (e.g., sanitary) and special glasses (e.g., for traffic lights).

According to the studies compiled in Table 4 airborne cadmium emissions from the manufacturing of glass and ceramics amount to approximately 1.4–5.0 t/yr. It may be speculated that the major part of this amount can be traced back to the use of cadmium-containing pigments. Although this view cannot definitively be substantiated through the published figures and reports, it seems to be strongly supported by the fact that the coloring process operates at extremely high temperature levels that induce major parts of the cadmium input to evaporate into the exhaust air. Assuming that five sixth of the cadmium input are volatilized and released to the exhaust air,[8] accounting for 35 t Cd used in the coloring of glass and ceramics in 1987 (see Table 8), and assuming that the removal factor of the employed filter systems amounts to 90–95 percent, one would be led to an estimate of approximately 1.45–2.9 t of airborne cadmium emissions caused by the use of cadmium-containing pigments in the coloring of glass and ceramics. This result is roughly in line with the figures presented in Table 4.

Table 8 — Destination of Cadmium Used in Pigments, 1983 and 1987

	1983		1987	
	t	percent	t	percent
Plastics	250	82.2	250	85.9
Paints	20	6.6	6	2.1
Ceramics	23	7.6	24	8.2
Glass	11	3.6	11	3.8
Total	304	100.0	291	100.0

Source: Böhm and Tötsch (1989, p. 48).

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[8] This fraction is claimed by Böhm and Tötsch (1989, p. 84) for the coloring of glass. We assume that it can also be applied to the coloring of ceramics.

In order to provide an idea of the current development of airborne cadmium emissions caused by the manufacturing of glass and ceramics it should finally be noted that these activities are also subject to the tightened regulations of the Technical Directive on Air Pollution. Hence, it can be expected that the current emissions caused by the manufacturing of glass and ceramics are smaller than indicated by the figures presented in Table 4. Further quantifications, however, are not possible because of a lack of more recent data.

6. Incineration of Solid Waste

Beside the production of iron and steel from scrap metals, the incineration of waste is a second case in which the intentional use of cadmium in upstream activities leads to the inadvertent entry of cadmium into downstream activities. The amount of airborne cadmium emissions caused by the incineration of waste depends on two quantities:

- the cadmium contamination of waste, caused by cadmium-containing waste products (plastics, batteries, etc.), and
- the removal factor of the filter technologies employed (measured as the percentage of cadmium input that is not emitted into the air).

Suitable coefficients concerning the cadmium content of waste are available only for household waste but not for industrial waste. This lack of data, however, seems to be of minor importance, since the major part of airborne cadmium emissions from waste incineration can be traced back to the consumption of cadmium-containing products by households (see Table 4). Table 9 summarizes the available data on the cadmium content of household waste, and

Table 9 — Cadmium Content of Household Waste, Removal Factor of Filter Technologies, and Calculated Emission Coefficient of Waste Incineration, Situation as of the Early 1990s

	Cadmium content	Removal factor	Emission coefficient
	g Cd/t waste	percent	g Cd/t waste
ERL Report (1990)	9.8	88.4	1.1
Böhm and Schäfers (1990)	10.0	92.5–95.9	0.4–0.8
Sachverständigenrat für Umweltfragen (1990)	3.5–8.7	–	–
Reimann (1991)	3.0–15.0	–	–

the efficiency of filter technologies used in waste incineration. It shows that there is considerable uncertainty with respect to both quantities. As a result, the respective emission figures presented in Table 4 vary widely. In particular, the estimates of the Umweltbundesamt (1991) range from 1.1–5.3 t/yr. In addition, the Umweltbundesamt (1991) provides a mean value of 2.5 t. This figure seems to be reasonable in view of the coefficients shown in Table 9 and the quantities of waste burned shown in Table 10.

Table 10 — Incineration of Municipal and Industrial Waste in West Germany, 1980–1990 (1,000 t)

	1980	1982	1984	1987	1990
Municipal waste	6,253	6,340	7,185	7,962	8,275
Industrial waste	4,111	4,080	4,637	4,892	4,120
Total	10,364	10,420	11,822	12,854	12,395

Source: Statistisches Bundesamt (1984, 1987a, 1990b, 1991a).

The data on cadmium emissions from the incineration of waste in the eighties can hardly be extrapolated to the current situation. This is due to the fact that the incineration of waste has recently become subject of dramatically tightened legal regulations. Not only the strict standards concerning the emission of heavy metals by 'high polluting sources', laid down in the amended version of the Technical Directive on Air Pollution of 1986 (see Table 6), apply to waste incineration but also the Ordinance on Waste Incineration Plants (*Verordnung über Verbrennungsanlagen für Abfälle*) of 1990 does. According to the latter regulation, an emission standard of 0.05 mg Cd/m^3 exhaust air has to be met by each incineration plant until 1996. Reimann (1991) has calculated that this required standard implies an average emission coefficient of 0.23 g Cd/t waste. This translates into an improvement by a factor of four compared with the requirements of the Technical Directive on Air Pollution of 1986. Moreover, the future state of the art in removal technologies is expected to bring about an emission coefficient of 0.05 g Cd/t waste or 0.01 mg Cd/m^3 exhaust air (see Reimann 1991). Hence, technical progress will lead to drastic reductions in airborne cadmium emissions from waste incineration. However, this trend may partly be compensated by an increasing amount of waste treated in incineration plants. According to Böhm and Schäfers (1990) the capacity of municipal incineration plants will increase by roughly 8 million t/yr within the next few years. Therefore, it may be expected that waste incineration will continue to be one of the major sources of airborne cadmium emissions.

II. Aqueous Cadmium Emissions

According to the usual classification scheme, aqueous cadmium emissions can be grouped into three different categories, which are based on the emission source (see, e.g., Deutsche Kommission zur Reinhaltung des Rheins 1989, p. 8):

(1) emissions originating from industrial point sources that are directly discharged to surface waters;
(2) emissions originating from municipal wastewater treatment plants; and
(3) emissions originating from nonpoint sources, e.g., atmospheric deposition and inputs of phosphate fertilizers.

This classification, however, is not completely consistent with the methods usually employed to quantify cadmium emissions from industrial activities. Normally, these emissions are not directly measured at the 'end of the pipe' but estimated by applying specific emission coefficients to the respective figures regarding the quantity of output produced or the quantity of cadmium used as input. These emission coefficients usually account not only for the direct discharge to surface waters but, where appropriate, also for the indirect discharge via municipal wastewater treatment plants. Therefore, the available estimates of aqueous cadmium emissions from industrial activities, which are computed with emission coefficients, include direct discharges (category (1)) and the part of the emissions from municipal treatment plants (category (2)) originating from industrial sources. However, this difference between measured industrial emissions (category (1)) and total emissions (category (1) plus (2)), which may be crucial for pollutants other than cadmium, is easy to solve in the case at hand because the use of cadmium-containing products (e.g., batteries) normally does not lead to a significant cadmium input into the private households wastewater.[9] Consequently, cadmium-containing wastewaters entering municipal

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[9] The only exception may be the use of toilet paper manufactured from waste paper. However, as empirical studies indicate, the cadmium content of these products ranges only from 0.03–0.20 mg Cd/kg (see Brahms et al. 1989, p. 224). Accounting for a total consumption of about 300,000 t/yr toilet paper (see, e.g., Heinstein and Seeberger 1986), this is clearly not enough to contribute significantly to the municipal wastewater's cadmium load.

wastewater treatment plants originate from industrial sources and from the runoff from surfaced areas like, e.g., streets. According to case studies, this runoff amounts to about 10 percent of the total cadmium load (see Section B.III.2.b). This implies that the available estimates of industrial cadmium emissions discussed in Section B.III.1 completely cover direct emissions (category (1)) and most emissions from wastewater treatment plants (category (2)). In the following, we refer to these emissions as "point-source emissions" because in both cases the discharge to surface waters occurs at one specific point in space.

1. Aqueous Emissions from Point Sources

There exists an extensive engineering literature on aqueous cadmium emissions caused by specific production processes (see, e.g., Elgersma et al. 1991, pp. 93–99). However, up to now only a few attempts have been made to estimate total aqueous point-source emissions by countries and sectors. For West Germany, only two comprehensive studies are available.[10] The results for West Germany presented in the first study, the ERL Report (1990),[11] appear to be highly unreliable because of a number of methodological shortcomings. The second study, hereafter cited as Elgersma et al. (1991),[12] focuses exclusively on aqueous cadmium emissions in the Rhine River Basin, and therefore total German cadmium emissions are not covered. However, the restriction to the Rhine River Basin has facilitated a more detailed study of the individual emission sources and for that reason the results presented by Elgersma et al. (1991) seem to be more reliable than the figures in the ERL Report (1990).

Table 11 contains the estimates of aqueous cadmium emissions in West Germany by activities as published in the ERL Report (1990).[13] These estimates suggest that West Germany is responsible for more than one fifth of the overall emissions in the EC. In particular, the German iron and steel

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[10] Besides these two studies, there are various other specific data on aqueous cadmium emissions in West Germany available in the literature. However, these figures are not broken down by sectors or activities, and they often exhibit a considerable degree of divergence.

[11] For further information about the report see Section B.II, footnote 6.

[12] This study was undertaken at the International Institute for Applied System Analysis (Laxenburg/Austria).

[13] Besides the activities mentioned in Table 11, the authors of the ERL Report consider also the following activities to contribute significantly to aqueous cadmium emissions in West Germany: nonferrous mining, refining of copper, cadmium oxide production and alloy manufacturing. However, no attempts have been made to estimate these figures because of lack of data.

Table 11 — Estimates of Aqueous Cadmium Emissions in West Germany, 1983–1988

	Emissions	Share on EC-wide emissions[a]	Year under review
	t/yr	percent	
Iron and steel production	6.3	29.7	1987
Zinc refining	5.1	29.5	1985
Lead refining	2.5	25.0	1985
Battery manufacturing	1.1	34.4	1988
Pigment manufacturing	6.0	28.6	1988
Stabilizer manufacturing	0.63	63.0	1986
Cadmium plating	4.6	23.4	1987
Incineration of sewage sludge	0.1	50.0	1983
Total	26.3	21.2	various

[a] Caused by the respective activity.

Source: ERL Report (1990, p. IV).

industry as well as zinc refining and pigment and plate manufacturing seem to contribute considerable to total cadmium emissions. However, a comparison with the study by Elgersma et al. (1991) reveals that the figures published in the ERL Report (1990) overestimate the actual aqueous cadmium emissions caused by industrial activities in West Germany.

Table 12 contains the estimates of the annual aqueous cadmium emissions from industrial point sources in the German part of the Rhine River Basin for the year 1988 and for the time periods 1978–1982, 1983–1984 and 1985–1987 as published by Elgersma et al. (1991). Although this study covers only the Rhine River Basin and although the breakdown by activities differs slightly from the one in the ERL Report (1990), a comparison of Tables 11 and 12 clearly indicates that the results of the two studies are not in line with each other. In particular, the following inconsistencies stand out:

— The ERL Report (1990) estimates 5.1 t of cadmium emissions from primary zinc refining in 1985, whilst the respective figure by Elgersma et al. (1991) is only 0.5 t/yr for the period 1983–1987. Since almost 50 percent of total German zinc production in 1985 was located in the

Rhine River Basin,[14] there is a remarkable difference between these estimates.

- In the case of pigment manufacturing, a cross-checking between the results of the two studies is of particular ease because there are only three main cadmium pigment producers in West Germany, which all are located in the Rhine River Basin (Besigheim, Bonn, Leverkusen).[15] Therefore, the estimates presented in both studies should be almost congruent. However, the figures published by the ERL Report (1990) and by Elgersma et al. (1991) respectively differ by a factor of 30.
- For 1987 the ERL Report (1990) estimates 4.6 t of aqueous cadmium emissions from plating, whilst the respective figures estimated by Elgersma et al. (1991) are only 0.1–0.7 t/yr for the period 1985–1987 and 0.1 t for the year 1988. Since in West Germany approximately 75 percent of all cadmium plating activities take place in the Rhine River Basin (see Elgersma et al. 1991, p. 65), there is a remarkable inconsistency between these two estimates.

Table 12 — Estimates of Aqueous Point Source-Cadmium Emissions in the German Part of the Rhine River Basin, 1978–1988 (t/yr)

	1978–1982	1983–1984	1985–1987	1988
Nonferrous mining	0.1	0.1	0.1	0.0
Iron and steel production	9.9	4.2	4.2	1.1
Primary zinc/lead industry	1.0	0.5	0.5	0.1
Secondary zinc industry	50.0	25.0	0.0	0.0
Secondary lead industry	0.6	0.6	0.6	0.6
Battery manufacturing	0.9–1.3	0.5–0.7	0.5–0.7	0.3
Pigment manufacturing	1.3	0.3	0.3	0.2
Stabilizer manufacturing	0.6–1.4	0.4–0.9	0.4–0.9	0.0
Cadmium plating	2.0–4.4	0.1–0.7	0.1–0.7	0.1
Coke production	3.1	0.5	0.5	0.5
Total	69.5–73.1	32.2–33.5	7.2–8.5	2.9

Source: Elgersma et al. (1991).

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[14] According to Elgersma et al. (1991, p. 38) the annual zinc production in the Rhine River Basin amounted to approximately 170,000 t in the period 1983–1987, whilst the total German zinc production amounted to approximately 366,000 t in the year 1985.

[15] Note, that the producer located at Leverkusen left the market in 1988 (see Elgersma et al. 1991, pp. 45–46).

What are the reasons for these large discrepancies? Obviously, the most crucial factor in estimating emissions from industrial point sources is the determination of appropriate emission coefficients that relate the amount of cadmium emissions to the amount of cadmium used in the process or to the amount of goods produced. Table 13 summarizes the emission coefficients from Elgersma et al. (1991) and from the ERL Report (1990). Obviously there are enormous discrepancies between the respective coefficients. The primary reason for these discrepancies comes from the fact that the technological conditions that determine the respective emission coefficients often vary from country to country and even from source to source. Therefore, in principle it would be necessary to obtain individual emission coefficients for each single emission source. Concerning this problem, the authors of the ERL Report (1990, p. II) complain that they "... *were largely unable to obtain data concerning emission control technologies in operation in different Member States. The effect of this is that emission factors that were derived from a particular plant, or data from a particular country, have been applied uniformly to all EC States.*"[16] In contrast to this rather loose-knit approach, Elgersma et al. (1991) succeeded in obtaining emission coefficients on a real source-by-source base for almost each of the considered activities in the Rhine River Basin. Therefore, the emission coefficients employed by Elgersma et al. (1991) seem to be much more reliable.[17]

In particular, applying uniform emission coefficients to all EC member states seems to be highly questionable because of large differences in the national regulations concerning wastewater treatment. In Germany, the water quality policy was drastically tightened in 1976 by the introduction of the fourth amendment to the Water Management Law (*Wasserhaushaltsgesetz*). According to this regulation, a permit to discharge into surface waters is granted only if the concentration of pollutants does not exceed the so-called minimum requirements (*Mindestanforderungen*), which are fixed on a sector-by-sector base according to the "generally recognized rules of technology" (*allgemein anerkannte Regeln der Technik*) for wastewater treatment.[18]

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[16] For instance, the emission coefficient used to calculate aqueous cadmium emission from zinc refining is solely based on information supplied by the Belgian nonferrous metal industry (see ERL Report 1990, Annex A24).

[17] However, in favour of the ERL Report (1990), it should be borne in mind that the scope of the study by Elgersma et al. (1991) is limited to the Rhine River and, hence, the number of emission sources to be considered is much smaller.

[18] Additionally, the Water Management Law obliges the regulatory authority to prohibit emissions — even if they meet the minimum requirements — if the quality of the surface water would result in untolerable damage.

Table 13 — Comparison of Emission Coefficients (g/t)

	Elgersma et al.		ERL Report
	1985–1987	1988	
Nonferrous mining[a]	1.00	1.00	–
Iron and steel production[b]			
Basic oxygen steel	0.20	0.05	0.18
Electric arc steel	0.20	0.05	0.14
Zinc refining[c]			
Thermal process	5.00	0.50	26.00
Electrolytic process	0.10	0.10	5.70
Lead refining[d]			
Primary production	5.00	0.50	8.40
Secondary production	6.20	6.20	6.16
Battery manufacturing[e]			
Pocket plate	1.50	1.00	3.00
Sintered plate	2.00–3.00	1.00	0.50
Pigment manufacturing[e]	0.50	0.30	15.20
Stabilizer manufacturing[e]	0.60	0.40	1.81
Cadmium plating	1.00–6.00	0.30	23.00

Dimension of emission coefficients: [a]g Cd/t Zn, Pb-concentration. — [b]g Cd/t steel. — [c]g Cd/t Zn. — [d]g Cd/t Pb. — [e]kg Cd/t Cd used in process.

Source: Elgersma et al. (1991); ERL Report (1990).

Moreover, since 1986 the Water Management Law has required for wastewaters with hazardous substances like cadmium that even stricter minimum requirements according to the "state of the technology" (*Stand der Technik*) have to be applied.[19] Table 14 shows the minimum requirements concerning heavy metals for the sectors under consideration and the general standard introduced in 1991 that has to be met by all regulated sources. On top of the regulation through the Water Management Law, the Law on Effluent Charges of 1976 has introduced an additional charge in order to provide further incentives for reductions in emissions. The charge is levied on the so-called pollution unit (*Schadeinheit*), which translates different pollutants into a common unit (see Table 15). The charge per pollution unit was set at DM40 in 1986, and it did increase to DM50 in 1991 with a further increase of DM10

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[19] "Generally recognized rules of technology" are techniques that have been tested in practice and that are generally employed. In contrast, the "state of the technology" describes newer techniques that have been tested but that are not yet generally employed (see Förstner 1992, Chapter 1).

Table 14 — Minimum Requirements on the Concentration of Heavy Metals in the Wastewater of Selected Industries, Situation as of the Early 1990s

	Minimum requirement (mg/l wastewater)				Implementation
	Cd	Pb	Cu	Cr	
Nonferrous mining	–	0.5	–	0.5	1983
Iron and steel production	–	0.5	–	–	1982
Zinc and lead refining	0.2	0.5	0.5	0.5	1989
Battery manufacturing	0.2	0.5	0.5	–	1989
Pigment manufacturing	0.01	0.04	0.5	0.5	1991
Cadmium plating	0.1–0.2	0.5	0.5	0.5	1989
Ceramics	0.07	0.5	0.1	0.1	1992
General standard	0.2	0.5	0.5	0.5	1991

Source: Lohaus (1990); Der Bundesminister für Umwelt, Naturschutz und Reaktorsicherheit (1991, 1992).

Table 15 — Definition of Pollution Units According to the *Abwasserabgabengesetz*

Pollutant	1 Pollution unit equals
Chemical oxygen demand	50 kg oxygen
Phosphorous	3 kg
Nitrogen	25 kg
Organic halogen compound	2 kg organic halogen compound
Mercury	20 g metal
Cadmium	100 g metal
Chromium	500 g metal
Nickel	500 g metal
Lead	500 g metal
Copper	1 000 g metal
Toxicity for fish	3000 m^3 wastewater divided by the dilution factor necessary to reach nontoxicity

Source: Abwasserabgabengesetz (1986).

every two years thereafter until it reaches DM90 in 1999.[20] However, this rate does not apply to all emissions. In particular, it is halved if the minimum

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[20] This step-by-step increase, however, has recently become subject to a serious political controversy. At present it is not clear whether or not the charge rate will in fact be increased according to the initial plan.

requirements are achieved, and it is further reduced if the concentration of pollutants falls below these requirements. A detailed description and evaluation of the German effluent charge is given in OECD (1994).

The combination of direct regulations and economic incentives has turned out to be highly successful in enforcing the minimum requirements shown in Table 14. As a consequence, aqueous cadmium emissions in West Germany were drastically reduced during the eighties. This development cannot be captured by applying, e.g., Belgian emission coefficients to German plants, as it has been done by the authors of the ERL Report (1990).

An additional source of divergency between Elgersma et al. (1991) and the ERL Report (1990) arises because the emission coefficients used in the latter study often do not account for the effects of wastewater treatment. For instance, in the case of pigment manufacturing, the authors of the ERL Report (1990) argue that 6 percent of the cadmium input is lost in production, of which 4.47 percent is reclaimed in the plant, 1.4 percent is emitted to municipal wastewater treatment plants and 0.12 percent is directly discharged to water. From this partitioning, which seems to be undisputed in the literature and which is also used by Elgersma et al. (1991), they conclude that total aqueous cadmium emissions equal 1.52 percent of cadmium input, i.e., 15.2 kg Cd/t Cd used in process.

This conclusion, however, is misleading because it does not account for the effects of wastewater-treatment activities. As Elgersma et al. (1991, p. 46–47) point out, the cadmium removal factor of municipal treatment plants equals 40–60 percent, i.e., roughly half of the wastewater's cadmium load is filtered out and only the remaining partition is discharged to surface waters. Moreover, in West Germany cadmium pigments are only produced in large chemical plants that are equipped with their own wastewater treatment facilities. According to Elgersma et al. (1991, p. 47), the cadmium removal factor of these facilities usually amounts to 90 percent and more. Hence, in order to obtain a reliable emission coefficient, the above mentioned partitions of cadmium lost in process have to be corrected by the removal factors of the respective treatment facilities.[21] This recalculation leads to the emission coefficient employed by Elgersma et al. (1991).

To summarize: The results of the ERL Report (1990) concerning aqueous cadmium emissions in West Germany are unsatisfactory because of the employment of unsuitable emission coefficients. On the contrary, the estimates published by Elgersma et al. (1991) seem to be much more reliable, but they cover only the Rhine River Basin. In view of this situation, it seems to be the

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[21] A similar objection has to be made concerning the emission coefficient used in the ERL Report (1990) to calculate aqueous cadmium emissions from plating.

most sensible strategy to use the figures published by Elgersma et al. (1991) for estimating total German aqueous cadmium emissions.

For this purpose, we assume that the technological standards prevailing in the German part of the Rhine River Basin are representative for the respective industries all over West Germany. Under this assumption, the emission coefficients used by Elgersma et al. (1991) can be applied to the respective production or input data for West Germany as a whole. The results of this projection are shown in Table 16.

Table 16 — Projection of Aqueous Cadmium Emissions in West Germany, 1988

	Emission coefficient	Output/input quantity	Aqueous cadmium emissions
	Cadmium as inadvertent input in production process		
Nonferrous mining[a]	1.00 g/t	93,500 t	0.09 t
Iron and steel production[b]	0.05 g/t	35,508 kt	1.78 t
Coke production[c]	0.03 g/t	8,274 kt	0.55 t
Thermal zinc refining[d]	0.50 g/t	81,000 t	0.04 t
Electrolytic zinc refining[d]	0.10 g/t	271,000 t	0.03 t
Primary lead production[e]	0.50 g/t	185,600 t	0.09 t
Secondary lead production[e]	6.20 g/t	68,500 t	1.04 t
Total			3.62 t
	Cadmium as intentional input in production process		
Battery manufacturing[f]	1.00 kg/t	292 t (1987)	0.29 t
Pigment manufacturing[f]	0.30 kg/t	393 t	0.12 t
Stabilizer manufacturing[f]	0.40 kg/t	270 t (1987)	0.11 t
Cadmium plating[f]	0.30 kg/t	72 t	0.02 t
Total			0.54 t

Dimension of emission coefficients: [a]g Cd/t Zn, Pb-concentration. — [b]g Cd/t steel. — [c]g Cd/t coke. — [d]g Cd/t Zn. — [e]g Cd/t Pb. — [f]kg Cd/t Cd used in process.

Source: Own calculations based on: Böhm and Schäfers (1990); Elgersma et al. (1991); Metallgesellschaft AG (1989); Statistisches Bundesamt (1990a).

Obviously, the quality of our projection crucially depends on the assumption that the emission coefficients obtained in the German part of the Rhine River Basin are reliable proxies for the technological standards in West Germany as a whole. We have not found evidence speaking against this assumption. In particular, there are no reasons to believe in regionally different patterns of technological development (i.e., the diffusion of innovations, etc.), since there are uniform economic and legal conditions in the whole of West Germany as well as in the German part of the Rhine River Basin. Moreover, the contribution of the Rhine River Basin's industry to the activities under question exceeds 50 percent (measured as the share on total output or total cadmium use) in virtually all cases. And finally, our results are roughly in line with estimates of the German *Umweltbundesamt*, according to which total cadmium emissions to surface waters in 1986 are 7–9 t/yr[22] (see Böhm and Schäfers, 1990, p. 12), and with estimates of Rauhut (1990), who asserts for the same year that aqueous cadmium emissions caused by the industrial use of cadmium amounted to 1.6 t.

From the above discussion it seems to be justified to claim that our estimates presented in Table 16 are considerably more reliable than the respective figures published in the ERL Report (1990). A comparison of Tables 11 and 16 suggests that the authors of the ERL Report overestimate aqueous point-source emissions of cadmium in West Germany by a factor of more than six. Particularly, aqueous cadmium emissions actually caused by zinc refining, pigment manufacturing, and cadmium plating turned out to be substantially smaller than asserted in the ERL Report (1990).

Basically, there are three conclusions that can be drawn from our discussion of aqueous point source emissions:

- Because of substitution processes and improvements in emission control technologies caused by tightened legal regulations, aqueous cadmium emissions from industrial point sources in West Germany have decreased enormously over the last decade: In contrast to the beginning of the eighties, when point source emissions amounted to approximately 70 t/yr alone in the Rhine River Basin, emissions came down by 1988 to approximately 2.9 t/yr in the Rhine River Basin and approximately 4.2 t/yr all over West Germany. This implies that aqueous point source emissions decreased by a factor of more than 20 within a time span of less than ten years.
- The intentional use of cadmium as a productive input (plating, manufacturing of batteries, pigments, stabilizers) accounts for only 13 percent of the total aqueous point source emissions, whilst the remaining 87 percent are due to the inadvertent entry of cadmium into the production process. Within the latter category, there are three activities that cause more than 90 percent of emissions: iron and steel production

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[22] This number, which is not further broken down by sectors or activities, includes emissions from point sources and from diffuse sources.

(49 percent), secondary lead production (29 percent) and coke production (15 percent).

- The partition of emissions suggests that measures aimed at reducing aqueous point source emissions of cadmium should primarily try to come to grips with the problem of the inadvertent entry of cadmium into the production process. However, as it was shown in Section B.I, this problem is partially (and with a considerable time lag) caused by the use of cadmium as productive input.

2. Aqueous Emissions from Nonpoint Sources

Up to now, the discussion of aqueous cadmium emissions has concentrated exclusively on industrial point sources. This, however, is not the full story. As Stigliani (1990, p. 334) emphasizes, aqueous emissions from nonpoint sources are "*... a significant fraction of total emissions of environmental harmful chemicals, and it appears likely they will become even more important as industrial point sources are increasingly regulated.*" For instance in the case of the Rhine River Basin, it is estimated that in 1985 about 68 percent of the discharge of heavy metals and organic chemicals stemmed from nonpoint sources, and projections indicate that the share of nonpoint sources will increase to more than 80 percent by 1995 (Stigliani 1990, p. 333).

a. Estimating Nonpoint Emissions

From an empirical point of view, the most striking distinction between point sources and nonpoint sources is the fact that emissions from nonpoint sources are neither directly measurable nor can they be determined through the use of emission coefficients. Instead, aqueous cadmium emissions from nonpoint sources can only be computed as mathematical residuals of cadmium flows in rivers. Since this procedure involves the use of river-specific information (local cadmium load, characteristics of sedimentation process), it has to be carried out separately for each river under consideration. Usually, the following basic relationship is used to derive the annual emissions from nonpoint sources:

$$(1) \qquad L_2 = L_1 + (E_p + E_n) - S.$$

Here, L_1 and L_2 indicate the cadmium load (t/yr) of a river at two different monitoring stations numbered in downstream direction. E_p and E_n indicate point source and nonpoint source emissions that occur between the respective stations, and S indicates the annual amount of cadmium that accumulates in the riverbed between the monitoring stations through sedimentation processes. Equation (1) simply defines the change in load between two monitoring stations, which equals the sum of point source and nonpoint source emissions minus the amount of pollutants that is accumulated through sedimentation. Rearranging terms yields:

$$(2) \qquad E_n = (L_2 - L_1) - E_p + S.$$

According to (2), aqueous emissions from nonpoint sources can be computed as the residual of the change in load, point source emissions and sedimentation. However, there is one problem that, in most cases, impedes an empirical determination of this relationship. Because of the high complexity of the respective physical and chemical processes, adequate estimates of cadmium sedimentation in German rivers are not available. The only exception is the German part of the Rhine River, for which it is usually assumed that no sedimentation occurs (i.e., $S = 0$).[23] Hence, in this case there is no need to worry about sedimentation, and aqueous emissions from nonpoint sources can easily be computed as the residual from change in load and point source emissions.[24]

However, even in the absence of sedimentation, there remain two other sources of error in computing nonpoint emissions as a residual from the change in load and point source emissions: firstly, it cannot be ruled out that there may be unidentified emissions from unknown (perhaps illegal) point sources, and secondly, the assessment of the cadmium load itself may be in doubt due to methodological shortcomings or monitoring problems (see below). Moreover, in the case of the Rhine River there is the problem that this river is partly the border between Germany and France, i.e., there are emissions from both countries which would need to be distinguished.

Table 17 indicates the annual cadmium load (t/yr) of the major German rivers that discharge into the North Sea (Rhine River, Elbe River, Weser River and Ems River). The monitoring stations referred to in this table are selected in such a way that they show the change in cadmium load that occurs during the time in which the respective river passes through the German territory. Therefore, Table 17 contains the cadmium loads calculated for the first monitoring station after the river's entry to the German territory and the last

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[23] However, Elgersma et al. (1991, p. 30) point out that this assumption may not be completely valid for each period of time and each part of the German segment of the Rhine River.

[24] This specific advantage is one reason why empirical studies on aqueous emissions from nonpoint sources in Germany are generally limited to the Rhine River.

Table 17 — Cadmium Load of Major German Rivers Discharging to the North Sea, 1982, 1987, and 1989 (t/yr)

	Load at first station	Load at last station	Change in load
Rhine River	Weisweil	Kleve-Bimmen	
1982	6.3	50.5	44.2
1987	6.0	16.7	10.7
1989	3.2	9.5	6.3
Elbe River	Schnackenburg	Glückstadt	
1982	13.1	15.7	2.6
1987	16.0	11.5	–4.5
1989	16.8	8.5	–8.3
Weser River	Hemeln	Intschede	
1982	3.2	6.3	3.1
1987	2.5	3.2	0.7
1989	1.0	1.9	0.9
Ems River	—	Herbrum	
1982	0.0	0.8	0.8
1987	0.0	1.2	1.2
1989	0.0	0.5	0.5

Source: Own calculations based on: Deutsche Kommission zur Reinhaltung des Rheins (1983, 1988, 1990); Arbeitsgemeinschaft für die Reinhaltung der Elbe (1983, 1988a, 1988b, 1990); Arbeitsgemeinschaft der Länder zur Reinhaltung der Weser (1983, 1988, 1990); Niedersächsisches Wasseruntersuchungsamt (1983); Niedersächsisches Landesamt für Wasser und Abfall (1990).

monitoring station before the river leaves the German territory.[25] The figures strongly support the observation that annual cadmium emissions from industrial point sources have decreased enormously during the eighties. As a consequence, for all rivers shown in Table 17 the change in load between the first and the last monitoring station declined considerably.[26] However, this decline

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[25] In the case of the Elbe River, the first station (Schnackenburg) is located at the border to the former GDR and the last station (Glückstadt) is located at the tidal border. For the Ems River, no first station is specified since this river flows entirely through German territory.

[26] The only exception is the Ems River, where the cadmium load at the last station in 1987 considerably exceeds the load observed in 1982. This result, however, is due to measurement problems caused by a flood event in 1987. The negative change in load obtained for the Elbe River indicates that total emissions fall short of the

significantly falls short of the decline in point source emissions discussed in Section B.III.1. In particular, the change in load of the Rhine River only decreased by a factor of approximately 7 between 1982 and 1989 while point source emissions decreased by a factor of more than 20 (see Table 12). This difference indicates that aqueous cadmium emissions from nonpoint sources have not decreased as much as emissions from point sources did. However, any attempt to determine the magnitude of nonpoint source emissions to the Rhine River from the load figures in Table 17 is confronted with two methodological problems:

- The usual way to calculate a river's cadmium load is to measure the cadmium concentration (µg cadmium per litre) in its water and to multiply this figure by the throughput of water during the time period under consideration. In the case of the Rhine River, cadmium concentration and throughput of water are measured at intervals of two weeks. For the German monitoring stations Weisweil and Kleve-Bimmen the respective figures are published by the *Deutsche Kommission zur Reinhaltung des Rheins* (German Commission for the Protection of the Rhine River). The cadmium loads presented in Table 17 are calculated from these data by separately multiplying each concentration figure by the water throughput during the respective two-week interval.[27] However, because of the enormous decrease in emissions, which occurred during the eighties, the cadmium concentration at both monitoring stations began to drop below the limit of 0.3 µg/l, below which measurement errors are considered too large. In calculating the load figures of Table 17, a concentration of 0.15 µg/l was assumed for each period in which the concentration was below the verification limit. Because of this simplification, which is in accordance with the methodology applied by the *Deutsche Kommission zur Reinhaltung des Rheins,* the calculated load figures are likely not to fully reflect the true trend in cadmium emissions.
- The second problem is related to the fact that a part of the Rhine River constitutes the border between Germany and France (see Figure 3). Hence, there are emissions from both countries that have to be considered separately in calculating aqueous cadmium emissions from

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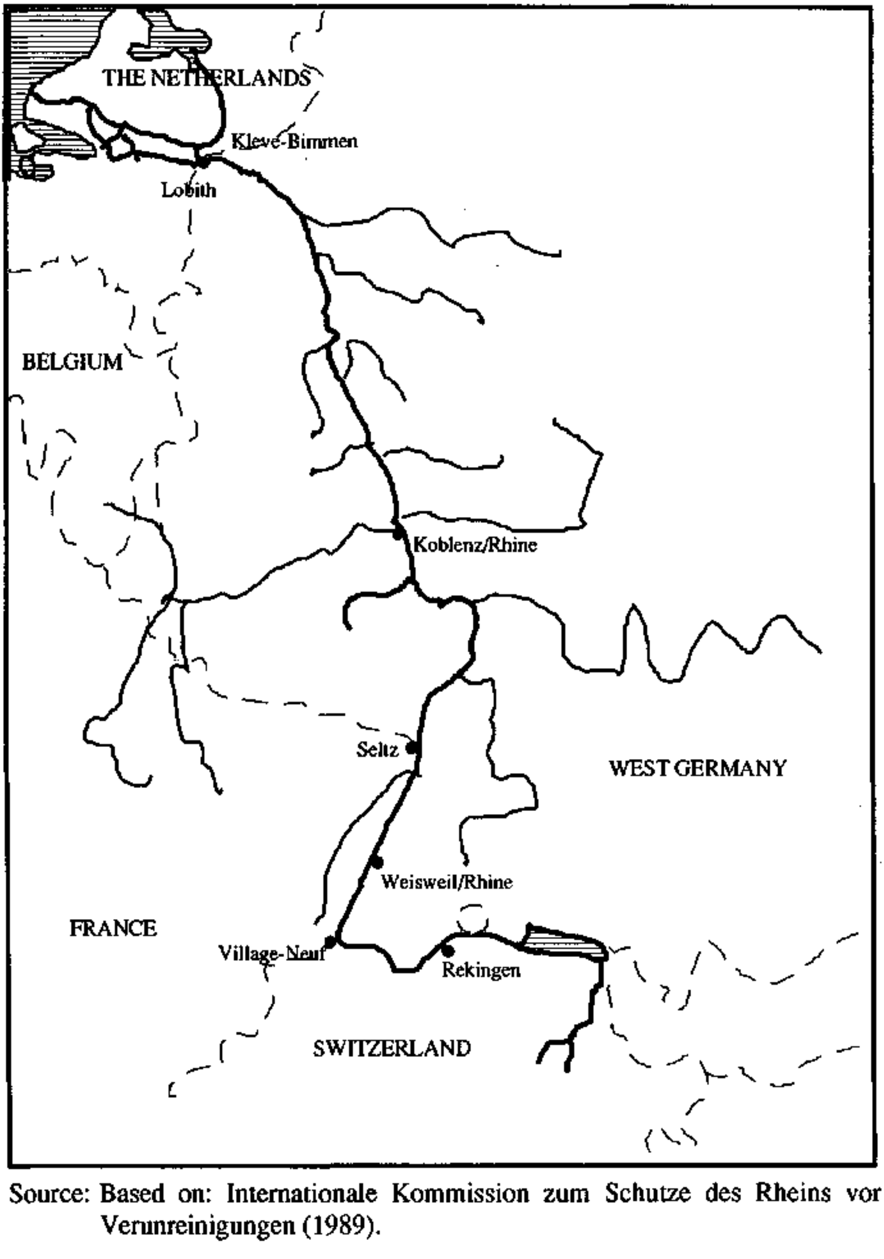
amount of cadmium that is accumulated in the riverbed as a result of sedimentation processes.

[27] To avoid confusion, it should be noted that this approach differs from the methodology used by the *Deutsche Kommission zur Reinhaltung des Rheins*, which merely multiplies the average annual cadmium concentration by the annual throughput of water. Therefore, the load figures published by the *Deutsche Kommission zur Reinhaltung des Rheins* differ from the figures presented in Table 17.

Figure 3 — Location of Water Quality Monitoring Stations at the Rhine River



Source: Based on: Internationale Kommission zum Schutze des Rheins vor Verunreinigungen (1989).

nonpoint sources from Germany alone. Such a differentiation, of course, is not possible on the base of the figures presented in Table 17.

Both problems can, at least in part, be resolved by applying monitoring data from French and Dutch stations. These data are published by the Internationale Kommission zum Schutze des Rheins gegen Verunreinigungen (1989), which is the head organization of the national commissions of France, Germany, and the Netherlands. The advantage of the concentration data obtained at French and Dutch monitoring stations comes from the fact that they are not subject to the restrictive German verification limit of 0.3 µg/l. The French and Dutch agencies report concentration data below 0.3 µg/l with an accuracy of two decimal digits. Of course, there are doubts about the reliability of the measurement of such small concentrations,[28] but because of the lack of higher quality data, the use of these data could yield more reliable aqueous nonpoint source emissions if the measurement errors during the many measurement periods are not too biased. Using the concentration and throughput data obtained at the monitoring stations Village-Neuf (France), Seltz (France) and Bimmen-Lobith (Germany/The Netherlands),[29] results in the load concentrations are presented in Table 18.

Table 18 — Absolute Cadmium Load and Change in Load of the Rhine River, 1988 (t/yr)

Monitoring station	Absolute load	Change in load
Village-Neuf	0.7	–
Seltz	12.9	12.2
Bimmen-Lobith	19.6	6.7

Source: Own calculations based on: Internationale Kommission zum Schutze des Rheins vor Verunreinigungen (1989).

Based on the location of the monitoring stations, the German part of the Rhine River can be subdivided into two segments that can be treated separately (see Figure 3): Along the first segment between Village-Neuf and Seltz, the

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[28] In particular, it is known that even under ideal laboratory conditions the monitoring of concentrations in the range of 0.3 µg/l is already subject to measurement errors of 20–30 percent.

[29] The concentrations at Bimmen-Lobith are averages of the figures obtained at the German monitoring station Kleve-Bimmen and the Dutch monitoring station Lobith (see Internationale Kommission zum Schutze des Rheins vor Verunreinigungen 1989).

Rhine River constitutes the border between France and Germany, whereas along the second segment between Seltz and Bimmen-Lobith, the Rhine River passes exclusively through German territory. Hence, the change in load between Village-Neuf and Seltz is due to French and German sources whilst the change in load between Seltz and Bimmen-Lobith is almost solely due to German sources.

Since there are no significant industrial activities in the German part of the Rhine River Basin between Village-Neuf and Seltz, it seems to be reasonable to assume that the change in load between these two monitoring stations — 12.2 t/yr — was predominantly due to point-source emissions from France, and to nonpoint source emissions from France and West Germany together. According to Elgersma et al. (1991), annual French point source emissions in the Rhine River Basin amounted to approximately 1.1–2.4 t in 1988 (see Table 12). This figure implies a difference between change in load and point source emissions of approximately 9.8–11.1 t, which may be interpreted as a rough guess of the approximate magnitude of nonpoint source emissions. Assuming that these emissions were equally distributed between France and Germany leads to the — even rougher — guess that there were approximately 4.9–5.6 t of aqueous cadmium emissions from German nonpoint sources between Village-Neuf and Seltz.

Concerning the second segment of the Rhine River between Seltz and Bimmen-Lobith, Table 18 indicates a change in load of about 6.7 t. Accounting for annual German point source emissions of about 2.9 t in 1988 (see Table 12) indicates that there were approximately 3.8 t of German nonpoint source emissions between Seltz and Bimmen-Lobith. This calculation, however, neglects 1.2 t Cd that were discharged into the Rhine River by the tributary Moselle near Koblenz (see Elgersma et al. 1991, p. 34). Since it is not clear which part of these 1.2 t were caused by French or German point or nonpoint sources,[30] we assume the most conservative outcome and guess that the German nonpoint source emissions between Seltz and Bimmen-Lobith amounted to (at least) 2.6 t Cd/yr.

Taking into account all the caveats and shortcomings of the data bases mentioned above, our "educated guess" is that total nonpoint source emissions in the German part of the Rhine River Basin amounted to about 7.5–8.2 t in 1988. Accounting for point source emissions of about 2.9 t, this implies a ratio

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[30] An important French point source of aqueous cadmium emissions to the Moselle is the iron and steel industry of Lorraine. However, because of a number of dams along the German part of the Moselle, it is likely that the major part of these emissions will accumulate in the riverbed before the junction of the Moselle and the Rhine River is reached.

between point and nonpoint source emissions of at least 1 : 2.5.[31] Assuming that this ratio was representative for West Germany as a whole and applying it to the data presented in Table 16 leads to a total of approximately 10.4 t of aqueous cadmium emissions from nonpoint sources in 1988. It should be born in mind, however, that this guess is more or less speculative, since it rests on several highly simplifying assumptions. Nevertheless, the message of these calculations is obvious: aqueous cadmium emissions from nonpoint sources considerably exceed emissions from point sources.

b. Sources of Nonpoint Emissions

Basically, there are four potential sources responsible for nonpoint aqueous cadmium emissions in West Germany:

- runoff from the use of cadmium-containing phosphate fertilizer,
- runoff from sewage sludge disposal in agricultural use,
- runoff from surfaced areas such as roads, houses, etc., and
- other sources like atmospheric fallout of cadmium to surface waters and erosion of cadmium-containing soils.

Although only sketchy information about the quantitative significance of these emission sources are available, we have compiled a reasonably consistent picture of the respective material flows.

Phosphate Fertilizer

For a long time, the dominating phosphate fertilizer in West German agriculture was Thomas phosphate, a by-product of the traditional iron and steel production. Because of the high temperatures of these processes, the cadmium that is originally contained in the phosphate is removed from it and emitted into the atmosphere or collected in dust arresters such that the basic slag is practically free of cadmium.

However, new processes for producing iron and steel have replaced the use of phosphate such that the supply of Thomas phosphate, as a cadmium-free fertilizer, which amounted to about 50 percent of phosphate fertilizer consumption in West Germany in the 1960s, was reduced to less than 10 percent in 1990/91 (see Table 19). Parallel to this development, the use of other, cadmium-containing phosphate fertilizers increased until the early 1970s and fell most pronounced in the 1980s. In sum, the overall input of fertilizers con-

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[31] This result is roughly in line with Stigliani (1990, p. 333), who asserts for 1985 that approximately 72 percent of cadmium emissions discharged to the Rhine River stemmed from nonpoint sources.

Table 19 — Production and Consumption of Phosphate Fertilizers in West Germany, 1955/56–1990/91 (1,000 t P_2O_5)

	Single nutrient fertilizers		N-P-K-fertilizers (compounds)	Total
	Thomas phosphate	other phosphates		
	Production			
1955/56	298.6	105.7	93.8	498.1
1960/61	41.2	510.8	215.9	767.9
1965/66	414.5	207.7	326.4	948.7
1970/71	317.7	179.3	448.8	945.8
1975/76	74.9	274.7	299.4	649.0
1980/81	153.7	204.7	328.3	686.7
1985/86	60.5	98.2	287.6	446.2
1990/91	–	–	–	–
	Consumption			
1955/56	291.9	70.9	116.3	479.1
1960/61	366.6	52.9	242.8	662.4
1965/66	400.5	45.0	387.8	833.2
1970/71	302.8	48.5	561.8	913.1
1975/76	176.8	73.2	529.7	779.7
1980/81	130.4	64.3	642.8	837.5
1985/86	49.3	76.4	611.2	736.8
1990/91	42.3	47.6	419.2	509.1

Source: Statistisches Bundesamt (1987b, 1991b).

taining cadmium fell even though their share in the total consumption of phosphate fertilizers rose (see Table 19). This reduction in the use of inorganic fertilizers stems from the downward trend in the prices of agricultural commodities, which lowered the derived demand for inputs and the increase in the planned use of nutrients in manures, i.e., the rational use of organic fertilizers (see International Fertilizer Industry Association 1988; Schindler 1986).

(i) Domestic Production and Import of Phosphate Fertilizers

Since raw phosphate and phosphate fertilizers from different locations have different cadmium contaminations, an assessment of the cadmium input into agriculture has to take into account the regional structure of imports of raw phosphate and phosphoric acids — the inputs in the production of fertilizer — and of phosphate fertilizers that are imported as finished products. Table 20 shows the regional structure of the West German imports of raw phosphate,

Table 20 — West German Imports of Raw Phosphates by Country of Origin, 1980–1988 (1,000 t)

	1980	1982	1984	1986	1988
Algeria	4	–	4	46	28
Benelux Countries	–	–	–	2	17
China	1	–	–	–	–
Israel	133	161	192	156	176
Jordan	–	–	–	37	3
Morocco	339	–	22	224	158
Senegal	91	–	–	56	–
South Africa	–	6	167	257	204
Syria	4	–	–	–	–
Togo	170	45	53	7	–
United States, Puerto Rico	1443	905	828	718	496
Soviet Union	387	–	–	20	75
Others	–	810	654	105	–
Total	2572	1927	1920	1572	1154

Source: United Nations (b).

which is processed in West Germany and turned into phosphate fertilizer. Since the different sources of supply correspond to different cadmium contents, the cadmium load of these imports can only be estimated with the help of the average concentration of cadmium in the raw phosphates. In Table 21 cadmium concentrations of different raw phosphates and of phosphoric acids are presented, which show that especially African supplies have relatively high concentrations. Most notably phosphoric acid but also raw phosphate from Senegal, Togo, and Tunisia have contributed significantly to the cadmium load. Therefore, West German producers of fertilizer have voluntarily restricted imports (see Becker 1989) in order to maintain reasonably low cadmium concentrations, as is evident from Table 20.

The import structure of raw phosphates only determines the final cadmium content of phosphate fertilizers produced in West Germany. However, because an increasing share of the demand for phosphate fertilizers is satisfied through imports of finished products, the total cadmium input from the use of fertilizer has to take into account the concentration of these imports as well. Table 22 makes evident the increasing importance of imported fertilizers, and the trend towards the use of compound fertilizers (N-P-K-fertilizers). The cadmium inflow through these imports is predominantly caused by the compound fer-

Table 21 — Phosphate and Cadmium Content of Raw Phosphates and Phosphoric Acids by Country of Origin

	Phosphate content	Cadmium content
	percent	ppm
	Raw Phosphates	
Algeria	100	17.0–23.0
Israel	100	18.4–28.7
Jordan	100	5.3–8.2
Morocco	100	12.2–15.3
South Africa	100	0.03–1.7
Syria	100	7.5
Togo	100	59.1–61.9
United States	100	7.0–9.0
Soviet Union	100	< 1.0
	Phosphoric Acids	
Florida	29.6	6
Morocco	56.0–57.8	15–24
North Carolina	51.0–54.0	30–36
Senegal	39.9	54–120
Togo	28.8–28.4	33–42

Source: Frankenfeld and Ruschke (1985); Böhm and Schäfers (1990).

Table 22 — West German Imports of Phosphatic Fertilizers, 1980/81–1989/90 (1,000 t P_2O_5)

	Total		Single nutrient	Compound fertilizers
	incl. Thomas phosphate	excl. Thomas phosphate	excl. Thomas phosphate	
1980/81	270.6	196.1	27.7	169.1
1981/82	277.3	228.1	14.9	213.1
1982/83	321.3	294.4	24.9	269.5
1983/84	354.9	299.3	30.2	269.1
1984/85	327.4	282.9	39.7	243.2
1985/86	397.7	385.0	46.5	311.5
1986/87	404.1	363.2	38.4	324.8
1987/88	451.0	408.7	29.0	379.7
1988/89	398.9	353.4	37.3	316.1
1989/90	398.3	365.9	33.4	332.5

Source: Statistisches Bundesamt (1987a); FAO (1991).

tilizers, since the imports of single nutrient phosphate fertilizer are dominated by Thomas phosphate, which is not contaminated with cadmium.

Unfortunately, it is not possible to determine the structure of West German imports of compound fertilizers by country of origin in terms of the amount of phosphate fertilizer, i.e., in t of P_2O_5. Only the total weight of the compound fertilizers is reported in the statistics, but the composition of the different components is not reported. Therefore, one can only assess in a rough calculation the likely cadmium concentrations of those imports. In order to estimate these loads, one has to know the cadmium concentration of the raw phosphates that the major suppliers of compound fertilizers to West Germany use in the production of these fertilizers. Table 23 summarizes the major ex-

Table 23 — West German Imports of Fertilizer by Country of Origin, 1987

	P–fertilizer	N-P-K-fertilizer	P-fertilizer	N-P-K-fertilizer
	1,000 t		percent	
Austria	–	158.6	–	8.6
Belgium-Luxembourg	422.5	229.0	69.5	12.5
Denmark	0.8	229.0	0.1	12.5
France	85.4	125.3	14.0	6.8
Great Britain	–	22.7	–	1.2
Hungary	–	85.5	–	4.7
Iraq	15.0	–	2.5	–
Israel	–	0.6	–	–
Italy	–	158.6	–	8.6
Jordan	–	1.0	–	0.05
Morocco	8.3	–	1.4	–
Netherlands	36.0	270.6	5.9	14.8
Norway	–	18.1	–	1.0
Poland	–	10.7	–	0.6
Portugal	–	12.8	–	0.7
Rumania	–	50.7	–	2.8
South Africa	–	0.1	–	–
Spain	–	9.8	–	0.5
Sweden	–	13.9	–	0.8
Switzerland	–	2.0	–	0.1
Tunisia	39.0	17.5	6.4	0.9
Turkey	–	19.6	–	1.1
United States	–	264.0	–	14.4
Yugoslavia	–	131.5	–	7.2
Total	608.0	1,834.0	100.0[a]	100.0[a]

[a] Errors due to rounding.

Source: United Nations (b).

porters through which West German consumption is served. The largest suppliers of compound fertilizers are the Benelux countries, the United States, and Denmark. Single nutrient phosphate fertilizer imports are dominated by Belgium and Luxembourg, for which one can suspect that a large proportion of those imports consists of Thomas phosphates from the Belgian steel industry, i.e., without cadmium.

The raw phosphate sourcing of these exporters is clear for the United States, which have their own phosphate ore deposits with low cadmium contents for phosphates from Florida and higher for those from North-Carolina (see Table 21). Since the shares of the two sources are unknown, one cannot deduct the likely cadmium concentrations of the fertilizer. Still, it is clear that they will be lower than those from other suppliers. The raw phosphate imports of the other major suppliers of compound fertilizers are summarized in Table 24. These countries buy their inputs predominantly from Morocco, the United States, and to a lesser extent from South Africa. Since all these supplies of raw phosphates have relatively low cadmium contents, the average cadmium content of the single nutrient and compound fertilizer imports of West Germany will probably not deviate significantly from the domestically produced fertilizers. The only supplier with somewhat higher cadmium concentrations is France, which still imports highly contaminated raw phosphates from Tunisia, Togo, and Senegal.

(ii) Total Inflow of Cadmium through Phosphate Fertilizers

Agricultural land becomes polluted with cadmium as result of the use of phosphate fertilizers; its subsequent diffusion throughout the soil depends, among other things, on the quantity used and on the concentration of cadmium in the fertilizer. The latter is not only influenced by the regional source of the raw material, it also depends on the processing of the raw phosphates, in particular whether any processes for the removal of cadmium are applied. An earlier study by the Umweltbundesamt (1981) has estimated an annual inflow of cadmium through phosphate fertilizers of about 65–70 t in the seventies.

Phosphate fertilizer is produced from raw phosphate, which through grinding and chemical processes is converted into phosphoric acid. This, in turn, is the basic material for most of the different kinds of phosphate fertilizers (see Fayard 1988). During this process waste materials, mainly gypsum, are removed such that the cadmium content of the phosphoric acid is higher than that of the phosphate ore (see Table 21). Depending on the process technique for producing phosphoric acid, the waste materials contain 20–50 percent of the cadmium (see Elgersma et al. 1991) such that it is practically impossible to deduct from the cadmium content of the raw material its exact concentration in the fertilizer.

Table 24 — Major Exporters of Fertilizers to Germany and the Countries from Which They Obtain Raw Phosphates, 1987 (t)

	Netherlands	Belgium-Luxembourg	Denmark	Italy	Austria	Yugoslavia	France	Cadmium content (ppm)[a]
Share of German fertilizer imports (percent)	14.8	12.5	12.5	8.6	8.6	7.2	6.8	x
Total imports of raw phosphates[b]	2,213	2,522	228	578	271	1,374	3,755	x
Algeria	26	4	13.1	–	–	47	208	~20
Israel	515	–	–	–	–	–	959	~23
Jordan	–	10	–	–	–	365	18	~6
Morocco	615	1,589	124	–	–	530	851	13–22
Senegal	–	9	–	–	–	82	212	60–120
South Africa	171	354	67.3	–	–	–	13	1–3
Syria	–	–	–	–	–	183	163	8
Togo	181	25	–	–	–	128	266	~65
Tunisia	–	43	–	–	–	–	194	> 30
United States	695	362	–	–	–	5	857	~6
Others	–	–	12.5	–	–	19.5	11	.

[a] Average cadmium content of raw phosphates. — [b] SITC 271.3.

Source: United Nations (b); Tables 21 and 23.

Without considering any removal activities, the inflow of cadmium through imports of raw phosphates fell throughout the eighties. Given the import data and the average concentrations by country of origin, we estimate that in 1980 about 38 t Cd entered West Germany through imports. By 1988 this amount was reduced to about 11 t (see Table 25). The overall reduction of raw phosphate imports and the elimination of mainly African imports with high cadmium contents are responsible for this reduction of cadmium flows from domestically produced fertilizers.

Table 25 — Cadmium Inflow through Imports of Raw Phosphates in West Germany, 1980–1988 (kg Cd)

	Average cadmium content (ppm)	1980	1981	1982	1983	1984	1985	1986	1987	1988
Algeria	20	80	–	–	–	80	440	920	1,020	560
Israel	23	3,059	2,369	3,703	3,841	4,416	4,025	3,588	3,611	4,048
Jordan	7	–	–	–	21	–	70	259	21	21
Morocco	16	5,424	7,424	–	–	352	192	3,584	4,832	2,528
Senegal	75	6,825	–	–	–	–	4,200	–	–	–
Soviet Union	0.5	179	194	–	–	–	–	10	–	38
South Africa	2	–	128	12	122	334	400	514	380	408
Syria	8	28	152	–	–	–	–	–	–	–
Togo	62	10,540	5,704	2,790	1,798	3,286	868	434	992	–
Tunisia	30	–	–	–	480	240	–	120	–	–
United States, Puerto Rico	8	11,544	656	7,240	7,512	6,624	6,784	5,744	4,904	3,968
Unidentified	5[a]	–	–	4,050	4,066	3,230	3,015	505	440	–
Total		37,679	24,627	17,795	17,840	18,562	19,994	15,678	16,200	11,163

[a] Cadmium content set to 5 ppm. Most of the imports are probably from the Soviet Union.

Source: Computed from United Nations (a, b) and Tables 9 and 10 as imports weighted by average cadmium contents.

Since only about 34 percent of the West German consumption of phosphate fertilizer is domestically produced, the cadmium load of phosphate fertilizers in West Germany is to a large extent determined by the cadmium contamination of imported fertilizers. 90 percent of the imports are compound fertilizers, and the remaining single nutrient fertilizers consist to a large extent of Thomas phosphates (see Tables 22 and 23). Therefore, it is mainly the cadmium content of the compound fertilizer imports that may contribute to the inflow of cadmium into West Germany. It has been shown above that the cadmium load of the West German compound fertilizer imports is likely to be similar to that of the domestically produced fertilizer. If we extrapolate the cadmium load through the West German supplies to that of the net imports, then the total input of cadmium into West Germany through fertilizers should amount to approximately 32 t/yr.[32]

Sewage Sludge

An important input of toxic materials to agricultural soils comes from the application of sewage sludge. It is hardly possible, however, to determine how much of it is actually applied in a specific area. The amount of raw sludge produced in West Germany in 1987 was approximately 85 million m^3, i.e., about 4 million t of dry substance.

Table 26 shows the amounts of sludge produced by the various sectors. Unfortunately, the use of this raw sludge is not well documented. The fate of industrial sewage sludge is practically unknown. Loll (1989) estimates for sewage sludge from public facilities that 19 percent of the 50 million m^3 raw sludge are used in the agricultural sector (see Figure 4). This would amount to 667,000 t of dry substance per year. Whether industrial sewage sludge is also used in agriculture seems to be unknown. Since these sludges usually have higher metal concentrations, it is more likely that the bulk of sludge used in agriculture comes from the public wastewater treatment facilities.

Table 26 — Production of Raw Sewage Sludge in West Germany, 1987

	Volume	Weight
	million m^3	million t dry substance
Public sewage treatment	51.7	2.4
Mining industry	10.5	0.5
Manufacturing	22.7	1.1

Source: Sachverständigenrat für Umweltfragen (1990).

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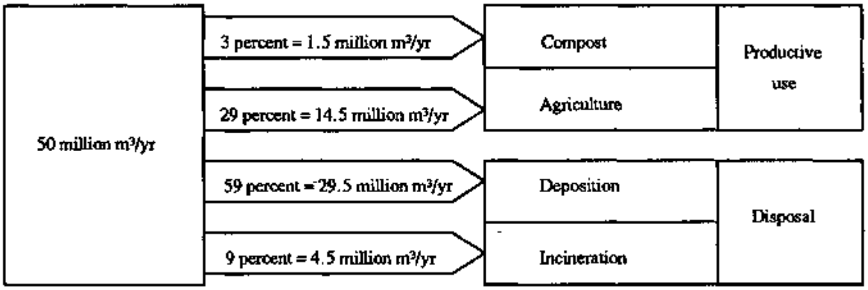
[32] This is significantly less than the quantities of 48.8 t/yr that are estimated by Böhm and Schäfers (1990), who have based their figure on rather high average cadmium contents of the raw phosphates.

Figure 4 — Productive Use and Disposal of Sewage Sludge from Municipal Wastewater Treatment Plants, 1985



Source: Loll (1989).

The application of sewage sludge to agricultural soils is regulated by the Ordinance on Sewage Sludge (*Klärschlammverordnung*) of 1982. It controls the maximum allowable concentration of heavy metals in the sewage sludge, their maximum allowable concentration in the soil, and the total amount of sludge that can be applied to the land. Not more than 20 mg Cd/kg are permitted in sewage sludge; and the sludge may only be applied to soils with less than 3 mg Cd/kg. This has the consequence that sewage sludge may not be used near urban areas and close to industrial centers, since these soils already show a contamination of cadmium beyond the permitted level. In addition, not more than 5 t/ha of sewage sludge may be applied over a three-year period.

Unfortunately, it is unknown how much sewage sludge is applied on a specific area. Therefore, one can only give a rough indication of the possible ranges of cadmium depositions through an orderly use of sewage sludge in agriculture. A survey of 7,400 samples of sewage sludge has revealed that the average concentration of cadmium in sewage sludge amounts to about 4 mg Cd/kg (see Scheffer and Schachtschabel 1989). Given this average concentration, a farmer who uses the allowed 5 t/ha in a three-year period could at most add about 7 g Cd/ha to his soil per year. The maximum amount would come to 33 g Cd/ha if the legal limit of 20 mg Cd/kg in the sludge were to be reached. The overall load of cadmium on agricultural soils through the application of sewage sludge can be estimated to amount to not more than 2.3 t/yr (see Böhm and Schäfers 1990).[33]

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[33] In contrast to this figure, which is based on monitoring data concerning the sewage sludge's cadmium concentration, the authors of the ERL Report (1990, p. 32) claim that the cadmium load due to the application of sewage sludge amounts to 19.7 t.

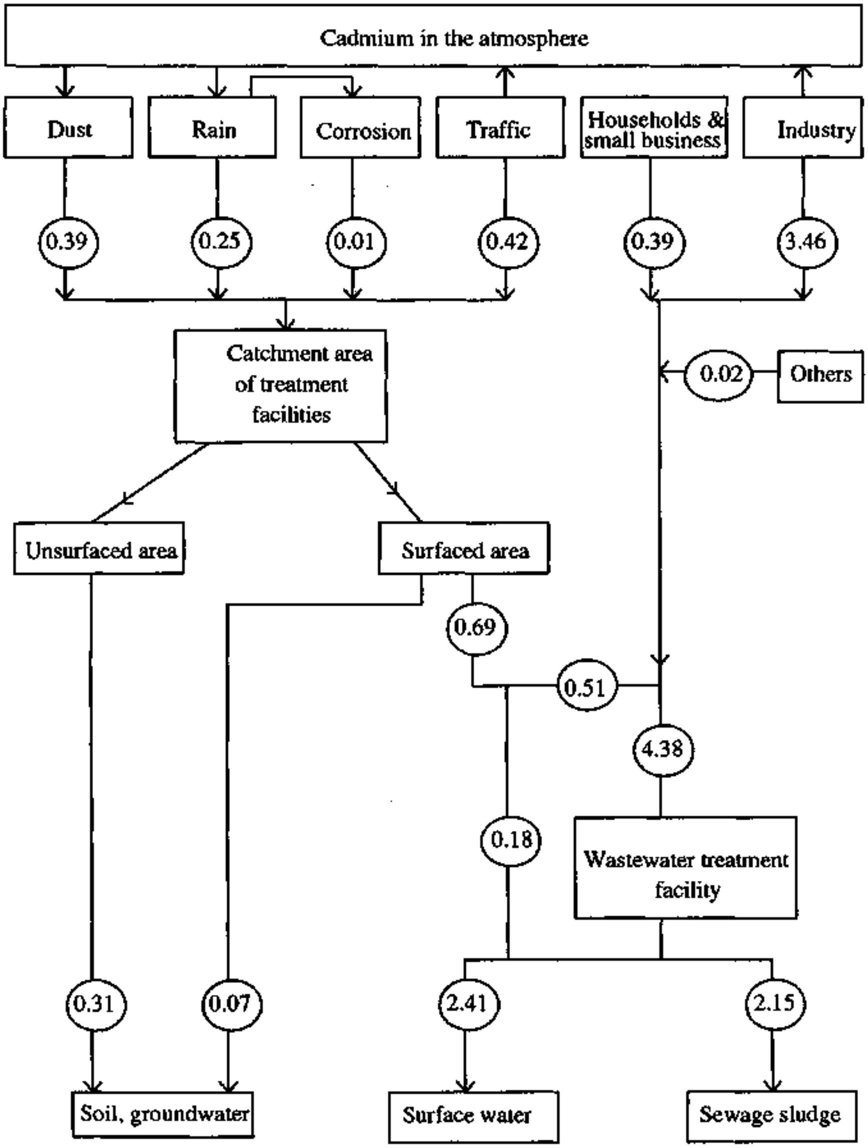
The environmental effects of adding sewage sludge to agricultural soils is, however, not as straightforward as one might expect. There is no one-to-one correspondence between the cadmium load and the environmental effects — be it the contamination of agricultural products or the further transport of cadmium into other media. Sewage sludge adds organic material that is able to accumulate some of the heavy metals and to contain it tightly in its molecular structure. It has been found that the cadmium content of crops even falls after the application of sewage sludge because of this process of absorption (see Feuereissen 1986). Since sewage sludge is slightly basic, it raises the pH of the soil, and this reduces the uptake of cadmium (and zinc) by the different crops (Feuereissen 1986). These effects slow down the potential health threat of cadmium contamination in food, and at the same time, the rise of the pH also reduces the washout of cadmium (see also Section B.IV).

The cadmium contamination of agricultural soils through the application of sewage sludge can be reduced either through the replacement of sewage sludge by other fertilizers or by reducing the cadmium load of the sewage sludge inside the treatment facility. This would, however, amount to reducing the fallout of dissolved cadmium in the treated water, thereby increasing the cadmium load of the water discharged into the rivers. Finally, measures could be taken that limit the cadmium content in the wastewater entering the treatment facilities in which the sewage sludge is produced. This option would require, firstly, an identification of the sources of cadmium in the wastewater stream and, secondly, the investigation of technically feasible and economically rational strategies for reducing the emissions at the respective sources.

For the state of Hesse, the material flow of cadmium in the water and in particular into the wastewater treatment facilities has been estimated (Nolte 1989). Figure 5 summarizes the quantities of cadmium that were transported by the different water flows for the state of Hesse in the early eighties, and it identifies the sources from which the cadmium entered wastewater and runoff. However, these sources do not include those industrial wastewaters that are treated in industrial water treatment facilities. It becomes clear that the diffuse inputs into the runoff from the deposition of dust, from rain, corrosion, and from traffic contributed comparatively little to the cadmium load of wastewaters. Of the total deposition of about 1 t Cd/yr from these sources, somewhat less than one third entered soils and the groundwater directly, whereas the rest was collected and treated in wastewater treatment facilities. The major contribution to the cadmium load in these treatment facilities, however, came from industrial wastewaters, which amounted to 3.46 t Cd/yr.

Nolte's (1989) estimates are derived from the emission data for the early eighties and would — if they were extrapolated — result in rather high emissions of cadmium for West Germany. This may be true for the early

Figure 5 — Sources of Cadmium in Wastewater, Situation as of the Early 1980s (t Cd/yr)



Source: Nolte (1989).

eighties. However, on the one hand, since that period emissions have been drastically reduced (see Section B.III.1) and, therefore, the absolute size of the figures in Figure 5 is most likely too high for the present. The composition of the emissions, on the other hand, may not have changed as much, so that the relative contributions from the different sources may still be reliable.

The cadmium in the sewage sludge originates to about 80 percent from industrial wastewaters, to about 9 percent from household and small business wastewaters, and to roughly 11 percent from those flows of nonpoint sources that are caught in the public sewer systems from surfaced areas such as roads, houses, etc. Those inputs of cadmium are then approximately equally divided between treated water flows entering rivers and lakes and sewage sludge, which is partly deposited in landfills or on agricultural soils.

Atmospheric Fallout to Surface Waters

According to Böhm and Schäfers (1990, p. 4) the annual atmospheric cadmium deposition over West German territory amounts to approximately 1 kg/km^2 on average. Accounting for an area covered by the West German part of the Rhine River Basin of approximately 102,000 km^2 (including tributaries), this deposition rate indicates that there may be an annual fallout of about 102 t Cd over this area. This number clearly contradicts all estimates about airborne cadmium emissions in West Germany (see Section B.II). The highest estimate of the Umweltbundesamt (1991) amounts to about 60 t/year for West Germany, i.e., at most half of the estimate of Böhm and Schäfers (1990). Although it may be possible that Böhm and Schäfers include airborne transfrontier transports of cadmium, we still have little confidence in their estimate. It seems more reasonable to use the magnitude of emissions of between 25 and 60 t/year in the early eighties. How much they contribute to diffuse water pollution is not clear, since there is no information at all about how much of this amount remains in the ground and how much leads to an increase in the Rhine River's cadmium load. It can, however, not be ignored that the atmospheric deposition contributes significantly to aqueous cadmium emissions from nonpoint sources. Hence, measures aiming at reducing aqueous cadmium emissions from nonpoint sources should primarily concentrate on reducing emission into the air and on reducing the input of cadmium caused by the use of phosphate fertilizers.

Transport of Cadmium through Erosion

One possible source of aqueous nonpoint emissions has not been mentioned so far: the transport of contaminated soils through erosion. Without doubt, soil erosion leads to a relocation of large amounts of material. Most of this material is most likely only relocated locally, e.g., downhill into the valleys, but some material is also washed out into rivers. It is quite likely that this erosion is responsible for a considerable part of the cadmium load of rivers and for the accumulation in the bed of a valley. The total quantity of eroded soil has only been estimated for the state of Bavaria, with about 14 million t/yr (see Umweltbundesamt 1990). For the whole of West Germany, no figures are available. If we would take the lowest cadmium concentration of agricultural soils, i.e., 0.1 mg/kg, a total of 1.4 t Cd would be relocated in Bavaria alone every year. If we assume an average soil loss of 13–16 t/ha (see Scheffer and Schachtschabel et al. 1989), then the total loss in West Germany on agricultural soils would amount to 176–217 million t/yr, i.e., to a cadmium relocation of approximately 18–22 t Cd/yr. How much of this amount would end up in rivers that transport it towards the ocean can hardly be assessed.

The amount of dredged material in the major rivers can give a very rough indication of the dimensions that may be involved in this transport. In the mid-eighties in West Germany, dredgings amounted to about 40 million m^3/yr (see Sachverständigenrat für Umweltfragen 1990). For the seventies, cadmium concentrations in sediments are reported with values between 1.5 and 40 ppm (dry substance) (see Sachverständigenrat für Umweltfragen 1990), but since the yearly cadmium loads have been drastically reduced in the last two decades, these values are probably much lower today. In the Elbe, the Weser, and the Ems, cadmium concentrations in the sediment varied between 1 and 4 ppm (dry substance) in 1987 (see Nordsee 1989) and around 3 ppm in the Rhine at the Dutch border (see Sachverständigenrat für Umweltfragen 1990). If we assume an average cadmium concentration of 2 ppm in the dredged material, then roughly 10 t/Cd are dredged every year.

Unfortunately, these 10 t Cd/yr cannot indicate the loads that are transported very well. First of all, one misses the sediment transport in rivers that leave West Germany. Secondly, 88 percent of the dredged material is again dumped into the rivers at different locations (see Sachverständigenrat für Umweltfragen 1990) such that it is not clear whether it may be dredged again in a later period or whether it is transported away. Nevertheless, the dimension of the cadmium load in the sediment together with the likely quantities of eroded soils indicate that a considerable part of the unidentified cadmium transport in rivers, which have been mentioned above, may come from eroded material. This, of course, would mean that there is little potential for reducing these aqueous cadmium loads besides measures to prevent soil erosion.

IV. From Emissions to (Final) Deposition: The Fate of Cadmium

Cadmium emitted through human activities creates an environmental problem only if the cadmium accumulations exceed the natural background content. To reduce or prevent environmental damages or health hazards, it is important to trace the flow of cadmium from the emission source down to its final deposition in the environment.

1. Total Deposition

The previous discussion on cadmium depositions through phosphate fertilizers, sewage sludge, and airborne emissions has already revealed how complex and diverse the processes are that determine the deposition of cadmium and its accumulation in the soil. For the overall deposition of cadmium on soils, we have ignored a last factor so far, which contributes large amounts of cadmium to the soil, but only in well defined locations: From the total cadmium flow in the economy the dominating part is incorporated in products (see Section B.I), which eventually are turned into municipal waste. An estimate of Böhm and Schäfers (1990) indicates that from a total of 300 t/Cd in municipal waste about two thirds are deposited in landfills, whereas the rest is incinerated. In addition, the unintentional use of cadmium produces industrial waste such as rubble and slack that is usually deposited in landfills. However, in many cases these activities produce little or no harmful environmental effects — e.g., cadmium in plastic products is tightly bound and cannot be dissolved and washed out — and even if there is a chance for contamination it is of a local nature. In the following, we will ignore the cadmium loads of landfills.

None of the three sources that cause cadmium contamination of the soils (phosphate fertilizers, sewage sludge, and airborne emissions) do so in a fashion that would result in this contamination being spread evenly throughout the environment. It is therefore impossible to predict the cadmium load that is deposited on a particular area. We can only characterize ranges of likely quantities of deposition from the various sources on characteristic areas. Table 27 distinguishes five typical areas that correspond to different types of deposition of cadmium.

Table 27 — Annual Cadmium Deposition on Different Types of Areas, Estimates for the Situation as of the Early 1980s (g/ha/yr)

Type of area	Deposition
(1) Rural areas without use of sewage sludge or phosphate fertilizer	1 – 2
(2) Rural areas with use of sewage sludge	up to 10
(3) Rural areas with use of phosphate fertilizer	3 – 7
(4) Rural areas with use of phosphate fertilizer and sewage sludge	9 – 13
(5) Industrial and urban areas	up to 35

Source: Scheffer and Schachtschabel et al. (1989); Schindler (1986); Filipinski (1992b); own calculations.

In category (1), only nonpoint cadmium depositions from airborne emissions can be added to the already existing stock of cadmium in the soil. Such depositions are measured to be in the range of 1.5–3 g Cd/ha/yr in rural areas in the early eighties (see Scheffer and Schachtschabel et al. 1989). Given the West German emissions of cadmium amounting to between 26 and 59 t/yr in the comparable time period, of the deposition of 1.5–3 g Cd/ha/yr only about two thirds would come from West German sources. If we would extrapolate this relationship to the emission situation of today, then the deposition of cadmium from West German sources would be around 0.5–1.0 g Cd/ha and the overall load would be 1.0–2.0 g Cd/ha, i.e., by about 30 percent less than in the early eighties. This estimated share of West German emissions is still strongly overestimated because a nonnegligible part of the emissions are in urban areas, where depositions are up to ten times higher than in rural areas.

The pattern of deposition varies due to atmospheric conditions and the location of emitting sources. Since the cadmium in airborne emissions is bound on dust particles, we can expect a correlation between the geographical distribution of the deposition of dust and the pattern of the cadmium load. Regions with larger dust deposition are the eastern border of West Germany (mainly because of the atmospheric import from the former GDR and Czechoslovakia), North Rhine-Westphalia (because of its high concentration of metal industries) and the Rhine-Main area (see Umweltbundesamt 1989). The rural eastern border regions probably import significant amounts of cadmium. In the urban areas with a large agglomeration of industries, the depositions can go up to 35 g Cd/ha/yr and even higher to 40–100 g Cd/ha/yr if there are metal industries in the vicinity. Other rural regions, however, may have negligible amounts of airborne cadmium depositions. This variability of the atmospheric transport of cadmium emissions into the air causes a large variation of depositions on otherwise undisturbed land, as it is defined in category (1).

If sewage sludge is used in these rural areas, the atmospheric deposition of cadmium together with the contamination of the sludge determine the cadmium concentration of the soil (category (2)). The additional load depends on the frequency and intensity of the use of sewage sludge and its cadmium contents. Therefore, we can only compute the possible maximum load of cadmium that one could add to the airborne deposition. Given an average concentration of 4 mg Cd/kg in sewage sludge, a farmer can — according to the *Klärschlammverordnung* —add no more than 7 g Cd/ha to the soil (see Section B.III.2.b). Consequently, the cadmium load in rural areas with the use of sewage sludge can be at most 8–9 g Cd/ha. It is probably much lower in most cases, however, since farmers may only infrequently use sewage sludge, its cadmium content is usually below the maximum concentration, and farmers may willingly stay below the legal limits of cadmium contents in the soil.

Category (3) concerns rural areas with a deposition of cadmium through the use of phosphate fertilizers only. It has been shown that the quantity of cadmium contained in those fertilizers that are consumed in West Germany amounts to about 32 t/yr (see Section B.III.2.b). Statistically this would result in a deposition of less than 2.5 g Cd/ha/yr on soils in agricultural use. The actual deposition on a specific area, however, mainly depends on the type of crop grown and on the specific cadmium content of the fertilizer. Nothing is known about variations in the cadmium content of phosphate fertilizer, but the fertilizer industry has promised to remain below 40 mg Cd/kg P_2O_5. Average phosphate use in agriculture often varies between 40–100 kg P_2O_5/ha (see Schindler 1986) so that the actual cadmium load is at most 1.6–4 g Cd/ha/yr, thus resulting in an overall yearly load on such agricultural land of 2.6–7 g Cd/ha.

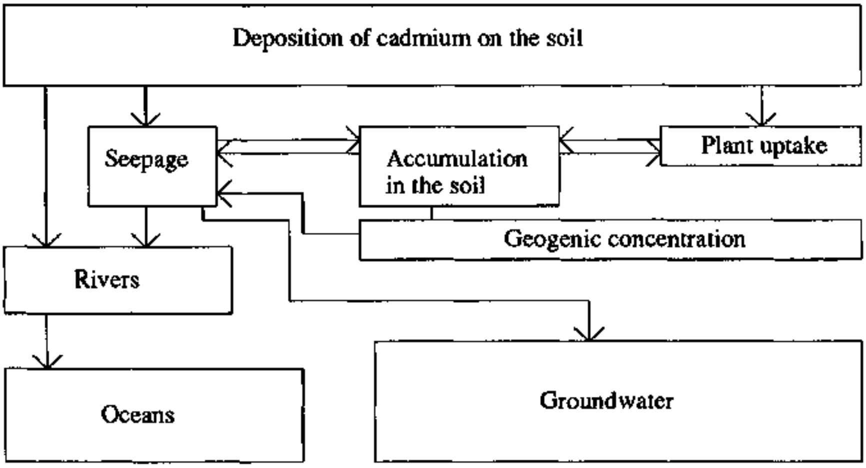
Category (4) concerns the cadmium deposition through the combined use of sewage sludge and fertilizer. Sewage sludge is applied mainly for adding organic substances to the soil (see Filipinski 1992b), but it also carries nutrients, so that the use of minerals can be reduced somewhat. Since the nutrient content of sewage sludge varies widely, these savings can hardly be predicted. However, a combined use of both is likely. The overall yearly load of cadmium to those soils could then be as high as 9–13 g Cd/ha.

The cadmium deposition in urban and industrial areas (category (5)) can mainly be attributed to three sources. There is the deposition of the long-range transport of dust contaminated with cadmium, which is probably quite low. Then there is the deposition of locally emitted cadmium from traffic and from heating (i.e., coal fired small scale heating systems). Those two sources seem to contribute significantly to the measured depositions of up to 35 g Cd/ha/yr in urban areas (see Scheffer and Schachtschabel et al. 1989). On agricultural land, which in urban areas is often used for horticultures, one would have to add depositions from phosphate fertilizers. These loads may also be significant because the fertilizer dosage in horticulture is relatively high, thus adding up to 4 g Cd/ha/yr to the atmospheric deposition. Sewage sludge cannot be applied in those areas, since the *Klärschlammverordnung* prohibits its use on contaminated soils. Category (5) represents areas in which the cadmium content of soils can at present — and could increasingly so in the future — become a serious problem for agriculture and possibly for outdoor recreation.

2. Cadmium Dynamics in the Soil

In the previous sections, the different paths have been described through which cadmium is transported before it becomes deposited in the soil. However, the soil is not necessarily the final medium for cadmium. It can proceed from there into rivers, lakes, or groundwater, and, finally, the oceans, and it can be taken up by plants (Figure 6). The processes that determine this cadmium transport are complex, and it is intended in this section only to indicate in which direction and in which relationship the transport is likely to take place and what the most important factors influencing this transport may be.

Figure 6 — Transport of Cadmium in the Soil



Source: Klepper and Mahlau (1992).

The chemical and physical processes determining these transports are presented here in a grossly simplified fashion. The major factors determining the fate of cadmium in the soil are the concentration of cadmium in the soil, the composition of various components of the soil, the pH of the soil, and the electrolytic conditions. These factors determine whether cadmium is either securely stored in the soil, or adsorbed to specific materials but with the potential for becoming subject to desorption processes (exchangeable phase), or whether it is in a solvent phase (see Förstner 1992; Peters 1990). Since cadmium only becomes a potential threat if it is available for plants or can be washed out, the factors that determine the amount of cadmium in the solvent and in the exchangeable phase are of particular importance. Among the factors influencing adsorption and desorption processes between dissolved and exchangeable cadmium, the pH turned out to be the most important one (see Herms 1989; Peters 1990).

The total contamination of soils with cadmium at a particular point in time is the result of several processes: the accumulation through historical depositions, the natural background load of cadmium, and the soil conditions, which in turn determine adsorption and desorption processes over time. Therefore, the current depositions do not reflect the overall contamination of particular soils and regions, and even a simple adding up of historical depositions would be inaccurate. The cadmium content of soils, as a result of these historical processes, varies widely: Scheffer and Schachtschabel et al. (1989) report an average content of 0.1 mg/kg, which can in specific areas go up to 3 mg/kg. Anthropogenic emissions have led to contents of up to 200 mg/kg in an area where centuries of ore mining have resulted in dangerously toxic concentrations. The usual concentration, however, is about 40 mg/kg in the vicinity of cadmium emitting factories, around 3 mg/kg right at congested roads, and between 0.5 and 5 mg/kg in city parks and gardens. In rural areas, the cadmium contents of soils vary around 0.1 mg/kg, so that the anthropogenic contribution can hardly be distinguished from the background load. However, since cadmium is still deposited thus leading to a doubling of the concentration of 0.1 mg/kg over a period of 20–40 years, policy measures are still needed in order to avoid a long-term effect on as yet practically clean soils. In addition, even such low cadmium concentrations may under specific circumstances create environmental problems, which will be discussed below.

As long as cadmium is bound to particles, it is unlikely to create environmental damages, but in the solvent phase it can be accumulated in plants or washed out. The share of cadmium in the solvent phase depends on a number of factors. One factor is the concentration of cadmium in the soil. This is important, since in soils with given characteristics the distribution of cadmium in the adsorbed phase, relative to the solvent phase, varies with the total cadmium content. With an increasing cadmium load, the concentration of the cadmium in the solution increases overproportionately, i.e., the potential threat to the water and to plants increases exponentially with the cadmium concentration (see De Haan and van Riemsdijk 1989). In addition, the anthropogenic cadmium is often supplied in a solvent phase or, if it enters the soil as a dry deposition, can change into the solvent phase more easily than geogenic cadmium (see Sauerbeck 1986; Miehlich and Gröngröft 1989; Golwer 1989). According to Filipinksi (1992a), the solubility of anthropogenic cadmium is twice as high as that of geogenic cadmium.

One of the decisive factors determining the mobility of cadmium in the soil is the pH. Whereas other heavy metals are less sensitive to a decline in the pH, the sorption capacity of cadmium decreases strongly when the pH falls below 4.5 (see DVWK 1988; Herms 1991). For a pH between 4 and 7.7, it was found that the sorption capacity increases two to three times with a one point increase in the pH (see Jensen and Bro-Rasmussen 1992). A pH of 4.5 seems to represent the critical level beyond which cadmium is increasingly dissolved. Sauerbeck (1985) even speaks of an exponential relationship between dissolved cadmium and a pH below 4.5.

The mobility of cadmium ions, i.e., their movement with the water through the soil, also depends on the cation exchange capacity of the soil, which varies directly not only with the amounts of clay and organic matter but also with the pH (see Scheffer and Schachtschabel et al. 1989; Deutscher Verband für Wasserwirtschaft und Kulturbau 1988). Another way through which the distribution of cadmium between the solid phase, the plant uptake and the seepage is influenced, is the inflow of chlorides into the soil. The adsorption of cadmium decreases with increasing cadmium-chloride complexation, and these stable complexes are water-soluble (see De Haan and van Riemsdijk 1989), so that they are easily washed out.

All these interacting factors determine the composition of cadmium between the solid and solvent phase, and therefore, its further transport through the soil, either from the upper soil downward and eventually into the groundwater or into the plants. A calculation of De Haan and van Riemsdijk (1989) shows that a particular cadmium concentration in the solvent phase, i.e., the potential washout, can be achieved through widely varying cadmium concentrations in the soil depending on the soil conditions (see Table 28). For example, the EC standard for drinking water of 5 mg/l can be met in some soils only with cadmium concentrations far below the natural background contamination of 0.1 mg/kg whereas in heavily polluted soils but with favorable conditions this goal can be easily met. Apparently, the fate of cadmium in the soil and its potential environmental threat either through plant uptake or through washout and transport into the groundwater or rivers and lakes depends much more on the soil conditions than on the cadmium concentration in the soil.

Table 28 — Calculated Cadmium Content in the Soil as a Function of Soil Properties and Dissolved Cadmium (ppm)

Index of soil properties	Measured cadmium concentration in soil solution			
	1.5 mg/l	2.5 mg/l	5 mg/l	10 mg/l
0.001	0.001	0.002	0.004	0.006
0.01	0.01	0.02	0.04	0.06
0.1	0.1	0.2	0.4	0.6
0.3	0.4	0.6	1.1	1.9
0.5	0.7	1.0	1.8	3.2
0.9	1.2	1.9	3.3	5.7
6.0	8.3	12.5	21.7	37.9

Source: De Haan and van Riemsdijk (1989).

These findings have interesting implications for policies intended to reduce environmental threats of cadmium. Since the soil properties, and in particular the pH, have such a strong influence on the desorption of cadmium, the prospects for reducing the negative environmental effects of cadmium depositions seem to be better rooted in activities that increase the adsorption capacity of the soil than in activities that reduce cadmium emissions, which eventually will be deposited on soils. A small increase in the pH or the application of lime may have a much stronger effect on the adsorption than, say, a 50-percent reduction in emissions of which only a small fraction actually enters soils with critical conditions for solving cadmium. In addition, the environmental threat of phosphate fertilizers that are contaminated with cadmium is much smaller than other depositions, since fertilizing agricultural soils keeps them at a pH high enough to prevent any significant desorption of cadmium.[34]

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[34] An exception, however, may occur on sandy soils with low adsorption capacities.

C. The Control of Cadmium

I. Controlling Airborne Cadmium Emissions

Cadmium is emitted in different forms, the most important being elemental cadmium and cadmium oxide (CdO). In coal combustion processes and the nonferrous metal production, it also occurs as cadmium sulfide (CdS) and in waste incineration plants as cadmium chloride ($CdCl_2$) (see Jensen and Bro-Rasmussen 1992). Whereas elemental cadmium and $CdCl_2$ are both volatile at flue gas temperatures, CdO and CdS are nonvolatile. The nonvolatile forms are emitted as fly ash, and the volatile forms are in a vapour state and precipitate during the cooling process; but they all become finally bound to dust particles. There exist essentially three options for controlling cadmium emissions:

- The substances in question (i.e., raw cadmium and cadmium-containing materials) can be avoided at the input side by substituting them with other materials. This option requires that substitutes are technically available at reasonably low costs.
- Through changes in production techniques, emissions into the environment can be reduced because it becomes easier to control the residuals in the production process.
- If emissions cannot be avoided in the production process, end-of-pipe measures can help to control the form in which the substances leave the production site. For example, emissions into the air can be prevented by collecting dust and turning it into solid waste, which then is disposed of at landfill sites.

In the past, the main focus in the regulation of hazardous substances was on the control of emissions through end-of-pipe measures, whereas more recently technological advances have increasingly led to emission reductions through process changes or through input substitution. In the following, these three options are investigated, and their potential for a further reduction of cadmium emissions is assessed. In addition, the costs of alternative measures are compared as far as this is possible in light of a very limited data base.

1. End-of-Pipe Measures

Hazardous substances that cannot be avoided at the input side and that cannot be completely contained in the production process are emitted unless they are controlled through appropriate technologies, i.e., so-called end-of-pipe measures. In the analysis of such abatement measures, one should distinguish between controlled and fugitive emissions. Controlled emissions are emitted from point sources, i.e., from process vents, chimneys, and other outlets that are technically easy to locate and to monitor. Fugitive emissions, in contrast, escape from larger areas such as hoods, open furnaces, melting pots, storage piles, or unloading facilities. Both the measurement and the control of fugitive emissions pose difficult problems, which are distinct from the problems posed by point emissions. In the following, firstly, we discuss the control of point emissions. Secondly, we analyze end-of-pipe measures for fugitive emissions.

a. The Control of Point Emissions

Using end-of-pipe measures to control point emissions seems to be the most natural way of avoiding the transport of hazardous substances into the environment. The economic efficiency and the ecological effectiveness of such an approach depend on the choice of the abatement technology. Therefore, we present first the various end-of-pipe technologies that are available for removing dust and consequently cadmium from the exhaust air of industrial processes. Then the corresponding abatement costs are discussed. Finally, the most advanced technologies and the potential for new technologies are assessed.

Abatement Technologies

Reducing the concentration of dust in the raw gas is essential for the control of cadmium emissions into the air, since cadmium is adsorbed at dust particles. Compared with other heavy metals, cadmium precipitates predominantly on small dust particles. Table 29 summarizes the concentration of heavy metals in filter dust from coal combustion and shows that the smallest particles of less than 3 µm have the highest cadmium content. Since, for example, in coal combustion the size distribution of particles in the stack dust depends on the combustion technology, abatement measures need to take into account this preference of cadmium for small dust particles. This has consequences for the specific cadmium removal rates, since different arresters remove particles of different sizes. The most common types of dust emission control technologies for industrial waste gas purification are, in the order of increasing purification rates: cyclones, scrubbers, electrostatic precipitators (ESP), and fabric filters.[35]

Table 29 — Size Distribution of Heavy Metals in Filter Dust from Coal Combustion (mg metal/kg dust)

Particle size fraction	Pb	Cu	Cd	Hg
< 3 µm	580	500	14	2.3
3– 6 µm	500	330	5	1.9
6– 9 µm	320	390	4	2.4
9–19 µm	160	260	2	2.3
19–50 µm	35	160	1	1.2

Source: Swedish Environmental Protection Agency (1991).

Cyclones are cylinders or cones in which the waste gas is rotated. The induced inertial forces cause particles whose mass exceeds certain values to migrate to the shell, where they are captured. However, the cleaning performance of this process is rather unsatisfactory, since it hardly removes particles that are smaller than 5µm. Because of the concentration of cadmium and other heavy metals on dust particles of less than 3µm (see Table 29), cyclones are particularly ineffective in removing cadmium from the raw gas. The cleaning performance of cyclones, however, can be improved considerably through the prior use of scrubbers, which cause the particles to adhere to water droplets, thus making collection by inertial forces easier.

Electrostatic precipitators ionize gas molecules through the application of high voltage. Dust particles are then transported with the ionized molecules to the collection electrodes, where they are removed in regular intervals of 10–30 minutes. The highest purification rates can be achieved with membrane and fabric filters. Such filters are made of flexible cloth (e.g., needle felt or a woven fabric made of synthetic or natural fibres). The raw gas passes through these materials and the dust particles are retained in the filter.

Figure 7 illustrates the average cleaning performance of the different dust arresters in terms of remaining dust concentration. There is a clear hierarchy of technologies from membrane and fabric filters to electrostatic precipitators, scrubbers, and finally cyclones. German regulations of emissions into the air limit airborne dust emissions to 50 mg/m^3 for large facilities (gas flow of more

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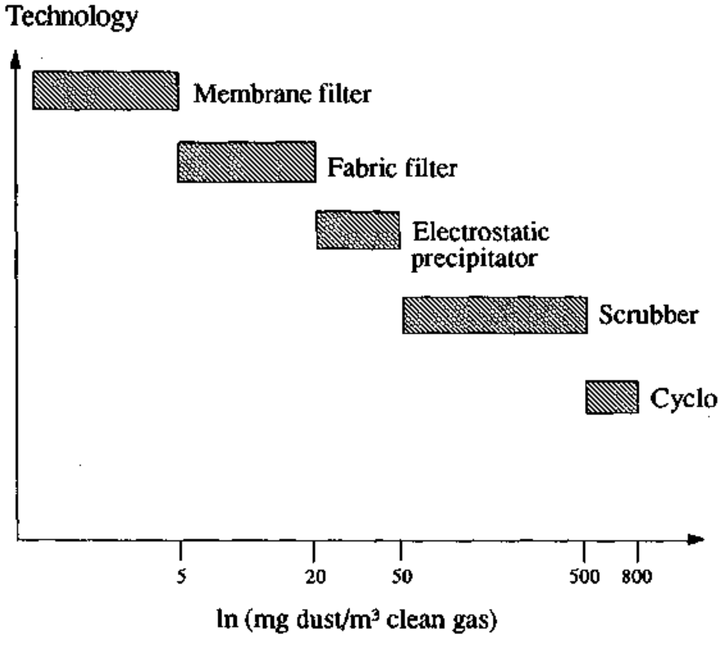
[35] For a more detailed description of these techniques see Güthner (1989), Umweltbundesamt (1989), and Swedish Environmental Protection Agency (1991), from which most of the technical material is taken.

than 10,000 m^3/h) and to at least 150 mg/m^3 for smaller ones (see Table 32 in Section C.I.1.a). Many processes are subject to tighter limits going as low as 10 mg/m^3 for lead production and waste incineration. Consequently, the German regulations force the introduction of electrostatic precipitators or fabric filters for large facilities, whereas for small facilities, to achieve the 150 mg/m^3 dust in the clean gas, the combined use of a scrubber and a cyclone is sufficient.

Figure 7 — Average Cleaning Performance of Dust Arresters for Industrial Waste Gas Purification (mg dust/m^3 clean gas)



Source: Güthner (1989), Swedish Environmental Protection Agency (1991), Umweltbundesamt (1989).

At first sight, one might get the impression from Figure 7 that the best available end-of-pipe technology for removing cadmium is the use of fabric or membrane filters. Unfortunately, things are not that simple. Each technology has its own requirements and limitations in terms of the raw gas characteristics:

- Fabric filters cannot be used for hot gases with a temperature of raw gas above 280° C.

- The most efficient membrane-type filters (with a cleaning performance in the range of 0.1–5.0 mg/m^3 and a removal of particles as small as 0.1 mm) cannot clean dust that contains oil.
- Dry electrostatic precipitators require dry waste gas, whereas wet electrostatic precipitators need an additional wastewater purification plant.

It is therefore clear that the use of different dust arresters depends not only on the quality of the cleaning performance and on the cleaning cost, but also on the specific characteristics of waste gases in different processes. Consequently, neither the most effective nor the most cost-efficient end-of-pipe technology can be chosen by looking simply at cost and performance figures.

As far as the removal of cadmium is concerned, things become even more complex, since there does not exist a simple relationship between the removal of dust and the removal of cadmium. Although cadmium reduction technologies have to rely on dust arresters, since most of the cadmium is bound to dust particles, the removal capacity of dust arresters with respect to the dust reduction is not comparable to that of the cadmium reduction. A number of factors determine the relationship between the cadmium load at the input side, the cadmium concentration in the raw gas, and finally, the cadmium emissions to the air. Consequently, the emission coefficients for cadmium can vary over a wide range, and the usefulness of emission coefficients for the prediction of reduction potentials of specific regulations or policies is limited as long as the specific circumstances are not taken into consideration.

The emission coefficients for specific production technologies and specific end-of-pipe technologies depend first of all on the cadmium contamination of the raw material. As this raw material is processed, in most cases through a thermal process, raw gases are produced with cadmium concentrations that are quite different from those of the raw material inputs. The increase in the concentration varies widely, as some examples in Table 30 indicate. The determinants of the accumulation of cadmium are manifold. The process technology, but also the process temperature, the occurrence of other trace elements, as well as the concentration in the raw material all interact in complex ways, with the consequence that the raw gas concentration of cadmium varies widely even in the same production process. This variation can increase even further if, e.g., the dust particles are returned into the smelting process. The cadmium concentration of the raw material in the cement production of 0.29 ppm increased in a test to a gas concentration of 12.4 ppm without the feeding back of the dust, and with the feeding back it increased to 1,000 ppm (see Umweltbundesamt 1989).

Table 30 — Cadmium Accumulation in Selected Production Processes (ppm)

	Cadmium concentration[a]		
	raw material	raw gas	accumulation (raw gas/raw material)
Glass melting tank	0.86	747	870
	0.86	898	1,040
Cement production	0.26	32.0	94
	0.6	6.9	13
Nickel smelting	1.4	180.0	128
	2.1	200.0	95

[a] Numbers refer to two different test samples.

Source: Umweltbundesamt (1989).

The removal capacity of dust arresters not only depends on the cadmium concentration of the raw gas, it also depends on the size distribution of the dust particles in the raw gas. The cleaning performance of different dust arresters with respect to cadmium is related to their ability to remove small dust particles from the process gas. A raw gas with predominantly small particles, e.g., below 3–5 µm, is more difficult to clean than a gas with larger dust particles. Since cadmium prefers being bound to smaller particles — 75 percent of the cadmium in the raw gas from coal combustion is bound to particles of less than 6 µm, and 50 percent to particles of less than 3 µm (see Table 29) —, the technical difficulty in removing cadmium is aggravated. This means that dust arresters such as scrubbers and cyclones, which reduce dust to up to 50 mg/m³ do worse in terms of cadmium removal compared with dust removal because the remaining dust in the clean gas is predominantly composed of small particles.

Given all these different aspects of the relationship between the cadmium load of raw materials on the one hand and the cadmium concentration in the raw gas and, after treatment, in the clean gas on the other hand, it is clear that the cleaning performance of the different end-of-pipe technologies in removing cadmium can not be summarized by a single emission coefficient, which relates an end-of-pipe technology to its removal capacity. Emission coefficients for cadmium can be measured in a meaningful way only for a specific production process with a known input of cadmium and a specific end-of-pipe technology. This has important consequences for the determination of abatement cost. Since the emission coefficients depend on several parameters, the abatement costs for cadmium will depend on at least as many factors. Unfortunately, not enough information is available for a complete assessment of these costs. Therefore, the following section focuses on two processes, which are rather well documented, namely on industrial furnaces and on zinc refining.

Abatement Costs

End-of-pipe technologies not only reduce airborne cadmium, they also reduce a large number of different substances such as dust in general, other heavy metals, and organic compounds. Consequently, it does not make any sense to attribute the total costs of applying these technologies to just cadmium.[36] Consequently, the following figures refer to the costs of reducing whatever substances are removed with the dust arresters. This is only a rough approximation to the costs of removing cadmium. One of the most important factors that distort these cost figures is the ability of the different filter technologies to remove dust particles of different sizes. Dust arresters are commonly described by the percentage of dust that they remove from the raw gas. However, the new technologies such as fabric filters not only exhibit higher removal capacities, they also remove smaller dust particles. Since cadmium is predominantly bound to the smaller dust particles, the change from a technology with a purification rate for dust of 95 percent to one with 99 percent will increase the removal of cadmium by more than the 4 percentage points for the dust removal.

Very little systematic information is available on the cost functions of the different dust arrester technologies. However, some general characteristics of these cost functions can still be deducted from the scetchy data. One of the important characteristics is that the investment costs of dust arresters are high and increase with the improvements of the technology. Electrostatic precipitators and fabric filters with a gas flow of 50,000 m^3/h have investment costs of beyond one million DM, whereas a scrubber of similar capacity is at least half as expensive. Operating costs, however, are considerably higher for the scrubber than for the more advanced technologies, and they seem to be linear within the capacity of the unit. For a specific arrester unit with a given capacity, the larger part of the operating costs varies with the operating time, such that the operating costs per unit of time are more or less constant, i.e., the variable costs of a dust arrester are linear in the working time. If the arrester runs below its capacity, the operating costs per m^3 gas flow and a given working time are reciprocal to the volume of gas treated, i.e., the costs decrease as a function of the volume of gas treated.

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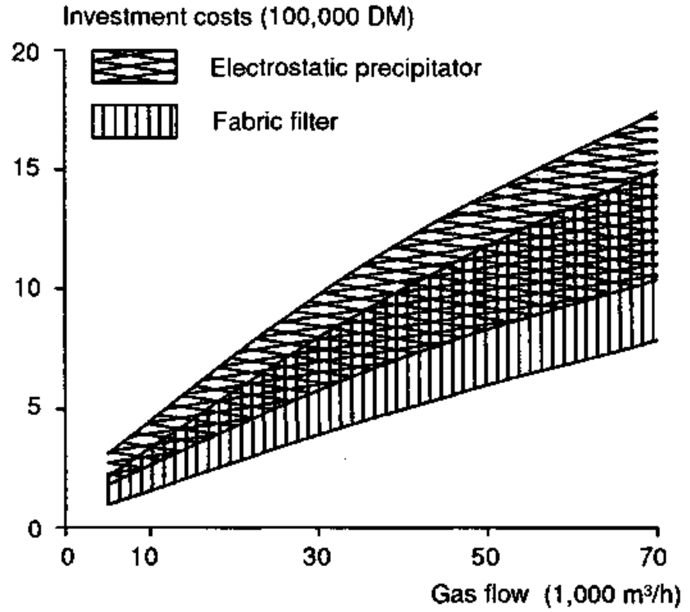
[36] The economic problem could be formulated in a form comparable to the joint production problem, with the difference that, instead of a marketable commodity, a nonmarketable commodity vector "emission reduction" would be produced. However, such an analysis is beyond the scope of this monography.

The investment costs of electrostatic precipitators and fabric filters for coal-fired industrial combustion facilities of different capacities are illustrated in Figure 8. It is remarkable that the average investment costs of these dust arresters fall with rising capacity. This is in line with findings of the cost-engineering and industrial organization literature, which has estimated investment cost functions of the form $C_i = \ln \alpha_i + \beta_i \ln v_i$ for different technologies i (see, e.g., Humphreys and Katell 1982, Hay and Morris 1991). The coefficient β_i for cyclones is 0.85 and for electrostatic precipitators 0.90 (see Jelen 1970), hence capital costs increase regressively.

Figure 8 — Investment Costs of Advanced Dust Arresters for Coal Combustion Facilities



Source: Gruber (1991).

We can conclude from these cost data that the modern dust arresters are characterized by falling average cost curves with respect to capacity, with respect to the treated gas volume at a given capacity, and with respect to the operating hours. The marginal costs of capacity also decreased with the consequence that large manufacturing plants, compared with smaller ones, have lower abatement costs. For a given and not fully used capacity, the marginal costs of treating additional gas volumes are very low and may even be falling. Finally, the marginal costs of longer operating hours seem to be constant.

In Table 31, the cost structures for two different production processes, a coal-fired industrial furnace and a thermal zinc refining process, each with two different abatement technologies are summarized. These numbers are only rough approximations but they nevertheless illustrate some important insights:

- The more advanced electrostatic precipitator and the fabric filter have comparable unit costs in terms of the treated gas volume, whereas the costs of the scrubber are higher, although it has lower purification rates in terms of dust removed as well as in terms of cadmium removed.
- The costs per t of dust removed vary widely, since the operating costs depend on the volume of gas and not on the dust throughput. In that sense, the cleaning of gas in the zinc process with a dust content of only 2 g/m^3 is more expensive than that in the coal-fired furnace with a dust concentration in the raw gas of 10 g/m^3.
- The same phenomenon occurs for the costs of reducing cadmium. The coal-fired furnace with the low cadmium concentration in the raw gas causes much higher costs per kg cadmium removed than the zinc process.
- Whereas the electrostatic precipitator needs higher investment costs than the fabric filter, the operating costs of the electrostatic precipitator seem to be significantly lower, so that its overall costs are still below those of the fabric filter. The choice between the two filter technologies may then, besides technical considerations, depend on the expected capacity utilization of the production plant. In a situation with variable and unpredictable gas flows over time, the fabric filter may be more economical because the effect of the lower fixed costs will keep the total unit costs at a lower level in times of a low capacity utilization.

The available data on the costs of the different abatement technologies indicate that policies that aim at reducing emissions of dust in general or cadmium in particular will not result in a continuous marginal reaction of firms. The relatively high fixed costs will prevent an instantaneous change from older to more advanced technologies even if the latter have lower unit costs, as it is the case in the example presented in Table 31. This also means that an increase in regulatory measures such as emission taxes will not necessarily lead to increasing abatement activities. Only if such an increase is strong enough to override the sunk costs that have been invested in the old technologies, the abatement of cadmium or other substances will then be increased.

Table 31 — The Cost Structures for Different Dust Arresters in Selected Production Processes

	Coal-fired industrial furnace (medium-sized)		Thermal zinc refining (imperial smelting)	
Gas flow (m^3/h)	50,000		50,000	
Dust content (g/m^3)	10		2	
Cadmium content (mg/m^3)	0.18		0.6	
Operating hours (h/yr)	8,000		8,760	
	Abatement technology			
	electrostatic precipitator	fabric filter	scrubber	electrostatic precipitator
Purification rates				
Dust emissions (percent)	> 99.5	> 99.5	95.0	99.7
Cadmium emissions (percent)	95.0	95.0	90.0	95.0
Investment costs (mil. DM)	0.80–1.40	0.60–1.10	0.45	1.31
Operating costs (mil. DM/yr)	na	na	0.56	0.33
Total costs (mil. DM/yr)	0.30–0.42	0.35–0.47	0.62	0.52
Total costs per volume of gas (DM/m^3)	0.75–1.05	0.88–1.18	1.42	1.18
Total costs per t of dust removed (DM/t)	75–105	88–118	747	592
Total costs per kg of cadmium removed (DM/kg)	4,386–6,140	5,146–6,901	2,630	2,070

Source: Gruber (1991); Pacyna (1991); Swedish Environmental Protection Agency (1991); Umweltbundesamt (1986); own calculations.

Michaelis (1993) has simulated the reaction function of a firm facing an emission tax. The optimal choice of abatement technologies and emission levels under varying tax rates for such a firm turns out to be discontinuous. The jumps are induced by the discrete choice of abatement technologies and their increasing returns to scale. The falling average cost curve makes it optimal for the firm to always use the dust arrester at full capacity, independently of the tax rate. The choice of the abatement technology, in turn, only takes place at critical levels of the tax rate where the abatement costs including the costs of the switch of technologies fall below the operating costs of the existing technologies. The reaction function is therefore a step function where the maximum emission control of the installed technology is always provided. Michaelis (1993) also shows that large firms are likely to switch to the new technologies earlier than smaller firms because the burden of sunk costs is smaller for large firms, which use larger dust arresters with lower fixed costs per volume of treated raw gas.

Best Available Technology

Instead of setting an emission tax and letting firms choose the desired abatement option, governments often use regulatory measures that prescribe the use of specific abatement technologies. The Technical Directive on Air Pollution of 1986 is such a regulation: it effectively requires the introduction of the best available technology (BAT). This requirement is then updated when new technologies are developed.

According to a report delivered to the ECE-Task Force "Heavy Metal Emissions" by the Swedish Environmental Protection Agency (1991), the installation of fabric filters can be considered as the best available end-of-pipe technology[37] for nearly all of the applications mentioned here (see Table 32). The only exceptions from this rule constitute the combustion of coal in power generation and the basic oxygen process in iron and steel making:

- In the case of coal combustion, the Swedish Environmental Protection Agency (1991) recommends both electrostatic precipitators and fabric filters as BAT, although the use of electrostatic precipitators results in a concentration of about 30 mg dust/m^3 cleaned gas, while the cleaning performance for fabric filters is 20 mg/m^3.
- In iron and steel making by the basic oxygen process, fabric filters sometimes cannot be used because of the temperature of the raw gas or its physical properties. In these cases, electrostatic precipitators must be considered best available technology although they only produce clean gas concentrations of about 50 mg/m^3, while the use of fabric filters would reduce concentrations to about 10 mg/m^3.

The first column of Table 32 summarizes the concentrations of dust in the exhaust air that can be reached through the use of the best available technology as it is defined by the Swedish Environmental Protection Agency (1991).

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[37] The Swedish Environmental Protection Agency (1991, p. 41) defines the best available technology as "*the latest stage of development (state of the art) of processes, of facilities or of methods of operation which indicate the practical suitability of a particular measure for limiting emissions. In determining whether a set of processes, facilities and methods of operation constitute the best available technology in general or in individual cases, special consideration is given to: comparable processes, facilities or methods of operation which have been recently successfully tried out; technological advances and changes in scientific knowledge and understanding; the economic feasibility of such technology; time limits for installation in both new and existing plants; the nature and volume of the effluents concerned; the precautionary principle.*"

Table 32 — BAT[a] Concentrations of Dust in Exhaust Air and Permissible Concentrations According to German Regulations (mg/m^3)

	BAT concentration	German standard
Coal combustion by power plants	20–30	50
Production of iron and steel		
Electric arc process	5–10	20
Basic oxygen process	10–50	20–50
Production of nonferrous metals		
Primary zinc and copper	5	20
Secondary zinc and copper	10	20
Primary lead	5	10
Secondary lead	10	10
Manufacturing of glass	10	50–150
Waste incineration	10–20	10

[a] Best available technology.

Source: Großfeuerungs-Anlagenverordnung (1983); Swedish Environmental Protection Agency (1991); TA-Luft (1986); Verordnung über Verbrennungsanlagen für Abfälle (1991).

Getting such BAT concentrations requires not only the most suitable type of dust arrester, but also the choice of the arrester needs to be supplemented by appropriate surveillance and maintenance and by an individual design, which should be taylored for each specific installation. The second column of Table 32 summarizes the permitted concentrations of dust in the exhaust air according to the current German regulations. In most cases, these concentrations are higher than the BAT concentrations defined by the Swedish Environmental Protection Agency (1991). However, a careful comparison with the feasible cleaning performance of different types of dust arresters (see Figure 7) reveals that in virtually all cases the German legal standards can only be achieved through the same type of technology that is recommended as "best available technology" by the Swedish Environmental Protection Agency (1991). This implies that the current German regulations already require the use of the best available end-of-pipe technologies.

Hence, at the present state of the technology, there seems to be no scope for further reductions of dust emissions through the use of superior end-of-pipe technologies. Neglecting the possibility of clean technologies (see Section C.I.3), only an optimization of the design, the surveillance and the maintenance of the end-of-pipe technologies already employed may allow further reductions of dust emissions. But even this opportunity is more restricted in scope than the figures in Table 32 suggest, since the actual concentrations of dust in exhaust air are often considerably smaller than those required by the respective regulations. We can therefore conclude that the potential for removing cadmium from the exhaust air with the known end-of-pipe technologies has been practically exhausted. Further small reductions could only be achieved through improvements of the installed processes, for which the potential can only be assessed on a plant-by-plant basis.

b. The Control of Fugitive Emissions

Fugitive emissions can be grouped into emissions caused during production processes (e.g., emissions from open furnaces, melting pots, launders) and emissions caused during storage, handling and transport. According to the Swedish Environmental Protection Agency (1991), the use of process containments (doghouses) is the best available technology for controlling process-related fugitive emissions. Process containments evacuate the dust-containing air flows and thereby transform the fugitive emissions into controlled emissions, which can be treated through end-of-pipe technologies.[38] The use of containments with end-of-pipe treatment is already required by the Technical Directive on Air Pollution of 1986 in Germany. Therefore, it is reasonable to conclude that the potential for reducing process-related fugitive emissions is practically exhausted.

Concerning fugitive emissions from storage, handling and transport, the Swedish Environmental Protection Agency (1991) recommends the following set of measures as best available technology:

— Storage should be located indoor or covered to avoid wind-blow emissions.
— Raw material should be received in sealed containers or in closed vehicles.
— Tipping to stockpiles can be made through chutes equipped with wet suppression systems or with dust suction to filter.
— Raw materials from stockpiles should be reclaimed by enclosed conveyor.
— Roads should be hard-surfaced and properly cleaned; contaminated runoff water from roadways should be collected, and a well designed wheel wash system should be used.

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[38] For an example of a process containment with end-of-pipe treatment of the air flow, see Umweltbundesamt (1987).

In Germany, the Technical Directive on Air Pollution from 1986 requires that emissions caused through storage, handling and transport of dust-spreading goods with a cadmium content of more than 50 ppm (e.g., zinc, lead and copper ores) should be minimized by using so-called most effective measures (*wirksamste Maßnahmen*). Although the practical realization of these measures depends on the specific conditions of the activity under consideration, the term "most effective" suggests that these requirements may be at least as stringent as the recommendations of the Swedish Environmental Protection Agency (1991). Hence, with the exception of possibly weak enforcement, there seems to be no need and no possibility for further activities aiming at reducing fugitive cadmium emissions from transport, handling and storage at present.

2. Input Substitution

In order to obtain a complete picture of all substitution possibilities that may have an effect on airborne emissions, we consider two different types of cadmium input:

- the intentional use of raw cadmium or cadmium-containing inputs (e.g., the use of cadmium-containing stabilizers in PVC production);
- the inadvertent cadmium entry into the production process due to the use of contaminated input materials.

The cadmium flows in the economy, as discussed in Section B.I, indicates that the use of raw cadmium or cadmium-containing inputs may have not only a primary (direct) but also a secondary (indirect) effect on airborne cadmium emissions. The primary effect is related to emissions that are caused by the production process itself, while the secondary effect is related to emissions that are caused by the consumption and/or disposal of cadmium-containing products.

The distinction between a primary and a secondary effect is also of particular importance for the choice of the appropriate policy mix. Policy measures that aim solely at the primary effect, i.e., reducing emissions caused by production processes, can concentrate on stimulating domestic substitution processes and refrain from restricting transfrontier trade in cadmium-containing products. If, however, environmental policy measures aim at exhausting the full scope of substitution possibilities, i.e., reducing emissions caused by production processes as well as by consumption and disposal, then there will be a need for additional restrictions on trade if imports significantly contribute to the total domestic consumption of the products under consideration.

a. Intentional Input of Cadmium

As discussed in Section B.I, the most important product groups containing cadmium as an intentional ingredient are stabilizers, pigments, batteries, and plated commodities (see Table 2).

Cadmium-Containing Stabilizers

Cadmium-containing stabilizers are used to protect products, mostly made from PVC, for outdoor use (mainly window frames) against degradation processes caused by high temperatures and light. In 1986, the last year for which data are available, the cadmium input to the domestic production of stabilizers amounted to about 425 t, of which, after correcting for exports, about 219 t remained in Germany (see Table 33). In addition to the domestic production, about 70 t Cd were imported in 1986, so that total domestic consumption of cadmium in stabilizers amounted to about 289 t.

Table 33 — Cadmium in Stabilizers, 1981–1986 (t)

	1981	1982	1983	1984	1985	1986
Domestic production	472	444	475	441	415	425
Exports	184	197	240	195	198	206
Imports	80	81	82	32	78	70
Domestic consumption	368	328	317	278	296	289

Source: Balzer and Rauhut (1987); Rauhut (1990).

It should be noted, however, that these data on imports and exports include only international trade in cadmium-containing stabilizers themselves but no transfrontier flows of manufactured products containing stabilizers that also contain cadmium. Hence, the numbers on domestic consumption are subject to considerable uncertainty. Balzer and Rauhut (1987) conjecture that the exclusion of these hidden cadmium flows lead to an overestimation of domestic consumption, since manufactured cadmium-containing products are products for which Germany has an export surplus.

According to studies by Böhm and Tötsch (1989) and Böhm and Schäfers (1990), which are the most recent studies on cadmium substitution, three options for substituting cadmium-containing stabilizers are available: (i) a substitution of cadmium-free stabilizers for cadmium-containing stabilizers, (ii) a general substitution of additional surface coatings for stabilizers, and (iii) a general substitution of other materials (mainly wood and aluminum) for PVC for the production of window frames and related commodities for outdoor use.

However, as Böhm and Tötsch (1989) discuss in detail, each of these substitution possibilities entails its own problems:

- The only available cadmium-free stabilizer system relies on lead stabilization and requires the fivefold amount of lead compared with cadmium stabilization. From an ecological point of view, this trade-off between cadmium and lead is hardly a sensible solution, since lead also belongs to the class of highly hazardous substances, which are known to cause a major threat to the environment.
- A total phasing-out of stabilizers in favour of additional surface coatings would be accompanied by a number of technical problems because the available coating systems are generally less resistant against mechanical and chemical effects. As a consequence, the products under consideration would be of inferior quality and durability. This, in turn, would increase the consumption of energy and resources and thereby cause other environmental problems.
- And finally, a complete substitution of aluminum or wood for PVC is also problematic because window frames made of aluminum are expensive and the employment of wood requires costly periodical upkeeping and maintenance activities. Their environmental net effect is far from clear. In both cases, only a comprehensive "cradle-to-grave" analysis, including all direct and indirect environmental effects caused by the production, consumption and disposal of the products under consideration, would allow an answer to the question whether the substitution of aluminum or wood for PVC would yield a positive net environmental benefit.

Although the replacement of cadmium-containing stabilizers would lead to a decrease in cadmium flows, the primary effect on airborne cadmium emissions is probably almost insignificant. Since the production of stabilizers and stabilized PVC-commodities accounts for less than 0.2 percent of total airborne cadmium emissions in Germany (see Umweltbundesamt 1991), a reduction of cadmium flows through substitution in the stabilizer production would result only in a negligible decrease in overall airborne cadmium emissions.

A secondary effect on airborne emissions may emerge in so far as scrapped commodities made of cadmium-stabilized PVC are subject to waste incineration. This, however, does not occur on a large scale, since scrapped window frames and related commodities for outdoor use are usually part of demolition wastes that are not incinerated but disposed of by direct landfill. In this case the cadmium-content is not mobilized and there is no effect on airborne cadmium emissions. According to Tötsch and Gaensslen (1990), the annual flow of municipal waste[39] in West Germany contains about 30 t Cd that can be traced back to the use of cadmium-containing stabilizers. Assuming that about 30 percent of municipal waste are incinerated and accounting for an end-of-pipe removal rate of about 98 percent with respect to cadmium (see Böhm and Schäfers 1990), the annual airborne cadmium emissions from the incineration of stabilizers would be in the order of about 0.18 t. Hence, even a total phasing-out of cadmium-containing stabilizers would lead only to a very small reduction of airborne cadmium emissions.

Cadmium-Containing Pigments

Cadmium-containing pigments are used to produce paints and to color products made from plastics, ceramics, enamel and glass. According to Böhm and Tötsch (1989), the coloring of plastics (mainly polyethylene, polypropylene, polystyrole, and polyamide) is responsible for about 86 percent of the total use of cadmium-containing pigments in West Germany, while the other areas of application are only of minor quantitative importance (paints 2 percent; ceramics and enamels 8 percent; glass 4 percent). Table 34 shows the cadmium input in the domestic production of pigments in 1986 amounting to about 555 t, of which about 301 t did remain in West Germany. If additional imports of about 35 t are accounted for, total domestic consumption of cadmium in pigments amounted to about 363 t. These figures, however, do not include international trade in manufactured products containing cadmium in the form of pigments. Therefore, total domestic consumption may be overestimated, since Germany is a net exporter of such products.

Table 34 — Cadmium in Pigments, 1981–1986 (t)

	1981	1982	1983	1984	1985	1986
Domestic production	664	603	634	611	590	555
Exports	408	338	382	278	228	227
Imports	35	52	41	31	72	35
Domestic consumption	291	317	293	364	434	363

Source: Balzer and Rauhut (1987); Rauhut (1990).

The availability of substitutes for cadmium in the coloring of plastics depends on the type of plastic, the required shade of color, and the characteristic features of the respective product under consideration (see Böhm and Tötsch

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[39] Municipal waste includes waste from private households, and public and commercial waste that is collected together with household waste.

1989). In some cases (e.g., the coloring of low density polyethylene), cadmium-free substitutes are easily available, while in other cases (e.g., the coloring of polyamide) a phasing-out of cadmium-containing pigments would imply that several shades of color as well as some advantageous characteristics (in particular nonfade properties) are no longer available. Moreover, even in those cases where suitable substitutes are available the problem often remains that the use of such substitutes may cause other environmental problems. In particular, cadmium-free pigments often contain other heavy metals (lead, chrome, nickel, zinc) or exhibit largely unknown toxicological characteristics like in the case of many organic substitutes. Hence, the scope of ecologically sensible substitution options can only be quantified on the basis of detailed case studies.

In the production of paints the use of cadmium-containing pigments is unavoidable only in those cases, where the respective paints have to meet extremely high requirements concerning heat resistance. Similar problems occur with respect to the coloring of glass, ceramics and enamel: In most cases only cadmium-containing pigments are sufficiently resistant against the high temperatures that prevail during the process of coloring. A phasing-out of cadmium-containing pigments would imply that several shades of color are no longer available. Hence, the scope of quantitatively significant substitution possibilities seems to be limited to the coloring of plastics.

In order to assess the quantitative potential for reducing airborne cadmium emissions through the replacement of cadmium-containing pigments, three different effects should be distinguished:

- The production of cadmium-containing pigments contributes only less than 1 percent to the total airborne cadmium emissions in West Germany (see Umweltbundesamt 1991). Hence, further reductions in cadmium input would lead only to a very small primary effect.
- The situation is more complicated, when it comes to the industrial use of cadmium-containing pigments. On the one hand, the coloring of glass and ceramics contributes significantly to airborne cadmium emissions (see Table 4), but there are no substitution potentials. On the other hand, there seem to be significant substitution potentials in the coloring of plastics, but this activity causes very little airborne cadmium emissions.
- And finally, the potential effect on airborne cadmium emissions caused by the incineration of waste should be taken into account. According to Tötsch and Gaensslen (1990), the annual flow of municipal waste in West Germany contains an amount of about 120 t Cd that is caused by the use of cadmium-containing pigments in the coloring of plastics. Given that about 30 percent of that waste is incinerated and that the

incinerators have removal rates of about 98 percent, it is estimated that about 0.72 t of airborne cadmium emissions are caused by the incineration of scrapped plastics that are colored with cadmium-containing pigments. Hence, a substitution of cadmium in the coloring of plastics can be expected to have a perceptible secondary effect on airborne cadmium emissions. It should be noted, however, that the major part of this effect would occur only with a time lag of some years because cadmium-containing-pigments are mainly used in the coloring of consumer durables and only to a much smaller extend in the coloring of packaging materials (see Brahms et al. 1989).

Cadmium-Containing Batteries

At present, the market for rechargeable batteries (accumulators) is dominated by two different systems: lead accumulators and nickel-cadmium accumulators. The latter cost more to produce, but they are superior to lead accumulators in terms of their capacity-weight ratio, their technical life-time and their maintenance requirements. Nickel-cadmium accumulators are produced in two different variants: big, vented accumulators, and small, sealed accumulators.

Because of the higher production costs compared with lead accumulators, the use of big, vented nickel-cadmium accumulators is almost completely restricted to those cases where the superior capacity-weight ratio is of crucial importance (mainly aircrafts, military and space technologies). The amount of cadmium used for vented accumulators is steadily declining as the result of the improved lead accumulators (Böhm and Schäfers 1990; see also Table 35). Hence, there is no scope and no need for additional policy measures aimed at stimulating the replacement of vented nickel-cadmium accumulators.

Table 35 — Consumption of Cadmium in Accumulators, 1984–1990 (t)

	1984	1985	1986	1987	1990[a]
Sealed accumulators	96	116	156	241	262
Vented accumulators	na	na	59	51	50
Total	na	na	215	292	312

[a] Forecast.

Source: Fachverband Batterien, quoted from Böhm and Tötsch (1989).

Small, sealed accumulators are mainly used in consumer durables (e.g., cordless vacuum cleaners). In contrast to the big, vented accumulators, they achieved increasing market shares during the last decade. As indicated in Table

35, the consumption of cadmium in these accumulators grew from 96 t in 1984 to 241 t in 1987, and a further increase of this magnitude is expected. Moreover, as Böhm and Tötsch (1989) and Böhm and Schäfers (1990) point out, the figures presented in Table 35 do not include imports of nickel-cadmium accumulators that are integrated in electrical appliances. They estimate that this trade effect leads to an additional annual net inflow of about 100 t Cd.

According to Böhm and Tötsch (1989), there is only little scope for replacing sealed nickel-cadmium accumulators by other types of rechargeable batteries or by solar cells. Hence, only two strategies for reducing the consumption of cadmium remain: a substitution of conventional (i.e., nonrechargeable) batteries for nickel-cadmium accumulators, or the general reduction of cordless electrical appliance. However, the former of these two options seems to be questionable from an ecological point of view, since it implies a drastically increasing consumption of conventional batteries, which also contain heavy metals (mainly nickel and mercury). Depending on the assumed number of recharge cycles and on the assumed type of conventional battery, between 100 and 500 batteries are needed to replace one nickel-cadmium accumulator. Once again, only a comprehensive "cradle-to-grave" analysis could give an answer to the question whether this kind of replacement would yield a positive net environmental benefit.

As far as the scope for inducing primary reduction effects on airborne cadmium emissions by input substitution is concerned, the situation is similar to that of stabilizers and pigments. Since airborne cadmium emissions caused by the production of nickel-cadmium accumulators are almost insignificant (see Table 4), only a very small primary effect can be expected. In contrast to this, it is likely that scrapped consumer durables equipped with nickel-cadmium accumulators significantly contribute to the cadmium load of municipal waste (see Böhm and Schäfers 1990). Under some reasonable assumptions, one can calculate the approximate magnitude of this secondary effect: Using the consumption data presented in Table 35 as a lower bound, assuming that the major part of sealed accumulators ends up in municipal waste after an average time lag of about 5 years, accounting for a 30-percent share of incineration, and, finally, assuming a 98-percent end-of-pipe removal of cadmium leads to an estimate of at least 0.9 t of airborne cadmium emissions caused by the incineration of scrapped nickel-cadmium accumulators in 1991. Furthermore, the sharp increase in consumption shown in Table 35 indicates that the magnitude of these emissions will grow considerably during the next years. Hence, a replacement of cadmium-containing accumulators would most likely lead to a decrease in airborne cadmium emissions, but this reduction would occur only after several years because of the time lag.

Cadmium-Containing Platings

The conventional method for protecting steel against corrosion is to apply a layer that inhibits any direct contact between the steel surface and the corrosive environment. The materials used as layer are mainly paints, polymer layers, and metallic coatings. Cadmium is the most superior material for metallic coatings, since it offers a unique combination of highly advantageous characteristics: low electrical contact resistance, high elasticity, low frictional resistance and wear, as well as high resistance against most chemicals.

However, because of the comparatively high price of cadmium coatings and the resulting environmental risks, the use of cadmium has been reduced to those applications where suitable substitutes do not seem to be available, mainly aerospace and military technologies. As a consequence, the annual input of cadmium to plating activities in West Germany declined from 420 t in 1976 to 122 t in 1986 (see Table 2).[40] The strongest effect comes from the reduction of cadmium-galvanized steel in the automobile industry. According to the Sachverständigenrat für Umweltfragen (1990), one of the major West German producers has succeeded in reducing the cadmium content per motor car from 500 to 1 g. Similar reductions may be conceivable in military and aerospace technology, but as Böhm and Tötsch (1989) and Böhm and Schäfers (1990) point out, the feasibility of alternative coatings depends on the specific technical requirements in each single case. Hence, the scope for further substitutions is not readily quantifiable.

The coating of steel products with cadmium is a chemical process (electroplating) which does not contribute to airborne cadmium emissions. Hence, there would be no primary effect from substituting cadmium in plating activities. However, since the major part of airborne cadmium emissions that is caused by the production of iron and steel can be traced back to cadmium-contaminated scrap metals, there would be an important secondary effect. Although the cadmium content of the scrap metals varies widely and the resulting emissions from iron and steel making can hardly be quantified, the close relationship between the intentional employment of cadmium in surface plating and the inadvertant entry of cadmium into the production of iron and steel is obvious. According to Böhm and Schäfers (1990), the average lifetime of plated metal parts ranges from 15 to 25 years. Hence, it seems reasonable to assume that the cadmium input to the production of iron and steel is mainly determined by the amount of cadmium used in plating with an average time lag of approximately 20 years. Therefore, cadmium emissions in the iron and steel

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[40] Data on international trade in cadmium-galvanized products are not available, but Rauhut (1990) estimates that there is a net outflow of cadmium induced by the particular trade structure of West Germany.

industry that are caused by plated scrap metal have two particular characteristics:

- The cadmium input into the production of iron steel through scrap metals will decrease by a factor of more than three within the next 15 years because of the reduction in plating with cadmium (see Table 2). Consequently, emissions will fall proportionally.
- If further reductions in the intentional use of cadmium for galvanization are sought, the fall of emissions in the iron and steel production will occur with a time lag of about 20 years.

b. Inadvertant Input of Cadmium

In Section B.I, we have shown that the inadvertant entry of cadmium to the production process through contaminated inputs leads to significant amounts of airborne cadmium emissions from the production of nonferrous metals, the production of iron and steel, and the generation of energy by coal combustion. The following sections contain a list of potential reduction options and an assessment of their benefits.

Production of Nonferrous Metals

Raw zinc ores, lead ores and copper ores contain certain amounts of cadmium that are partly volatilized during the process of refining. The specific amount of cadmium finally emitted to the air depends on three factors: the cadmium content of raw materials, the type of refining process, and the efficiency of the employed end-of-pipe measures.

The cadmium content of raw ores varies widely (see Table 3). As a consequence, reducing airborne cadmium emissions through input substitution would require a switching from high-cadmium ores to low-cadmium ores. This, however, is hardly possible, since there seems to be no systematic relationship between the cadmium content of the ore and the respective mining region or any other readily identifiable characteristics. Hence, reducing airborne cadmium emissions by input substitution is hardly feasible in the case of nonferrous metals.

Production of Iron and Steel

According to Böhm and Schäfers (1990), the cadmium input to iron and steel production caused by the use of natural iron ore is negligible compared with the huge amounts of cadmium that enter the production process through scrap metal. As a consequence, reducing emissions through input substitution would require a reduction of the input of scrap metals in favour of the smelting of natural iron ore. However, this kind of substitution does not seem to be sensible from an ecological point of view, since the use of scrap metals considerably reduces the energy input in the production of iron and steel. Moreover, cadmium emissions caused by these activities will sharply decline within the next years because of the reduced cadmium content of scrap metals and tightened emission standards that have to be met by each plant until 1996 (see Section B.II). Hence, there seems to be no need and no rationale for reducing airborne cadmium emissions reducing the input of scrap metals.

Combustion of Coal

Hard coal and brown coal contain different amounts of cadmium (see Table 3) that are partly released during the process of combustion. According to recent estimates, coal-fired utilities contribute about 5–10 percent to total airborne cadmium emissions in West Germany (see Umweltbundesamt 1991).We have shown in Section C.I.1 that these emissions can be reduced by end-of-pipe measures like electrostatic precipitators. Another device for emission control is fuel-switching among coals or switching from coal to other fuels (natural gas, renewable or nuclear fuels).

Switching from high-cadmium coals to low-cadmium coals requires that there exists a well documented systematic relationship between the coals' cadmium content and their respective mining region. For the fuels that are burned in West Germany, information on cadmium contents and mining regions are not available, and it is not clear at all if there exists any systematic relationship. However, empirical evidence from the United States suggests that there may exist regional differences in cadmium content, which could be exploited in order to reduce airborne cadmium emissions at comparatively low costs (see Tables 36 and 37). Such an approach, however, could contradict the German energy policy, which is focussed on protecting the domestic suppliers of hard coal.[41]

Switching from coal to natural gas would yield a 100-percent reduction in emissions from presently coal-fired utilities.[42] As indicated by the empirical estimates in Table 37, this kind of substitution would incur extremely high costs, which may not be justifiable from a narrow perspective that focusses only on the effect on cadmium emissions. However, the combustion of coal

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[41] In particular, the electricity sector in Germany is obliged to utilize certain amounts of domestic hard coal at administered prices (see Fels and Neu 1980).

[42] Of course, switching to renewable or nuclear fuels would also yield a 100-percent reduction in emissions. However, renewable fuels will not be available on a large scale in the near future, and the use of nuclear fuels seems too problematic because of the well-known reasons.

contributes not only to airborne cadmium emissions but also to a number of other environmental problems like global warming and acid rain. Hence, from a broader perspective including all relevant environmental effects, the substitution of natural gas for coal may be a sensible decision. Such a policy, however, would be incompatible with the protection of domestic hard coal.

Table 36 — Average Cadmium Content in US Coals from Selected Mining Regions (ppm)

Mining region	Cadmium content	Mining region	Cadmium content
Virginia	0.07	Washington	1.23
New Mexico	0.15	Illinois	3.27
Gulf Coast	0.59	Missouri	16.65

Source: Center for Clean Air Policy (1991, p. 118).

Table 37 — Relative Cost-Effectiveness of Cadmium Emission-Reduction Options for a 500-Megawatt Model-Plant, Situation as of the Early 1990s

	Average annual cost	Cost effectiveness
	$ millions	$ millions/t Cd
Fuel-switching		
Low cadmium coal	0–23	0–18
Natural gas	120–147	84–103
Baghouse filters	6–8	5–7

Source: Center for Clean Air Policy (1991, p. 70).

3. Clean Technologies

In a recently published report, the OECD concludes that end-of-pipe technologies suffer from a variety of technical, economic and ecological limitations. For example, "*at a time, when a broader range of pollutants are being included in control plans and increasing attention is being paid to the interactions between pollutants, the fact that most add-on control technologies usually only control a single pollutant or category of pollutants is a disadvantage. Taking a cross-media view of pollution, ... many add-on technologies produce waste that may cause disposal problems*" (OECD 1989, p. 88). Moreover, with respect to many pollutants, including heavy metals, the scope for reducing emissions by end-of-pipe measures seems to be almost exhausted (see Section C.I.1). Therefore, the potential of so-called clean technologies, i.e., technologies that are modified in such a way that they yield a smaller or less noxious amount of residuals, attracts growing interest. In the case of airborne cadmium emissions, the most promising examples of clean technologies are related to the combustion of coal and to the production of nonferrous metals.

a. Combustion of Coal

The combustion of coal in power plants is one of the most important sources of airborne cadmium emissions (see Section B.II). The specific emission coefficient (i.e., the amount of cadmium released into the atmosphere per t coal burned) depends not only on the coal's heavy metal content and the efficiency of the employed dust arresters but also on the kind of combustion technology used. Currently, three different combustion technologies for coal are used: grate-fired boilers, pulverized bed combustion, and fluidized bed combustion.

In the case of grate-fired boilers, lumpy coal is burned on a grate, whereas in the case of pulverized bed combustion, crushed and grinded coal is fed to an internal burner. In the case of fluidized bed combustion, inert material (e.g., sand) and pulverized coal are mixed, suspended and combusted in an upwards moving air flow. Table 38 shows the percentage contribution of these three technologies to the total power generation through fossil fuel combustion in West Germany. As these numbers show, pulverized bed combustion is the dominating technology in coal-fired power generation, but the importance of fluidized bed combustion is slowly increasing.

Table 38 — Contribution of Different Combustion Technologies to the Power Generation through Fossil Fuel Combustion in West Germany, 1983–1990 (percent)

	1983	1987	1989	1990
Pulverized bed combustion	24.2	55.0	59.8	59.1
Grate-fired boilers	3.5	1.8	1.4	1.5
Fluidized bed combustion	0.0	0.0	0.9	1.4
Oil and gas combustion	54.5	29.7	31.7	32.1
Others	17.7	13.5	6.2	6.0

Source: VDEW (current issues).

The growing interest in fluidized bed combustion can be traced back to the fact that this technology not only allows a higher energy output per t of coal burned but also lower emissions of nitrous oxides (NO_x) and sulphur dioxides (SO_2) per t of coal (see OECD 1989). Moreover, fluidized bed combustion releases as fly ash only about 15 percent of the total ash produced during the combustion process, while the remaining ash falls down to the bottom of the boiler, where it can easily be collected (see Swedish Environmental Protection Agency 1991). In contrast to this, about 20–40 percent of the resulting ash becomes fly ash in the grate-fired boilers; the respective figure for pulverized coal combustion is 70–100 percent (Swedish Environmental Protection Agency 1991). Correspondingly, the emission coefficients of the three technologies vary widely. Table 39 shows the specific dust content in raw gas (assuming 10 percent of ash in the coal), the specific cadmium concentration in dust, and the specific cadmium emissions per t of coal burned (assuming end-of-pipe-treatment with a removal rate of 99 percent), as estimated by Pacyna (1991). These figures indicate that a replacement of pulverized bed boilers through fluidized bed boilers would reduce airborne cadmium emissions per t of coal by a factor of more than 5. According to the estimates of emissions presented in Section B.II, this implies a reduction potential in the order of magnitude of 1–4 t Cd/yr.

Table 39 — Dust Content in Raw Gas, Cadmium Concentration in Dust, and Cadmium Emissions per Ton of Coal for Different Types of Coal Combustion Technologies

Type of boiler	kg dust/t coal	mg Cd/kg dust	g Cd/t coal
Pulverized bed	73.3	30.3	2.22
Grate-fired	59.1	18.4	1.09
Fluidized bed	13.6	31.0	0.42

Source: Pacyna (1991).

Besides fluidized bed combustion, there exist a number of other clean technologies for the combustion of coal, which are currently in an experimental or pilot-plant stage. Although the primary environmental goal of these technologies is related to SO_2 and NO_x, they usually also reduce emissions of heavy metals. The most promising development seems to be the integrated gasification combined cycle (IGCC), which allows lower emission levels than fluidized bed combustion (see OECD 1987). Although a demonstration plant was completed in the United States (OECD 1989), the large-scale feasibility of this technology has not been fully proven and the Swedish Environmental

Protection Agency (1991) concludes that IGCC can hardly be considered as best available technology yet.

b. Production of Nonferrous Metals

The conventional thermal technology employed in the production of nonferrous metals consists of smelting and sintering of zinc, lead and copper concentrates. These concentrates contain considerable amounts of cadmium, which are partly volatilized and released to the exhaust air during the process of refining. Although the end-of-pipe measures employed in the production of nonferrous metals are highly efficient in terms of removal rates, there still remain significant cadmium emissions due to the enormous throughput of cadmium-containing material. Since the scope of end-of-pipe measures seems to be almost exhausted, further reductions in emissions can only be achieved through new clean technologies.

In the case of zinc production, the conventional thermal process and the low-polluting electrolytic process result in airborne cadmium emissions that differ significantly. The emission coefficient of the thermal zinc refining processes employed in West Germany (imperial smelting) amounts to 50–60 g Cd/t Zn produced, whereas the emission coefficient of electrolytic refining amounts to only 0.2 g Cd/t. Since the mid-eighties, the thermal process has been reduced in capacity by a factor of almost 15 and, at present, only one minor plant is still in operation (Metallgesellschaft AG 1992). However, if one accounts for the large difference in emission coefficients, one can conclude that the complete replacement of the thermal process, i.e., closing down of the last plant, would result in a significant reduction of airborne cadmium emissions.

In conventional lead production, lead ore concentrates and different types of secondary materials are processed in three steps: sintering, reduction of sinter in a shaft furnace, and pyro- or hydrometallurgical refining. This process is known to cause significant cadmium emissions particularly in the case of primary production (see Table 40). In contrast to the conventional technology, there are some new clean technologies that replace sinter plants and shaft furnace operations by direct smelting in a closed system. At present, direct smelting processes are operated at three plants on an industrial scale (see Table 41). However, emission coefficients are only available for the so-called QSL process (see Table 40). These coefficients indicate that the replacement of the conventional technology by the QSL process would reduce airborne cadmium emissions per t of primary lead by a factor of more than 10. In absolute terms this implies a reduction potential of about 1–2 t Cd/yr.

Finally, it should be noted that the QSL process is superior to conventional technologies not only in terms of emissions but also in terms of costs. According to Matzke (1988) investment and operation costs are by 30–40 percent lower compared with the conventional technology. Because of this cost advantage, one can expect that the QSL process will be adopted by the firms, regardless whether the environmental regulations in this area are tightened or not.

Table 40 — Emission Coefficients for Conventional and New Lead Production Technologies (g Cd/t lead)

	Conventional lead production		QSL process
	primary production	secondary production	
Güthner (1989)	1.3	na	0.100
ERL Report (1990)	3.0	2.2	na
Metallgesellschaft AG (1990)	na	na	0.165
Pacyna (1991)	10.0	2.5	na

Table 41 — Location and Capacity of New Lead Production Technologies, Situation as of the Early 1990s

Process	Location of plant	Capacity (t/yr)
Kivcet process	Portovesme (Italy)	84,000
Boliden Kaldo process	Rönnskär (Sweden)	60,000
QSL process	Stolberg (Germany)	85,000

Source: Metallgesellschaft (1990); Swedish Environmental Protection Agency (1991).

II. Controlling Aqueous Cadmium Emissions

The discussion of the different sources of aqueous cadmium emissions in Section B.III has already indicated that controlling these emissions is going to be a very complex task. Whereas in the past, an impressive reduction of the cadmium transport in rivers was achieved through an effective control of the largest point sources in the zinc industry, further reductions will become much more difficult, since the share of point source emissions has fallen such that it is the nonpoint sources, that also need to be the subject of pollution control policies.

The major industrial activities contributing about two third of the 4–5 t Cd emissions per year are the closely connected coke production and the iron and steel industry. First, we assess the technological options and the likely economic effects of reductions in these activities. As far as nonpoint emissions are concerned, identifying and quantifying reduction potentials becomes excessively complex. Section B.III.2 has already shown that not only the estimate of the total amount of nonpoint emissions is subject to large measurement errors. Over and above that, one can say even less about the share of the different sources contributing to the overall nonpoint pollution. Still, their reductions can provide the largest potential for an improvement of the cadmium load in rivers.

1. Point Source Emissions

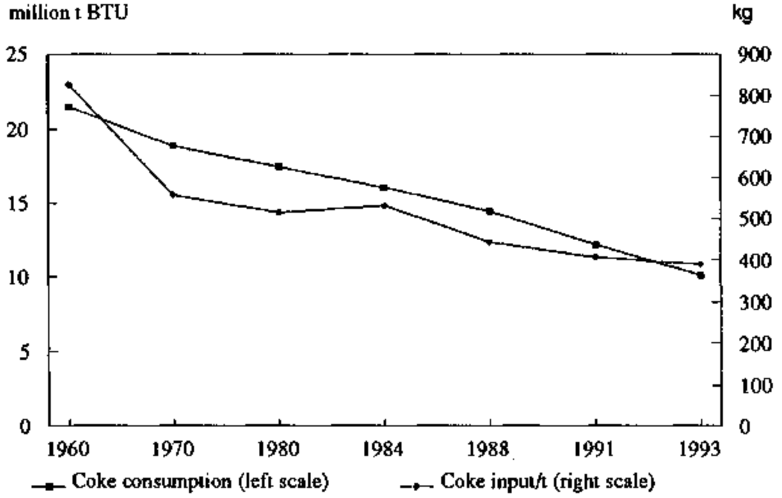
An estimate of the different point source emissions is faced with considerable uncertainty about the appropriate emission coefficients. Our estimate of roughly 4 t Cd that enters German rivers differs widely from the 26 t estimated in the ERL Report (1990). In Table 16, we have summarized our conclusions of the available information about the different industrial sources. According to our estimate, the most important emittors are by now the iron and steel industry (approximately 1.8 t/yr) together with the coke production (0.55 t/yr), which is closely connected with the iron and steel industry, as well as the secondary lead production (approximately 1.0 t/yr). All other emissions imposed through the inadvertant input of cadmium in the production process are almost negligible. As far as cadmium is used as an intentional input, the battery manufacturers still seem to emit almost 300 kg/yr.

The aqueous emissions of cadmium in coke and iron and steel production are to some extent closely related to the control of airborne emissions. In order to reduce the emissions of dust and other gases, dust arresters and other cleaning devices such as desulphurization have been introduced throughout the industry. As these investments have been responsible for the strong reduction in airborne emissions, they have increased aqueous emissions. Scrubbers and, later, wet electrostatic precipitators removed the dust particles by condensing them on water, which needed to be treated before it was discharged into rivers. This is another example of the substitution of emissions between environmental media. However, these older dust arresters are increasingly replaced by fabric filters with a better removal capacity (see Figure 7 and the discussion in Section C.I.1). Hence, the cadmium-containing dust is now increasingly removed from the raw gas and turned into solid waste, so that not only airborne but also aqueous emissions are reduced.

Another source of potential aqueous cadmium emissions is the process water in the coke production, the iron manufacturing, and, finally, the steel production. The different processes and production steps are too complex to be discussed in this study. However, the main options for reducing cadmium emissions — at least for Germany — are, firstly, a shrinking production of iron and steel, and, secondly, new processes with lower emission coefficients. Figure 9 shows that the consumption of coke in the iron production has been reduced considerably. This has apparently been achieved through more efficient production processes, what the falling coke input per t of iron produced indicates. This efficiency gain is also illustrated in Figure 10, which shows that the total amount of wastewater in the iron and steel industry has been falling since the eighties.

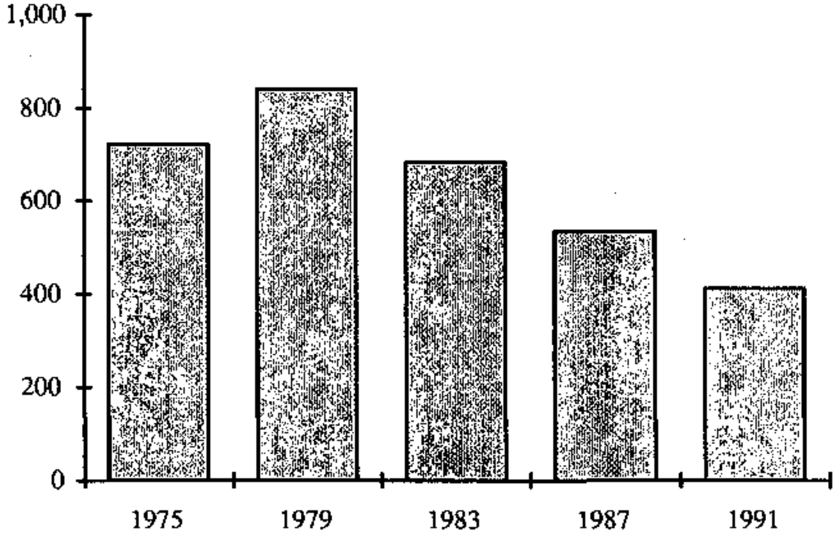
The technical scope for reducing cadmium emissions into the water in the production of secondary lead seems to be diverse. Some of the emissions occur through the washout from nonpoint airborne emissions, some stem from the wastewater of dust arresters. Since the water consumption falls when one switches from scrubbers to wet electrostatic precipitators and to fabric filters, the total amount of wastewater discharged into rivers will fall with the introduction of more efficient dust arresters. Moreover, a project designed to reduce nonpoint emissions in a secondary lead mill by reorganizing and upgrading of production steps has shown remarkable results (see Schenker 1985). And

Figure 9 — Coke Consumption in Blast Furnaces and Coke Input per Ton of Iron Produced in West Germany, 1960–1993



Source: Statistisches Bundesamt (1988, 1992, 1994).

Figure 10 — Wastewater in the Iron and Steel Industry in West Germany, 1975–1991 (1,000 m^3)



Source: Statistisches Bundesamt (1992); own estimate for 1991.

finally, further reductions of emissions into the water may also arise from the QSL process, which has practically no gas and dust emissions, thus reducing the need for dust arresters and their washing capacities (see Section C.I.3.b).

2. Nonpoint Source Emissions

As pointed out in Section B.III, aqueous cadmium emissions from nonpoint sources can be traced back to three major roots: runoff from the agricultural use of cadmium-containing phosphate fertilizer and sewage sludge, atmospheric fallout to surface waters, and erosion of cadmium-containing soils. Measures for reducing airborne emissions have already been discussed in Section C.I. Therefore, the following sections concentrate on phosphate fertilizer, sewage sludge, and erosion.

a. Phosphate Fertilizer

The inflow of cadmium into the soil through phosphate fertilizers can be reduced in three different ways: (i) raw materials with lower cadmium content can be used in the production of fertilizers, (ii) less phosphate fertilizers can be consumed in agriculture, and (iii) cadmium can be removed from the phosphates.

The first option has already been implemented through the reduction of raw phosphate imports from African countries (see Section B.III). The second option has also materialized — willingly or unwillingly —, which is evident from the declining consumption of fertilizer. The removal of cadmium from the raw phosphates has not been used so far, but several processes for the extraction of cadmium in the production of phosphate fertilizer are available today. Whereas the removal from raw phosphate through high-temperature processes turned out to be too costly, most of the separation processes for phosphoric acids were not designed for all types of acids with different phosphate and cadmium contents, or had problems with the disposal of the removed cadmium. A report by Becker (1989) concluded that only the extraction process from wet phosphoric acid by a solvent phospheric acid could be considered sufficiently universal and cost efficient. This process has by now been developed to large-scale applicability, and a plant with a capacity of 70,000 t P_2O_5/yr has already been built in Budenheim/Germany (see Chemische Fabrik Budenheim 1991).

According to Becker (1989), the "Budenheim process" seems to have several advantages vis-à-vis other processes. For example, it can process phosphoric acids from different sources with a wide range of contaminations.[43] Moreover, the "Budenheim process" has by far the lowest set up costs; a unit with the capacity of 1,000 t P_2O_5/day has unit fix costs of 0.92 ecus/t P_2O_5 compared with between 2.54 and 6.76 ecus/t P_2O_5 for the alternative processes (Becker 1989). Variable unit costs in terms of the quantity of P_2O_5 depend on a variety of factors, so that even a relatively wide range of values cannot be given. Table 42 gives four examples of costs, where the processed material varies in terms of the P_2O_5 content of the phosphoric acid, in terms of the cadmium content of the raw acid, and in terms of the reduction of the cadmium.[44] Unfortunately, we cannot deduct a cost function in terms of the degree of cadmium reduction from these information. However, we can draw a number of important conclusions:

- The higher the original cadmium content of the acid, the lower the variable costs of reduction in terms of the quantity of cadmium re-

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[43] The technical details are described in a report to the Minister of Science and Technology (see Frankenfeld and Ruschke 1985).

[44] An additional complication is caused by the high content of organic material in the Florida phosphate, which requires a separate processing step, which almost doubles the unit costs.

Table 42 — Unit Costs of Removing Cadmium from Phosphoric Acid in the "Budenheim Process", 1985

	Type of phosphoric acid			
	Florida	Morocco	North Carolina	Togo
Cadmium content (mg/kg)	6.00	18.00	33.00	37.00
P_2O_5 content (percent)	29.60	57.00	53.40	26.00
Cadmium reduction (mg/kg)	5.00	14.00	28.00	36.00
Remaining cadmium (mg/kg)	1.00	4.00	5.00	1.00
Cost/t P_2O_5 (DM/t)	7.30[a]	4.74	6.84	8.91
Cost/kg of Cd removed (DM/kg)	429.41[a]	189.60	131.54	64.10

[a] Cost without cleaning step of organic material.

Source: Frankenfeld and Ruschke (1985).

moved, i.e., separating one kilogram of cadmium from acid from Togo with 37 mg Cd/kg costs only DM64.10 compared with costs of DM429.41 for removing the same amount from the Florida acid with a contamination of only 6 mg Cd/kg.

- Different reduction percentages can be achieved through a variation of the extraction steps. It is in general possible to achieve a reduction to below a concentration of 1 mg Cd/kg. There is no clear relationship between reduction costs and the degree of removal, since the P_2O_5 content seems to exert a stronger influence, with rising costs for lower P_2O_5 contents of the acid, than the variation in removal rates. Frankenfeld and Ruschke (1985) therefore recommend to place the cadmium extraction as late as possible in the processing chain of the phosphoric acid.
- The removal costs in terms of the quantity of P_2O_5 clearly favour relatively low reduction percentages; the least expensive examples are the reductions from 18 to 4 mg Cd/kg (Morocco) and from 33 to 5 mg Cd/kg (North Carolina). From the viewpoint of the phosphate fertilizer producer, only the cadmium extraction from high to medium contamination seems economical.
- From an overall economic perspective, the results of the experiments presented in Table 42 suggest that the costs of reduction (measured in DM per kilogram of cadmium removed) fall more, the larger the total amount of cadmium removed is. Not only the fixed costs but also the declining variable costs contribute to this result, which represents a downward sloping average cost curve. Such scale effects indicate that —

seen from the perspective of the damage prevented — it is economical to reduce cadmium to concentrations of as low as 1 mg Cd/kg.

- If one compares the costs of removing cadmium from phosphate fertilizers with those of removing other depositions of cadmium on the soils, there is probably no other policy that could be as inexpensive as this one. For example, the reduction of nonpoint atmospheric depositions is much more expensive. Emissions from large coal-fired industrial furnaces could be reduced through more advanced dust filters, yet their costs of removing one kilogram of cadmium are in the range of DM4,000–5,000. For thermal zinc refining, reduction costs are in the range of DM2,000–2,600 (see Section C.I).
- The price effect of a cadmium removal in phosphate fertilizers would also be quite moderate. If we take a price of around 1,500 DM/t P_2O_5 for fertilizer (Statistisches Bundesamt 1991b; Schindler 1986), then additional costs of between DM5 and DM20 amount to price increases of far below two percent.

b. Sewage Sludge

Essentially, there exist two options for reducing aqueous cadmium emissions caused by the agricultural use of sewage sludge: (i) reducing the cadmium concentration in sewage sludge, and (ii) reducing the agricultural application of sewage sludge. Both options, however, pose their own technological, economic and environmental problems.

Concerning the first option, it should be recognized that about 80 percent of the cadmium content in the sewage sludge of communal treatment facilities originate from industrial wastewaters, whereas only about 20 percent can be traced back to other sources like household wastewaters and runoff from surfaced areas caught in the public sewer systems (see Section B.III). Consequently, if one wants to reduce the cadmium content of sewage sludge, one should concentrate on reducing the cadmium concentration in industrial wastewaters entering communal treatment facilities. However, the discussion in Section C.II.1 has already shown that, at present, there seems to be only a very limited scope for further reducing cadmium loads at the point of discharge.

The second option would have additional costs in the form of additional purchases of fertilizers and increase the humus content of the soil. In addition, the sewage sludge needs either to be disposed of in landfills or to be incinerated. Both measures, however, rechannel the cadmium from a direct application on agricultural soils to airborne emissions and depositions in landfills. Moreover, reducing the cadmium transport into the soil by reducing the use of sewage sludge will only lower the cadmium load on rural soils, which are not heavily contaminated at the moment.

c. Erosion of Cadmium-Containing Soils

As far as erosion is concerned, it is possible that significant amounts of cadmium may be transported into rivers and coastal waters (see Section B.III.2.b). A reduction of these loads could either be achieved through measures to reduce soil erosion or through measures to reduce of the cadmium content of soil under the threat of erosion. The option to reduce the cadmium deposition on these soils would have little effect, since the share of newly emitted anthropogenic cadmium in these soils is probably quite small, so that only in the very long run a reduction of cadmium in the sediments can be expected. Consequently, the only remaining option is to reduce soil erosion itself, e.g., by limiting deforestation.

D. Summary and Conclusions

I. Cadmium Flows and Environmental Threat

Cadmium as one of the most toxic heavy metals. The threat of cadmium for human health and the environment contrasts significantly with the little knowledge about the cadmium flows in the environment and — more specifically — in the economy. In the present study, all available information about the sources and the fate of cadmium has been evaluated within the context of an integrated industrial metabolism approach.

Obtaining a complete picture of cadmium flows is complicated by the different paths in which cadmium moves back and forth between different environmental media. Whereas over 1,000 t Cd are added to the stock of cadmium in the human environment in West Germany every year, the total flow through the economy is about 3,000 t. The additional 1,000 t become incorporated into products with very different lifetimes. These products then are disposed of or recycled, thus reentering production processes. Their contribution must be important if one considers that the flow is almost three times higher than the change in stock. This also means that the intentional use of cadmium in production is less important as far as environmental effects are concerned than the unintentional input through contaminated materials. Measures to reduce the flow of cadmium therefore depend to a considerable extent on past decisions about the use of cadmium in products.

The intentional use of cadmium is relatively well documented, so that the cadmium content of products intentionally contaminated with cadmium is known. However, the cadmium content of products unintentionally contaminated with cadmium and the cadmium emissions of production processes are practically unknown. These contaminations come from recycled materials as well as from raw materials containing cadmium as a trace element. Hence, even if the intentional use of cadmium were to be reduced, the inadvertant input would still need to be controlled. Ironically, waste management policies based on increased recycling would also channel cadmium back into production processes and would thus increase cadmium flows.

Cadmium that is not contained in products is returned to the environment, i.e., air, water, and soils. It is clear that airborne emissions are eventually deposited on the surface, be it water or soil. And even cadmium depositions onto the soil are partly mobilized and enter rivers and lakes. This mobilized cadmium eventually ends up in the sediment of the oceans or of lakes.

Nevertheless, we have tried to assess the emissions into all three media and have presented the results separately. It would be incorrect, however, to add up the emissions into the various environmental media.

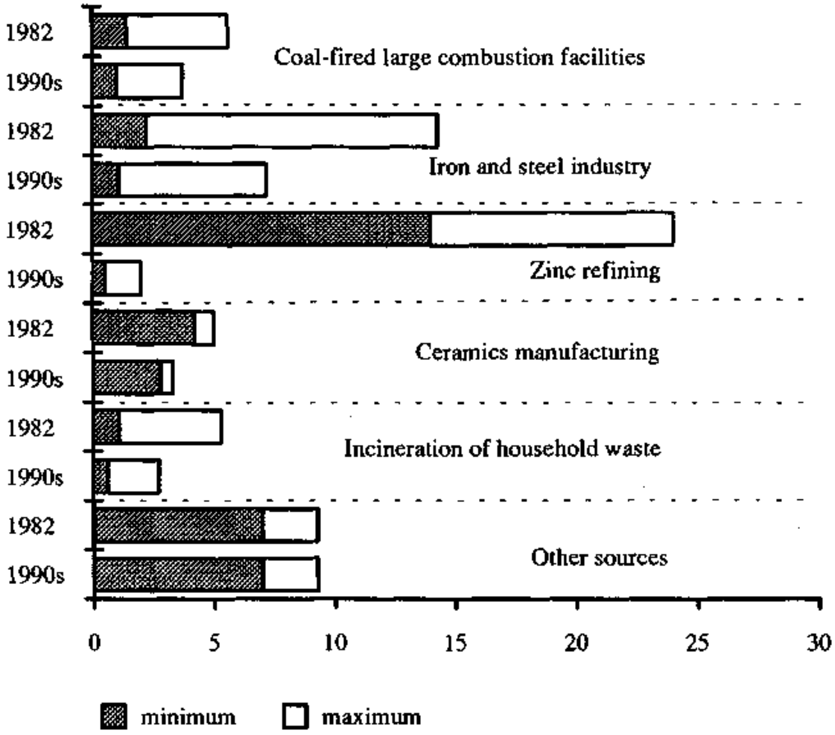
Most studies of cadmium emissions into the air rely on primary data sources from the early eighties which reveal that somewhere between 25 and at most 60 t Cd were emitted in that time period in West Germany, with the most important contributors being

- the iron and steel industry (through scrap melting);
- the combustion of fossil fuels, mostly coal;
- the manufacturing of ceramics;
- and the incineration of household waste.

Since the early eighties, however, the regulations concerning emissions of flue dust that carries airborne cadmium emissions have been considerably tightened by the Ordinance on Large Combustion Facilities of 1983, the Technical Directive on Air Pollution of 1986 and the Ordinance on Waste Incineration Plants of 1990. The industry has reacted to the new emission standards by applying better end-of-pipe technologies and by introducing production processes that have lower emission coefficients. The current time is a transition period during which the diffusion of the new technologies takes place. Our "best guess" about the result of this diffusion (see Figure 11) is based on the following assumptions for the five major cadmium emittors:

- The regulations on the combustion of fossil fuels have induced the installation of better end-of-pipe technologies, which have led to a 30-percent reduction of cadmium emissions from burning fossil fuels.
- The iron and steel industry is increasingly using electric arc processes with lower emission coefficients and is subject to much tighter emission standards, so that a 50-percent reduction between 1982 and the early nineties seems reasonable.
- The emissions caused by the joint production of zinc and cadmium depend predominantly on the process technology. Because the high-polluting thermal process has been used less considerably since the mid-eighties, we assume that only about 0.5–2 t Cd are still being emitted, compared with 25 t in 1982.
- In the glass and ceramics industry, the only reductions derive from improvements in end-of-pipe technologies. Since these industries are regulated by the Technical Directive on Air Pollution, we also assume a 30-percent reduction in cadmium emissions since 1982.

Figure 11 — Airborne Cadmium Emissions in West Germany, 1982 and Early 1990s (t/yr)



Source: Umweltbundesamt (1991); own calculations (best guess).

- The strongest reduction in permitted emissions has taken place for waste incineration. We therefore assume a 50-percent reduction in cadmium emissions.

Taking these reductions together and assuming that the other sources of emissions remained constant, we guess that the airborne emissions of cadmium have been reduced from about 25–60 t in the early eighties to about 13–24 t in the early nineties. Figure 11 shows that the most important contribution to this reduction came from the technology switch in the zinc industry.

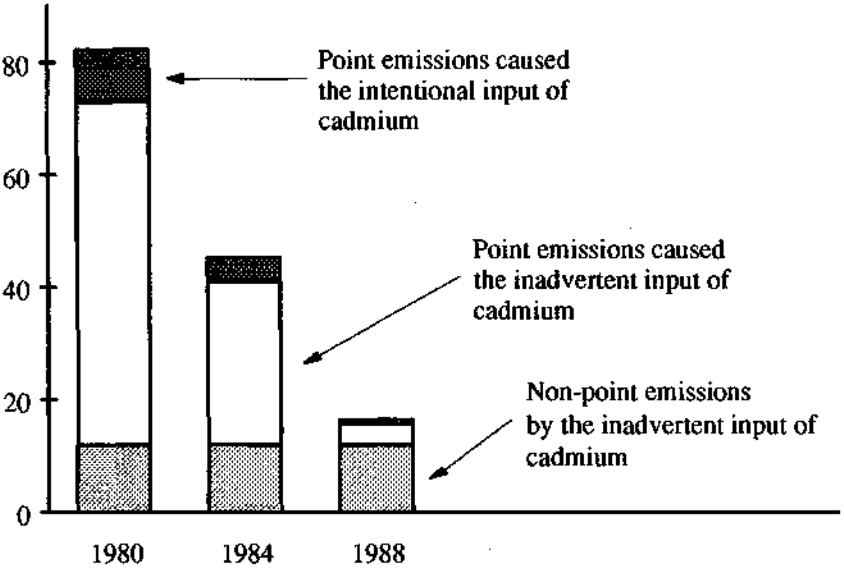
The medium- and long-run development of airborne cadmium emissions depends on a number of sector-specific factors. Emissions of coal-burning power plants would be strongly reduced if the requirement of the *Jahrhundertvertrag,* which forces the power industry to burn domestic coal instead of gas or oil, were reduced. In addition, further improvements in filter technologies could lead to some additional reductions. This is also true for the glass and ceramics industry. The emission standards for industrial thermal processes are not yet as tight as those for waste incineration. Such additional reductions must probably be paid with strongly rising marginal costs. Some tighter standards have already been incorporated for the period after 1996 in the current directives. Moreover, the emissions of the iron and steel industry will be reduced significantly after the middle of the nineties. This is due to the input of scrap metal, which enters production processes with a time lag of about 20 years after production. Since the peak of cadmium consumption in metal plating was in 1976, the cadmium content of scrap metal will possibly increase until the mid nineties and fall thereafter.

The emissions of cadmium into rivers and lakes can be grouped, on the one hand, as coming from point and nonpoint sources, and on the other hand, as resulting from intentional and unintentional use of cadmium in economic processes. Whereas point sources are comparatively easy to estimate, nonpoint sources by their very nature are almost impossible to measure. Nonpoint sources therefore can only be assessed by comparing cadmium loads in rivers with the emissions of point sources. The difference then can be attributed to nonpoint emissions, but only if the sedimentation of cadmium does not provide another complication, which has to be accounted for. For this reason, we have only used data of the cadmium load in the Rhine River Basin. For the other large rivers, cadmium loads can hardly be measured accurately because of complex conditions in the tidal zones.

Figure 12 summarizes our "best guess" concerning the development of aqueous cadmium emissions in West Germany. Since the difference between cadmium emissions from point sources and cadmium loads was about equal in 1982 and 1988, we assume, given the lack of better information, that nonpoint emissions remained constant over this period. Figure 12 shows that the emissions of point sources have been drastically reduced, so that nonpoint sources, which were only one sixth of point sources at the end of the seventies are now about three times higher than point sources. Hence, the potential for reducing emissions of point sources seems to be almost exhausted, so that further reductions in the cadmium load of rivers need to be achieved by measures that reduce nonpoint emissions.

The major sources of nonpoint emissions into rivers come from the deposition of airborne cadmium emissions and from the use of phosphate fertilizers. Although it is known how much cadmium is emitted into the air (in the early nineties probably between 13 and 24 t/yr) and applied through phosphates (around 30 t/yr), we do not possess information about the diffusion of these loads. Some of the airborne emissions are "exported" through atmospheric transports, other emissions are "imported", then they are deposited in the soil. Together with cadmium in phosphates, these depositions can enter the biomass, since plants accumulate cadmium quite easily, they can remain in the ground, or they can be washed out into rivers and lakes.

Figure 12 — Aqueous Cadmium Emissions in West Germany, 1980, 1984, and 1988 (t/yr)



Source: Own calculations, based on Tables 12 and 16 to 18 (best guess).

Whereas emissions into rivers are eventually transported into the oceans, where they are deposited in the sediment, airborne emissions are eventually deposited in soils. Hence, the environmental damage of aqueous emissions in the biosphere takes place in rivers — and if there is no sedimentation, only for a short time — during the transport of the cadmium. For airborne emissions, however, the damage materializes in the soil, where cadmium is stored for a relatively long time before it may become removed again. In addition to the atmospheric deposition, there are other sources that also contribute to the accumulation of cadmium in the soil, namely the application of fertilizer and of sewage sludge in agriculture.

The cadmium load in German soils shows wide regional variation, with heavy depositions and high cadmium concentration in the soil in the vicinity of industrial centers, as well as in urban areas. The regional pattern of likely depositions, which has been discussed in Section B.IV.1, varies widely and is attributable to the different emission sources and patterns of transport. The most important identifiable sources of cadmium depositions (fertilizer, sewage sludge, long-range and local atmospheric transport) are very unequally distributed over Germany. The qualitative assessment in Table 43 is based on the information about the transport of cadmium as well as on the regulations concerning the cadmium content of fertilizers and the use of sewage sludge. Table 43 shows that in urban and industrial areas local air pollution is the major contributor to the contamination of soils with cadmium.

Table 43 — The Potential Effects of Various Cadmium Sources on Land in Alternative Uses

	Urban and industrial areas	Rural agricultural land	Forests	Water
Fertilizer	some	some	none	little
Sewage sludge	none	(important)	none	none
Long-range atmospheric transport	some	some	important	important
Local atmospheric transport	important	none	none	some

Consequently, the largest reduction in the cadmium load could be achieved through measures directed towards local emitters. On land in agricultural production, sewage sludge may provide the most important input of cadmium. Its environmental threat, however, depends on the type of soil, i.e., its pH and its organic matter. Cadmium depositions through long-range atmospheric transport and through phosphate fertilizer are of less importance. Although forests receive little depositions, in absolute terms, they are rather sensitive to the atmospheric depositions, since the rain often has a pH as low as 4, thus supporting the washout of heavy metals as well as the uptake in the plants. The contamination of water in rivers is extremely small today, so that health threats are unlikely. Only the accumulation of cadmium in sediments of estuaries and especially the Wadden Seas has led over time to potential environmental hazards. Since in Germany the aqueous point emissions have been reduced significantly, the most important input probably comes from the deposition of long-range transports of dust and the large quantity of water that even at low cadmium concentrations carries quite large absolute quantities of cadmium.

II. Reducing Cadmium Flows: Potentials and Economic Costs

In order to identify economically efficient measures that would reduce the environmental effects of the various sources of cadmium emissions, one needs to set the potential to reduce the various emissions as well as their likely costs in relation to the environmental damages that the measures would abate. Unfortunately, in many cases only little is known about the costs of abatement and even less about the value of the damage. The technical options can be identified, however:

- Better and larger end-of-pipe technologies that exhibit a better cleaning performance of the raw gas or the wastewater could be introduced.
- New production processes with lower emission coefficients of cadmium (clean technologies) could be introduced.
- On the input side, cadmium as an intentional input could be substituted by other materials. If cadmium enters the production process as an unintentional input, i.e., as a contamination of other inputs, changes in the type of input could reduce the cadmium load and cadmium emissions.

The potential of the first technical option for reducing cadmium airborne emissions, namely introducing end-of-pipe technologies, is likely to be exhausted by now. The introduction of fabric filters and electrostatic precipitators has lead to an increase in the purification rates from about 95 to beyond 99.5 percent for dust, on which most of the cadmium particles are bound, and from 90 to about 95 percent for cadmium alone. These technologies can be considered as best available technologies without a major improvement in sight. German regulations require for large facilities exhaust air concentrations that effectively can only be met through these best available technologies. Hence, a significant further reduction of emissions cannot be expected by end-of-pipe measures, although some minor improvements through better design, surveillance, and maintenance are still conceivable.

The cost structure for introducing these new dust arresters is quite different from the prior generation such as scrubbers and cyclones. The investment costs have become significantly higher, whereas the operating costs have become lower. The overall unit costs of cleaning a given quantity of raw gas are still lower than for the older end-of-pipe technologies. Therefore, the incentive to switch to the new technologies already comes from the cost side — even without further regulation — if the old dust arresters are written off. Especially firms with large plants have a strong incentive for switching to the advanced arresters, since the average investment costs decrease with increases in the capacity of the plant. This advantage of the new end-of-pipe technologies for large emitters turns into a disadvantage for the many small emission sources, which are responsible for an increasing share of total emissions. They become increasingly less able to afford the high fixed costs of these technologies. One can also predict a behavioral feature for the use of dust arresters. If economic instruments like an emission tax were introduced, the firm would always use the full cleaning potential of the arrester, since the falling average costs will not make it profitable to run below the capacity limit.

Attempts to calculate the costs of cleaning the raw gas in terms of the quantity of cadmium reduced lead to widely varying figures depending on a number of factors such as:

- the production processes on which the dust arresters are installed;
- the cadmium concentration of the raw gas;
- and the distribution of cadmium on dust particles of different size.

The removal of 1 kg Cd with an electrostatic precipitator from a thermal zinc refining process costs approximately DM2,000, whereas the same removal in a coal-fired industrial furnace costs between DM4,000 and 6,000. However, such numbers are of limited economic value, since the abatement processes in question remove dust from the raw gas, and this dust by itself creates negative environmental effects. In addition, they reduce the emissions of many more substances with negative environmental effects that are contained in the raw gas. Consequently, one cannot define the abatement costs for airborne cadmium emissions in an economically meaningful way.

The second option for reducing cadmium emissions, namely introducing clean technologies, still offers room for improvements. Several technologies for coal-fired industrial furnaces with quite different emission coefficients are in use at present. The diffusion of less polluting furnace technology is still taking place; especially the fluidized bed combustion process is increasingly installed. The complete replacement of older processes through this new technology could reduce airborne cadmium emissions by 4–7 percent. Cost figures for cadmium abatement are equally meaningless, since the new processes also emit less NO_x and SO_2 per t of coal burned. There are also other technologies in the "pilot-plant stage" that will offer even more reduction potential together with a more efficient energy production.

In the nonferrous metal industry, a steady process of technical change towards less polluting technologies has been taking place since the eighties. In zinc refining the electrolytic process has, at least in Germany, replaced the thermal process, with the exception of one plant for the processing of scrap materials that cannot be processed otherwise. This has resulted in a drastic reduction of cadmium emissions. New processes — the most advanced being the QSL process — have been developed and are about to be introduced in lead production. Their principle is to encapsulate the whole production process thus reducing the emissions of cadmium and other substances by a factor of more than 10. The widespread introduction of such technologies will provide further potential for reducing the emissions of cadmium. The QSL process also has the advantage of lower unit costs, so that there is an incentive to introduce this technology regardless of the environmental regulations.

A large proportion of the material flow of cadmium in Germany is caused by the intentional use in the production of stabilizers, color pigments, batteries, plated commodities, and a few other products with little cadmium input. The first four product groups account for almost all of the cadmium in products, so that a reduction of the material flow of cadmium in Germany — and a reduction of the emissions — can only be achieved if the third option can be applied, i.e., if suitable substitutes for cadmium can be found. Cadmium in stabilizers is mainly used to protect plastic material for outdoor use, mostly window frames, from the radiation of the sun. However, all substitution options have limitations in that it is not clear whether the overall net effect on the environment is indeed positive. The substituted products themselves may have less cadmium, but may, at the same time, emit other noxious substances. The effect of input substitution on process-related emissions is extremely small, since the stabilizer industry has a large material flow of cadmium but very little emissions due to the clean production processes.

Small reductions of emissions could be achieved by replacing cadmium in pigments for coloring plastics and other products. This replacement may not so much reduce emissions that occur in the production process but those that result after these products have been turned into waste and are incinerated. The situation with batteries is very similar, there being little obvious chance for a significant reduction in emissions. The use of cadmium in plating has been falling by almost 75 percent since the mid-seventies and is likely to fall even further, since only in a few products, mainly space and military products, such plating is still needed.

The reduction of cadmium emissions through replacement of those inputs that contain cadmium as a contamination is more promising. Fuel-switching in the energy generation sector provides a significant potential for reducing airborne cadmium emissions. A replacement of coal with high cadmium content by coal with a lower content is an inexpensive option, which is only limited by the coal policy of the German government. Similar changes are not available in the metal industries, since the cadmium contamination of the ores is not geographically differentiated.

The investigation of airborne cadmium emissions has led to the conclusion that the most promising potential for reducing these emissions comes from technical progress in industrial production processes, the clean technologies, whereas end-of-pipe abatement and input substitution do not offer large reductions. The other media in which cadmium is emitted are water (i.e., rivers, lakes, and finally, the oceans) and the soil. The interactions between airborne emissions, soil deposition, and washout into rivers and lakes is highly complex, since it depends on atmospheric conditions, biochemical processes, and human activities.

For the transport of cadmium through rivers into the North Sea, it has been estimated that about 16 t/yr of cadmium leave Germany through rivers. However, only about 4.2 t/yr can be identified as originating from point sources such as municipal and industrial wastewater treatment plants. The other approximately 12 t/yr can originate from the

- direct atmospheric deposition of airborne emissions to surface waters,
- runoff from atmospheric deposition on soils,
- runoff from the application of sewage sludge on agricultural soils,
- runoff from the use of phosphate fertilizers containing cadmium, and
- the erosion of contaminated soils.

Given the small share of rivers and lakes on the total surface area of Germany, the direct effect of atmospheric deposition is probably quite low. However, for the other nonpoint sources this question cannot be answered by simply looking at the deposition of cadmium on soils, since rather complex processes take place after cadmium has entered the soil. The dynamics of these processes then determine the final fate of cadmium either in the runoff — on the surface and in the groundwater —, its fixation in the soil, or the further removal through the harvesting of crops that have assimilated the cadmium.

In addition, the cadmium load on German soils shows a wide regional variation with heavy depositions and concentrations in the vicinity of industrial centers. The short-range transport of airborne cadmium emissions and the relatively small other sources of cadmium depositions, i.e., phosphate fertilizers and sewage sludge, are responsible for this uneven distribution. In order to assess the reduction potential for nonpoint pollution in rivers, one therefore needs to go all the way back to the contamination of soils and its causes. The technical potential for reducing the deposition of cadmium on soils can be plausibly predicted and even some reckoning about the relative dimension of costs is possible. But translating those into t Cd reduced in rivers or into costs per t Cd removed from rivers is apparently impossible as the complex soil dynamics of cadmium, which are hinted at in Section B.IV, prevent establishing any meaningful relationship. There are simply too many uncontrolled variables involved in such an assessment.

Therefore, Table 44 summarizes only the likely technical potential and the possible dimension of costs for reducing the contamination of areas with different land use. It contains a condensed presentation of our judgement about the different reduction options and their costs, which have been presented in Chapter C.

Table 44 — The Technical Potential and Costs for Reducing Cadmium Deposition in Germany[a]

	Urban and industrial areas	Rural agricultural land	Forests	Water
Fertilizer	good *low cost*	good *low cost*	none –	little –
Sewage sludge	none –	some little direct costs	none –	none –
Long-range atmospheric transport	little *high costs*	little *high costs*	good *high costs*	good *high costs*
Local atmospheric transport	little *unknown costs*	none –	none –	little *unknown costs*

[a] The upper entry in each cell denotes the likely technical potential, the lower entry (in italics) the likely removal costs.

In urban and industrial areas, the *local atmospheric transport* is the most important source of soil contamination. Consequently, the largest reduction in the cadmium load could be achieved through measures directed towards local emitters, which consist mostly of automobile traffic, industrial emissions, and domestic heating facilities. Yet, measures to reduce these emissions will probably be quite costly, since emission controls on industrial processes are already quite tight and investment in new heating systems would be extremely costly in view of the very low emission coefficients of cadmium from fossil fuels. On land in agricultural production, sewage sludge may provide the most important input of cadmium. Its environmental threat, however, depends on the type of soil, i.e., its pH and its organic matter. Cadmium depositions through long-range atmospheric transport and through phosphate fertilizer are of less importance. Although forests receive little depositions in absolute terms, they are rather sensitive to the atmospheric depositions, since the rain often has a pH as low as 4, thus supporting the washout of heavy metals as well as the uptake in plants.

Cadmium can by now be removed from *phosphate fertilizer* relatively easy and at low costs. However, significant reductions of the cadmium deposition can only be expected on agricultural soils in rural, as well as in urban areas. Yet, the percentage contribution to the deposition in urban areas is relatively small. Fertilizer is the only cadmium source that is clearly identifiable and where its removal is technically straightforward. In the case of the other depositions this cannot be done as easily.

The cadmium load of the *sewage sludge* will in many cases not be identifiable as long as the diverse group of dischargers do not need to declare the substances contained in their wastewater. At present, it is therefore impossible to assess reduction potentials at the point of the discharger. The only remaining option is to reduce the use of sewage sludge in agriculture. This alternative would have additional costs in the form of additional purchases of fertilizer and would require other measures for increasing the humus content of the soil. In addition, the sewage sludge either needs to be disposed of in landfills, or it needs to be incinerated. Both options, however, rechannel the cadmium from a direct application on agricultural soils to airborne emissions and depositions in landfills. Reducing the cadmium transport into the soil through a reduction in the use of sewage sludge will only lower the load on rural soils that are not heavily contaminated at present.

Not the largest deposition per hectare but the most widespread deposition is from *long-range atmospheric transport*. The reduction potential in the different industry sectors varies considerably. Since the regulation on air emissions of the large emitters, e.g., large-scale incinerators, or the steel and metal industries, is already relatively tight, additional reductions that may significantly reduce these atmospheric depositions may be rather costly. And for the deposition that is imported via air from abroad no measures can be taken anyway.

Direct damages from the cadmium contamination of soils could only occur on a few specific localities characterized by a long history of cadmium accumulation. The damage through *plant uptake* is usually prevented by the prohibition to grow food on these soils. Although a complete assessment of the costs of alternative measures cannot be made, the present regulation is likely to be the most economical one, since a clearing of soils from the historical cadmium accumulation is technically infeasible. An alternative, at least for some soils, could consist of measures to increase the bonding capacity of the soil. An increase in the pH of acid soils would reduce the environmental threat, also an increase in the organic content of the soil would reduce the amount of cadmium that is available for plant uptake.

Similar arguments are valid for the damage created by cadmium through *washout and subsequent transport into the groundwater or rivers*. In these cases, soil conditions are probably more important than the cadmium concentration in the soils. Model calculations make evident that even in soils with only a geogenic cadmium load but unfavourable soil conditions with respect to the adsorption capacity, the cadmium desorption can be as high as that in heavily contaminated soils (Section C.I). In these cases, the only policy option consists in raising the adsorption capacity of the affected soils through, e.g., the adding of organic material (home grown manures, green manuring), or liming. In this respect, the supply of organic material through sewage sludge should not be underestimated.

As far as *erosion* is concerned, it is possible that significant amounts of cadmium may be transported into coastal waters. Possibly these transports contribute to a large extent to the overall load of cadmium that is transported in rivers. A reduction of these loads could either be achieved through measures to reduce soil erosion or through measures to reduce the cadmium content of soils under the threat of erosion. The option to reduce the cadmium deposition on these soils would have little effect, since the share of newly emitted anthropogenic cadmium in these soils is probably quite small, so that only in the very long run a reduction of cadmium in the sediments can be expected.

The assessment of the transport of cadmium from emission sources to diffuse depositions has shown that a simple and straightforward policy to reduce the environmental damage through cadmium cannot be formulated. A clearly identifiable emission source can cause damage in different forms as well as in different places once it has left the emitting source. Therefore, the relationship between emissions and environmental effects needs to be assessed in every case, be it the regional or the sectoral peculiarity that influences this relationship. Consequently, any attempt that wants to go beyond the identification of cadmium flows and their prevention, as it has been presented here, will need to rely on a careful ecological balancing of the use of cadmium as an intentional as well as an unintentional input in economic processes.

III. Policy Conclusions

The control of cadmium provides a good example for the difficulties that environmental policies face because it combines many of those features where emission control is particularly complex. The most important characteristics of the cadmium problem are:

- Cadmium emissions are neither confined to a specific process, a specific sector, a specific material, nor to a specific region. They are more or less ubiquitous.
- Cadmium is usually emitted in very small amounts or low concentrations, in some cases below the measurement limit.
- Cadmium is often emitted in conjunction with other hazardous substances, making it necessary to design emission control strategies beyond the scope of just one substance.
- Since cadmium is highly toxic, it can create significant damage if it accumulates in one area, for whatever reason. This may happen even though there are no toxic concentrations at the sources of emission.
- The relationship between the emissions of cadmium into the different media and its final deposition underlies complex processes, which depend on human activities but also on biological and chemical reactions, i.e., the functional relationship between emission and deposition is partly unknown and hardly predictable.
- Cadmium accumulates in the environment over a long time period, thus creating stock problems even at rather small flows. This accumulation of cadmium is almost irreversible, since a natural degradation does not take place and since only very few storage options exist that effectively remove cadmium from the human environment.

These circumstances require a control of all processes involving cadmium, with the consequence that those people who are implementing cadmium policies need to recognize the different technological possibilities for reducing emissions. They also should have some knowledge about the material flow of cadmium and possess information on abatement costs in order to design appropriate policy instruments.

Today's abatement technologies and today's emissions are to some extent influenced by the current type of regulations in the different sectors. German regulations usually require ambient emission standards leaving the choice of the emission control up to the firm. The regulations through the Technical Directive on Air Pollution, the Ordinance on Large Combustion Facilities, and the Ordinance on Waste Incineration Plants have led to the widespread introduction of the latest end-of-pipe dust arrester technologies, since these are the only control devices that are able to meet the regulated air quality standards. Since the diffusion of these technologies is — at least in large plants — practically completed, there is little technical potential for further reductions of cadmium emissions or dust emissions in general. Although the regulations in some sectors such as the glass or the ceramics industry are less strict, so that older arresters — cyclones or scrubbers — may still be in use, the possibility for further reductions is probably limited, since these plants may not reach the scale at which the modern dust arresters become economical, i.e., their average costs are still above those of the older technologies. However, different environmental policy instruments such as emission charges may change these cost calculations and accelerate the diffusion of electrostatic precipitators and fabric filters.

The incentive-based instruments, however, pose efficiency problems. The emission charge could be based on dust emissions. This would lead to emissions of dust being at the efficient level; but since the concentration of cadmium in the dust varies widely, the control of cadmium emissions using dust charges would be far from efficient. However, an emission charge on cadmium would ignore the other substances and the dust particles carrying these substances. For these jointly produced emissions, an efficient charge system can hardly be found.

The regulations mentioned above could also have some effects on the input substitution for the inadvertant use of cadmium through the burning of coal. Fuel-switching to low-cadmium coal or to natural gas would reduce emissions of dust as well as cadmium. The German coal policy, which forces the use of domestic coal, prevents these substitution processes so far. Input substitution for the intentional use of cadmium is rather limited and is driven mostly by technical considerations with respect to the quality of products containing cadmium substitutes. Furthermore, it is not at all clear whether these substitutes will have an overall better ecological balance than cadmium-containing products.

A significant potential for reducing the industrial emissions of cadmium can only come from the clean technologies. In the nonferrous metal industry the electrolytic process of zinc production has been introduced as far as it is technically feasible. The only remaining thermal plant is used for secondary zinc production, for which the electrolytic process is not suitable. If one compares the potential reduction in emissions gained by shutting this plant down with the potential reductions in emissions, and the costs of, using alternative methods, the question can be raised whether this plant's negative environmental effects are worth the value added that it currently produces. In lead production, the QSL process provides the only other quantitatively significant potential for reducing cadmium emissions into the air, a reduction potential of at least 75 percent is indicated by the published emission coefficients.

Given the hierarchy of quantitatively significant reduction potentials, we can conclude that current regulations have practically exhausted all possibilities of current technologies. Since these command-and-control regulations are commonly considered to be inferior to incentive-based environmental policy instruments, like charges or pollution certificates, one could compare the emission situation today with the hypothetical situation under market-like instruments such as a charge on dust, or on specific dust components, such as cadmium, in order to assess their likely effect. The logic of market-like instruments consists of leaving the choice between avoiding emissions and emitting — together with the necessary payments — up to the firm, which will reduce its emissions to the point where the marginal costs of abatement are just equal to the charge rate. Hence, predictions about the likely reaction need to rely on the approximate costs of abatement.

The information on the costs of different abatement technologies that we have found suggests that further end-of-pipe reduction measures would not be economical cadmium control policies. Abatement costs per kilogram cadmium removed in the range of DM2,000 up to over DM5,000 are high, even though they attribute the costs of reducing all different dust particles to cadmium alone. The sensible alternative, of course, would be to speed up the development of the clean technologies, which have overall lower production costs and provide emission reductions practically at no costs. The incentive character of market-like instruments would therefore increase the diffusion of new technologies, although they may not be sufficient to guarantee that other related pollutants will also be dealt with efficiently.

Cadmium emissions into the air have relatively little negative environmental effects as long as they remain in the atmosphere. They only become an environmental problem once they have been deposited on the ground or in the water. These depositions, however, are not all airborne, so that optimal policies also need to integrate abatement policy options for other emitting sources. For example, some of the cadmium on agricultural soils comes from contaminated phosphate fertilizers. This is of particular interest, since the reduction of cadmium from phosphate fertilizers is by far cheaper than the reduction of the same amount of cadmium from airborne dust emissions. This example shows that, seen from the perspective of the environmental damage from cadmium, the most economical options for reducing the cadmium contamination of soils will not necessarily be found in the industrial sector but in other not yet regulated areas.

IV. Possible Directions of Future Research

The industrial metabolism of cadmium has been the subject of this study and applying this particular approach has provided quite interesting insights into the different options for controlling cadmium, which would not have become apparent if the analysis would have focused on one specific environmental medium or one specific sector of the economy. This expansion to a multisectoral and multimedia view has already required a significant interdisciplinary approach. At the same time, the study has made all the more clear that even this wider approach is not sufficiently comprehensive. Several points have been identified that need further research before a successful and efficient policy for controlling a substance like cadmium can be designed. It is a general phenomenon that a more detailed analysis opens the desire to investigate an even more comprehensive picture of the industrial metabolism of cadmium. This creates the danger of getting lost in the complexity of the net of human–environment interactions. Nevertheless, a few remarks should be made about the limits of focusing on one substance in such analyses.

One clear message from this study is that it is practically impossible to define and estimate abatement costs for cadmium emissions. The reason being that many processes emit multiple pollutants, which often are removed by the same techniques. It then does not make sense to attribute the costs of removal to just one pollutant, hence the concept of an abatement cost function and the subsequent economic analysis is not applicable for cadmium alone but for all substances abated together. If the different hazardous substances that are to be controlled by some device do not react equiproportionally, as is the case with dust and cadmium, a cost accounting rule and an efficient charge structure becomes impossible to design. For designing optional policy interventions, the industrial metabolism approach provides information which cannot be used for, e.g., determining an optimal tax on cadmium since the optimal tax in the case of airborne emissions would need to be levied on dust anyway. Hence, a simpler analysis on sectoral abatement costs would suffice. In this case, however, it would become impossible to rank different cadmium control policies such as a reduction of emissions from industrial furnaces versus the reduction of cadmium in fertilizer.

It is well known that the German environmental policy, which has started to control aqueous emissions in the seventies, has been faced with a substitution of airborne emissions and solid waste for aqueous emissions, and that the subsequent control of airborne emissions has left only solid waste as the least regulated outlet, which is about to be changed now by the proposed Law on Life Cycle Management (*Kreislaufwirtschaftsgesetz*). A similar phenomenon has become apparent in this study when options for reducing the intentional use of cadmium have been discussed. It was not at all clear whether the replacement of cadmium by other substances is really an ecologically effective policy. As soon as input substitution becomes an option, one would need to start a new industrial metabolism study on the substitute in question. At least some kind of ecobalancing of the use of such a substitute would be necessary.

The social costs of substituting cadmium by some other substance, e.g., lead, consist not only of the private costs of changing the production process in question but also of the external costs of using the alternative input. Determining these costs requires a general equilibrium analysis of the changes in the economy taking place through the input substitution. As a conclusion of this study, we believe that the indirect effects, which make necessary a general equilibrium approach, are much more important than it was assumed in the past, where most analyses of emission control policies were done in a partial equilibrium framework.

A final problem in need of further research is related to the switch from end-of-pipe measures towards process changes and integrated pollution control. The level of emission reduction through end-of-pipe measures cannot be improved much at reasonable costs for many substances, so that further improvements need to be achieved through technological change. For an industrial metabolism study, which is also aimed at identifying optimal control options, this requires a detailed account not only of existing implemented technologies but also of more advanced best available technologies and potential technologies that are still in an experimental stage. But even the know-how about these technologies needs to be contrasted with the economics of technical change, a subject that is still quite underdeveloped in economic analysis in general, and even more so in environmental economics. Yet, one of the main conclusions of this study is that it is the new clean technologies and little else that can solve the cadmium problem in the future.

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