Reducing cadmium emission into the air

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CONTENTS

1. INTRODUCTION

Heavy metals enter production and consumption processes as trace elements in materials or as intentional inputs. The trace concentrations occur predominantly in soils, minerals, and fuels in which they are bound unless these materials are exposed to high temperatures. Consequently, airborne Cadmium emissions can be found in all production processes in which these materials are burned or heated, hence they are not confined to only a few industries and activities. KLEPPER/MICHAELIS (1991) identify the development of airborne Cadmium emissions in the 1980s and find that the major share of emissions comes from only a few industrial processes, namely the non-ferrous metal industries - mostly primary as well as secondary Zinc and Lead production -, the iron and steel industry, and to a lesser extent from the combustion of fossil fuels in power plants, households, industry and from waste incineration. Airborne emissions through production processes involving the intentional use of Cadmium are minor compared to the above mentioned major emittors.

Cadmium is emitted in different forms, the most important being elemental Cadmium (Cd) and Cadmium Oxide (CdO). In coal combustion processes and the non-ferrous metal production it also occurs as Cadmium Sulfide (CdS) and in waste incineration plants as Cadmium Chloride ($CdCl_2$) (JENSEN/BRO-RASMUSSEN 1992). Whereas Cd and $CdCl_2$ are both volatile at flue gas temperatures, CdO and CdS are nonvolatile. While the latter forms are emitted as fly ash, the volatile forms are in a vapour state and precipitate during the cooling process, but they all become finally bound to dust particles. Compared to other heavy metals, Cadmium precipitates predominantly on small dust particles. Table 1 summarizes the concentration of heavy metals in filter dust from coal combustion and shows that the smallest particles of less than 3mm 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 ability of different dust arrester technologies to reduce Cadmium since different arresters remove particles of different sizes. Different production processes naturally have different size distributions of the waste gas with the consequence that the size distribution of the particles carrying heavy metals will change. Insofar, the numbers for coal combustion are only illustrative and can not be directly used for characterizing other raw gas flows.

Table 1.1 — Size Distribution of Heavy Metals in Filter Dust from Coal Combustion (mg metal/kg dust)

Particle Size Fraction	Pb	Cu	Cd	Hg
< 3 mm	580	500	14	2.3
3 - 6 mm	500	330	5	1.9
6 - 9 mm	320	390	4	2.4
9 - 19 mm	160	260	2	2.3
19 - 50 mm	35	160	1	1.2

Source: SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991).

There exist essentially three options for reducing Cadmium emissions:

- The substances in question 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 process.
- If emissions can not be avoided in the 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 off.

In the past, the main focus in the regulation of hazardous substances has been 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 will be compared as far as this is possible in the light of a very limited data base.

2. END-OF-PIPE-MEASURES

Hazardous substances which can not be avoided at the input side and which can not be copmpletely contained in the production process will become emitted unless they are controlled through appropriate technologies, the so called end-of-pipe measures. The analysis of such abatement measures is facilitated if one distinguishes between controlled and fugitive emissions. Controlled emissions are emitted from point sources, i.e. from process vents, chimneys, and other outlets which 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 point emissions. In the following, we first discuss the control of point emissions. The subsequent chapter is then concerned with end-of-pipe measures for fugitive emissions.

2.1. THE CONTROL OF POINT EMISSIONS

2.1.1. ABATEMENT TECHNOLOGIES

Reducing the concentration of dust in the raw gas is essential for the control of Cadmium emissions into the air since the Cadmium is adsorbed at the dust particles. The most common types of dust emission control technologies for industrial waste gas purification are - in the order of increasing purification rates[1]

- Cyclones,
- Scrubbers,
- Electrostatic Precipitators, and
- Fabric Filters.

Cyclons 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 which are smaller than 5μm. Due to the concentration of Cadmium and other heavy metals on dust particles of less than 3μm (see Table 1), cyclons are particularly ineffective in removing Cadmium from the raw gas. The cleaning performance of cyclones can be improved considerably through the prior use of scrubbers which cause the particles to impact on water droplets thus making collection by inertial forces easier.

Electrostatic Precipitators (ESP) ionize gas molecules through the application of high voltage. Dust particles are then transported with the inonized molecules to the collection electrodes where they are removed in regular intervals of 10-30 minutes. The highest purification rates, however, can be achieved with Fabric Filters. Such filters are made of

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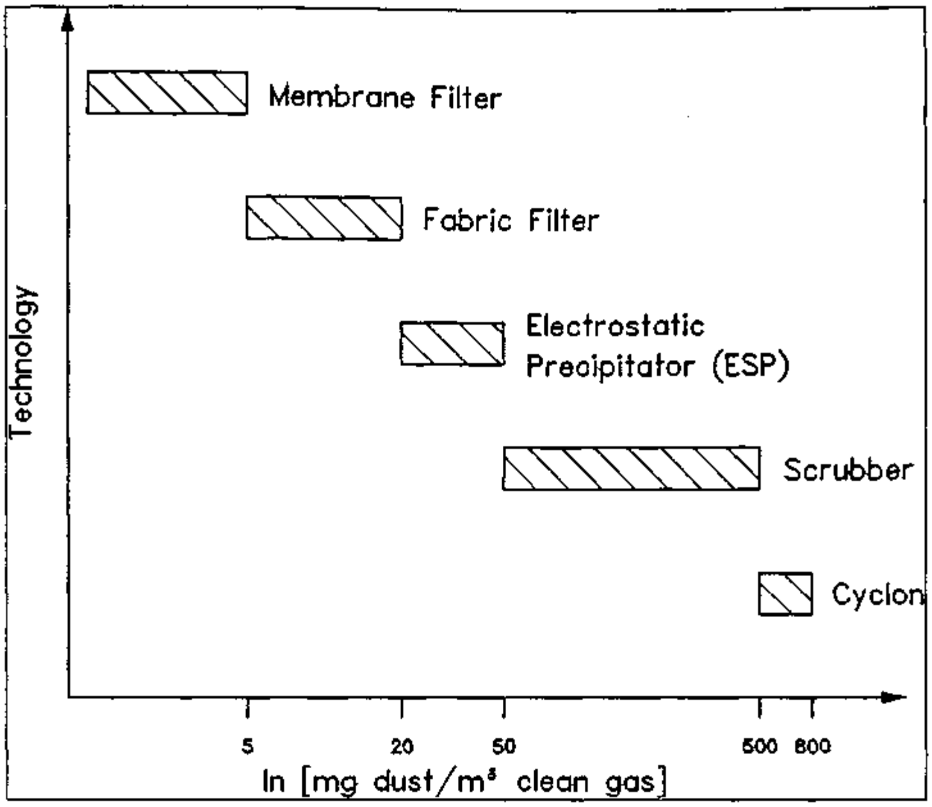
[1] For a more detailed description of these techniques see GÜTHNER (1989), UMWELTBUNDESAMT (UBA) (1989), and SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991) from which most of the technical material is taken.

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 2.1 — Average Cleaning Performance of Dust Arresters for Industrial Waste Gas Purification



Source: GÜTHNER (1989), UMWELTBUNDESAMT (1989), SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991).

Figure 2.1 illustrates the average cleaning performance of the different dust arresters in terms of remaining dust concentration. There is a clear hierarchy of technologies from Fabric Filters to ESP's, Scrubbers, and finally Cyclons. German regulations of emissions into the air limit air-borne dust emissions to 50 mg/m^3 for large facilities (gas flow of more than 10.000 m^3/h) and to at least 150 mg/m^3 for smaller ones. Many processes are subject to lighter limits going as low as 10 mg/m^3 for lead production and waste incineration (see Table 2.3 below). Consequently, the TA-Luft forces the introduction of ESP's or Fabric Filters for large facilities, whereas small facilities may achieve the 150 mg/m^3 dust in the clean gas through the combined use of a scrubber and a cyclon. The cleaning performance of the latter, however, depends crucially on the energy input as greater dust removal is directly related to higher energy inputs (see also chapter 2.1.2 on abatement costs).

At first sight, one might get the impression from Figure 1 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 can not be used for hot gases, with a temperature of the 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 µm) can not clean dust which contains oil.
- Dry Electrostatic Precipitators require dry waste gas, whereas wet ESP's need an additional waste water 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 costs, 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 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 of a production process the raw gas concentration, and finally the Cadmium emissions. Consequently, the emission coefficients for Cadmium can vary over a wide range and the usefulness of emission factors 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 factors 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 which are quite different from those of the raw material inputs. The increase in the concentration varies widely as some examples in Table 2.1 indicate. The determinants of the accumulation of Cadmium are manifold. The process technology, but also the process temperature, the occurence 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.

Table 2.1 — Cadmium Accumulation in Selected Production Processes

	Cadmium Concentration (ppm)*		
	Raw Material (1)	Raw Gas (2)	Accumulation (2)/(1)
Glass Melting Tank	0.86	747	870
	0.86	898	1040
Cement Production	0.26	32.0	94
(Rotary Kiln)	0.6	6.9	13
Nickel Melting	1.4	180.0	128
	2.1	200.0	95
* Numbers refer to two different test samples			

Source: UMWELTBUNDESAMT (UBA) (1989), taken from Tab. 4.2/35, Tab. 4.2/36, and Tab. 4.2/37.

This variation can increase even further if, e.g., the dust particles are returned into the melting process. The Cadmium concentration of the raw material in the cement production of 0.29 ppm did increase in a test (UBA 1989) to a gas concentration of 12.4 ppm without the feeding back of the dust, and with feedback it did increase to 1.000 ppm.

In addition to the Cadmium concentration of the raw gas, the removal capacity of dust arresters 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 - will be more difficult to clean than a gas with larger dust particles. Since Cadmium prefers to become bound to smaller particles - 75% of the Cadmium in the raw gas from coal combustion is bound to particles of less than 6 µm and 50% to particles of less than 3 µm [2] - the technical difficulty in removing Cadmium is aggravated. This means that dust arresters such as Scrubbers and Cyclons which reduce dust to up to 50 mg/m³ will do worse in terms of Cadmium reduction compared to dust

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[2] See Table 1.1. Different processes have very different size distributions. The combustion of heavy oil, incinerators for chemical waste, glas production, and the combustion of solid material have a significantly larger share of small dust particles. After the application of ESP's or Fabric Filters, this difference almost disappears for particles larger than 1 µm (UMWELTBUNDESAMT (UBA) 1989).

removal because the dust in the clean gas will predominantly be composed of small particles.

Given all these different aspects of the relationship between the Cadmium load of raw materials on the one side and the Cadmium concentration in the raw gas and - after treatment - in the clean gas, it is clear that the cleaning performence 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 complication has important consequences for the determination of abatement costs. Since the emission coefficients depend on several parameters, the abatement costs for Cadmium will depend on at least that many factors. Unfortunately, there is not enough information available for a complete assessment of these costs. The following chapter on abatement costs will therefore focus on two processes which are better documented, i.e. on industrial furnaces and on zinc refining.

2.1.2. ABATEMENT COSTS

Before the cost of abating Cadmium from airborne emissions are assessed, a few words of caution are in order. The economic concept of abatement costs for Cadmium alone does make little sense if the end-of-pipe technologies which have been described above are concerned. These technologies reduce a large number of different substances such as dust in general, other heavy metals, organic compounds, and many others. Consequently, it does not make any sense to attribute the total cost of applying these technologies to just one compound, in this case Cadmium.[3] Consequently, the following figures refer to the cost of reducing whatever compounds are removed with the dust arresters. This is only a rough approximation to the costs of removing Cadmium. One of the most important factors which distorts these cost figures is the ability of the different filter technologies to remove dust particles of different size. Dust arresters are commonly described by the percentage of dust which they remove from the raw gas. However, the new technologies such as Fabric Filters do 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

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

technology with a purification rate for dust of 95 % to one with 99 % will increase the removal of Cadmium by more than the 5 percentage points for the dust removal.

Very little systematic information is available on the cost functions of the different dust arrester technologies. From the scetchy data some general characteristics of these cost functions can still be deducted. One of the important characteristics is that the investment costs of dust arresters are high and increase with the improvements of the technology. ESP's 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, on the other hand, 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 in terms of the volume of gas for a given working time are reciprocal to the gas volume, i.e. the cost function is decreasing in the volume of gas treated.

The investment costs of ESP's and Fabric Filters for coal-fired industrial combustion facilities of different capacities are illustrated in Figure 2.2. It is remarkable that the average investment costs of these dust arresters fall with rising capacity. This is in line with general findings of the cost-engineering and industrial organisation literature[4] which have estimated investment cost functions of the form $C_i = \alpha_i v_i^{\beta_i}$ for different technologies i. The coefficient β for Cyclons is 0.85 and for ESP's 0.90 (JELEN 1970), hence capital costs increase regressively.

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

In Table 2.2 the cost structures for two different production processes, a coal-fired industrial furnace and a thermal Zinc refining process, each with two different abatement

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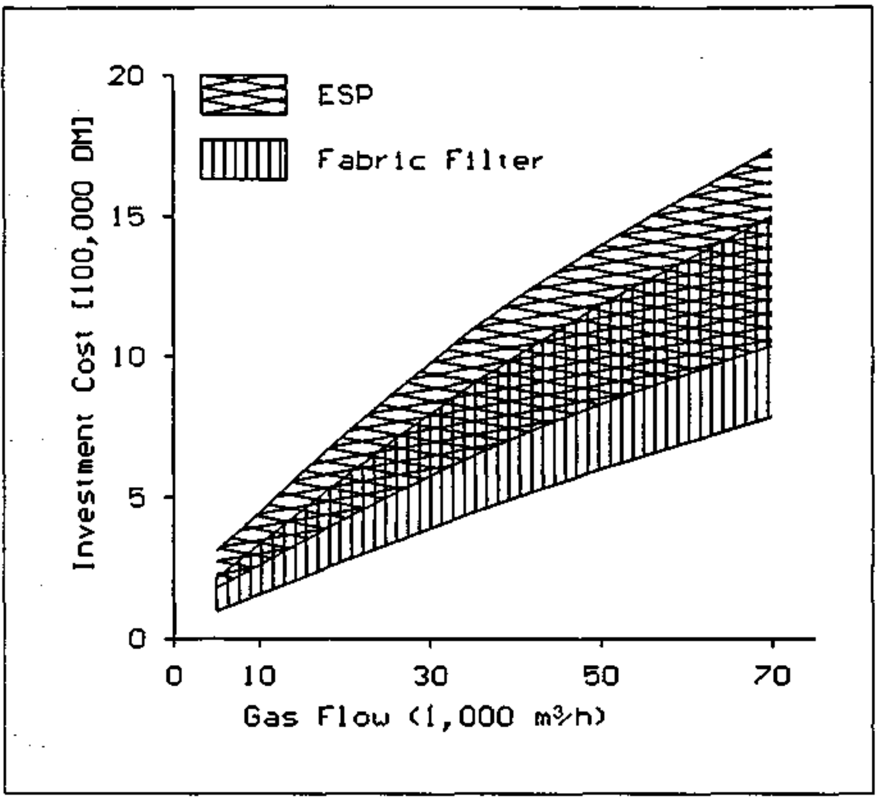
[4] See e.g. HUMPREYS/KATELL (1982) or HAY/MORRIS (1991).

Figure 2.2 — Investment Cost of Advanced Dust Arresters for Coal Combustion Facilities



Source: GRUBER (1991).

technologies are summarized. These numbers are only rough approximations but they nevertheless illustrate some important insights:

- The more advanced ESP 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 ton 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 gases in the Zinc process with a dust content of only 2g/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 cost of reducing Cadmium. The coal-fired furnace with the low Cadmium concentration in the raw gas causes much higher costs per kg Cadmium removed[5] than the Zinc process.

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[5] In order to calculate abatement cost per kg of Cadmium it has to be recognized that most of the coal-fired furnaces employed in industry are of the so-called 'stoker'-type (PACYNA 1991). For this

Table 2.2 — The Cost Structures for Different Dust Arresters in Selected Production Processes

	Coal-fired Industrial Furnace (medium-sized)		Thermal Zinc Refining (IS-process)	
Gas flow per hour	50.000 m^3/h		50.000 m^3/h	
Operating hours per year	8.000 h/a		8.760 h/a	
Average dust content of waste gas	10 g/m^3		2 g/m^3	
Average Cadmium content of waste gas	0.18 mg/m^3		0.6 mg/m^3	
	Abatement Technology		Abatement Technology	
	ESP	Fabric Filter	Scrubber	ESP
Purification rates:				
Dust emissions	>99.5%	>99.5%	95.0%	99.7%
Cadmium emissions	95.0%	95.0%	90.0%	95.0%
Investment cost (mio DM)	0.80 - 1.40	0.60 - 1.10	0.45	1.31
Operating cost (mio DM/a)	n.a.	n.a.	0.56	0.33
Total cost (mio DM/a)	0.30 - 0.42	0.35 - 0.47	0.62	0.52
Total cost per volume of gas (DM/1000 m^3)	0.75 - 1.05	0.88 - 1.18	1.42	1.18
Total cost per ton of dust removed (DM/t)	75 - 105	88 - 118	746	590
Total Cost per Cadmium Removed (DM/kg)	4.188 - 5.863	4.886 - 6.561	2.621	2.063

Source: UMWELTBUNDESAMT (1986), GRUBER (1991), PACYNA (1991), SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991), OWN CALCULATIONS.

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process the average cadmium concentration of stack dust amounts to 18.4 ppm (ibd.). This leads to an estimate of removal costs of 4,188-5,863 DM/kg Cadmium for electrostatic prepicitators and of 4,886-6,561 DM/kg Cadmium for Fabric filters.

- Whereas the ESP needs higher investment costs than the Fabric Filter, the operating costs of the ESP seem to be significantly lower such 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 impact 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 which 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 above. 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 which have been invested in the old structure, then the abatement of Cadmium or other substances will be increased.

MICHAELIS (1992) 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, takes only place at critical levels of the tax rate where the abatement costs inclusive of the cost 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 (1992) 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 the large firms employing larger dust arresters with lower fixed costs per volume of treated raw gas.

2.1.3. BEST AVAILABLE TECHNOLOGY

Often regulatory measures do not provide to firms the freedom to choose the desired level of abatement, as it is the case of emissions taxes. The "Technical Directive on Air Pollution" (TA-Luft) requires effectively the introduction of the best available technology. These requirements are then updated if new technologies become developed.

According to a report delivered to the ECE-Task Force "Heavy Metal Emissions" by the SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991) the employment of Fabric Filters has to be viewed as best available end-of-pipe technologie (BAT)[6] for nearly all of the applications mentioned in this paper (see table 2.3). The only exceptions from this rule are given by 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 best availale technology although the use of electrostatic precipitators results in a concentration of about 30 mg dust per m^3 of cleaned gas while the respective cleaning performance for Fabric Filters is 20 mg/m^3.
- In iron and steel making by the basic oxygen process Fabric Filters sometimes can not be used due to the temperature of the raw gas or its physical properties. In these cases, electrostatic precipitators have to be viewed as best available technology although they only produce clean gas concentrations of about 50 mg/m^3 while the use of Fabric Filters would reduce concentration to about 10 mg/m^3.

The first row of table 2.3 summarizes the concentrations of dust in the exhaust air which can be obtained by the use of the best available technology as defined by the SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991). It should be noted, however, that the achievement of these concentrations does not only depend on the general type of dust arrester but also on its surveillance and maintainance and on its individual design which has to be taylored for each specific installation.

The second row of Table 2.3 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

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[6] The SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991) 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 sucessfully 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 condercerned; the precautionary principle."

Table 2.3 — BAT Concentrations of Dust in Exhaust Air and Permissible Concentrations According to German Regulations

	BAT-Concentration (mg/m^3)	German Standard (mg/m^3)
Coal Combustion by Power Plants (a)	20 - 30	50
Production of Iron and Steel (b)		
Electric Arc Process	5 - 10	20
Basic Oxygen Process	10 - 50	20 - 50
Production of Non-Ferrous Metals (b)		
Primary Zinc and Copper	5	20
Secondary Zinc and Copper	10	20
Primary Lead	5	10
Secondary Lead	10	10
Manufacturing of Glass (b)	10	50 - 150
Waste Incineration (c)	10 - 20	10
Applicable Regulation: (a) Ordinance on Large Combustion Facilities (1983); (b) Technical Directive Air Pollution (1986); (c) Ordinance on Waste Incineration Plants (1990).		

Source: SWEDISH ENVIRONMENTAL PROTECTION AGENCY (SEPA) (1991), GROß-FEUERUNGSANLAGENVERORDNUNG (1983), TECHNISCHE ANLEITUNG LUFT (1986), VERORDNUNG ÜBER VERBRENNUNGSANLAGEN FÜR ABFÄLLE (1991).

the feasible cleaning performance of different types of dust arresters reveals (see alsoSection 2.1.1) that in virtually all cases the German legal standards can only be achieved by the employment of the same type of technology that is recommended as 'best available technology' by the SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991).[7] 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 3.) only an optimization of the design, the surveillance and the maintainance of the end-of-pipe technologies already employed may allow further reductions of dust emissions. But even

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[7] The only excemption from this general rule seems to be the manufacturing of glass.

this opportunity is more restricted in scope than the figures in table 2.3 suggest since the actual concentrations of dust in exhaust air are often considerably smaller than those required by the respective regulations. One 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 already installed processes for which the potential can only be assessed on a plant-by-plant basis.

2.2. THE CONTROL OF FUGITIVE EMISSIONS

Based on their origin, fugitive emissions can be grouped into emissions caused by processes (e.g., emissions from open furnaces, melting pots, launders etc.) and emissions caused by storage, handling and transport.

According to the SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991) the use of process containments ('doghouses') has to be viewed as best available technology concerning the control of process-related fugitive emissions. Process containments evacuate the dust-containing air flows and thereby facilitate a transformation of the fugitive emissions into controlled emissions which can be treated by end of pipe technologies[8]. In Germany, the employment of containments with end of pipe treatment is already required by the Technical Directive on Air Pollution (TA-Luft) of 1986. Therefore, it seems reasonable to conclude that the potential for reducing process-related fugitive emissions is almost exhausted in Germany.

Concerning fugitive emissions from storage, handling and transport the SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991) recommends the following set of measures as "best available technologie":

- 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 system or with dust suction to filter.
- Reclamation of raw materials from stockpiles should be by enclosed conveyor.
- Roads should be hard-surfaced and properly cleaned; contaminated run-off water from roadways should be collected and a well designed wheel wash systems should be used.

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[8] For an example of a process containment with end of pipe treatment of the air flow see UMWELTBUNDESAMT (UBA) (1987).

In Germany, the TA-Luft from 1986 requires that emissions caused by storage, handling and transport of dust-spreading goods with a Cadmium content of more than 50 ppm (e.g., zinc, lead and copper ores) have to be minimized by employing the so-called "most effective measures" ("wirksamste Maßnahmen"). Although the practical lay-out of these measures depends on the specific conditions of the activity under condsideration, the term "most effective" suggests that the requirements of the TA-Luft may be at least as stringent as the recommendations of the SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991). Hence, with the exception of possibly weak enforcement at present there seems to be no need and no possibility for further activities aiming at reducing fugitive Cadmium emissions from transport, handling and storage.

3. CLEAN TECHNOLOGIES

In a recently published report the OECD (1989) concluded 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 beeing included in control plans and increasing attention is beeing paid to the interactions between pollutants, that 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 2). Therefore, the potential of "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. Concerning airborne Cadmium emissions the most promising cases of "clean technologies" are related to the combustion of coal and the the production of non-ferrous metals.

3.1 COMBUSTION OF COAL

The combustion of coal by power plants is one of the most important sources of airborne Cadmium emissions. The specific emission coefficient (i.e. the amount of Cadmium released to the atmosphere per ton of 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. 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 intert material (e.g. sand) and pulverized coal are mixed, suspended and combusted in an upwards moving air flow. Table 3.1 shows the percentage contribution of these three technologies to the total power generation by fossil fuel combustion in Germany. As one can see from these numbers, pulverized bed combustion is the dominating technology in power generation by coal, but the importance of fluidized bed combustion is steadily increasing.

Table 3.1 — Percentage Contribution of Different Combustion Technologies to the Power Generation through Fossil Fuel Combustion in the FRG

	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 ton of coal burned but also lower emissions of nitrous oxides (NO_x) and sulphur dioxides (SO_2) per ton of coal (see OECD 1989). Another technological feature of fluidized bed combustion is the following: According to the SWEDISH ENVIRONMENTAL PROTECTION AGENCY (1991) only about 15% of the total ash produced during the combustion process is released as fly-ash, while the remaining ash falls down to the bottom of the boiler where it can easily be collected. In contrast to this, about 20-40% of the resulting ash becomes fly-ash in the grate-fired boilers and the respective figure for pulverized coal combustion is 70-100%. Correspondingly, the emission coefficients of the three technologies vary widely. Table 3.2 shows the specific dust content in raw gas (assuming 10% of ash in the coal), the specific Cadmium concentration in dust and the specific Cadmium emissions per ton of coal burned (assuming end-of-pipe-treatment with a removal rate of 99%) as estimated by PACYNA (1991).

The estimates shown in Table 3.2 indicate that a replacement of pulverized bed boilers by fluidized bed boilers would reduce airborne Cadmium emissions per ton of coal by a factor of more than 5. According to the estimates of emissions presented in KLEPPER/MICHAELIS (1991) this implies a reduction potential in the order of magnitude of 1-4 tons of Cadmium per year. Hence, compared to the estimates of the total airborn

Cadmium emissions, the percentage reduction which can be achieved through the employment of fluidized bed combustion is probably in the order of magnitude of 4-7%.

Table 3.2 — Dust Content in Raw Gas, Cadmium Concentration in Dust and Cadmium Emissions per Ton of Coal for Different Types of Coal Combustion Technologies.

	kg dust / ton coal	mg Cadmium / kg dust	g Cadmium / ton coal
Type of boiler:			
- 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).

Beside 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 usally also reduce emissions of heavy metals. The most promising development seems to be the Integrated Gasification Combined Cycle (IGCC) that allows lower emission levels than fluidized bed combustion (see OECD 1987). Although a demonstration plant has been 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.

3.2 PRODUCTION OF NON-FERROUS METALS

The conventional thermal technology employed in the production of non-ferrous metals consists of smelting and sintering of zinc-, lead- and copper-concentrates. These concentrates contain considerable amounts of Cadmium which are partly volatalized and released to the exhaust air during the process of refining. Although the end-of-pipe measures employed in the production of non-ferrous 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, it has to be expected that further reductions in emissions only can be achieved by the employment of new "clean" technologies.

In the case of zinc production significant differences in airborne Cadmium emissions exist between the the conventional thermal process and the low polluting electrolytic process. The emission coefficient of the thermal zinc refining processes employed in Germany (Imperial Smelting) amounts to 50-60 gram of Cadmium per ton of zinc produced. However, since the mid-eighties the thermal process has been reduced in capacity and at present only one thermal plant with a capacity of 80,000 tons/year is still operating in Germany. Accounting for an emission coefficient of only 0.2 g Cd/ton zinc in the case of electrolytic refining one can conclude that the replacement of the thermal process would result in a reduction of airborne Cadmium emissions of about 4-5 tons. This is of particular interest from a policy oriented point of view since it implies that the closing down of one single plant is likely to lead to a stronger reduction in overall emissions than the introduction of fluidized bed combustion in the whole energy sector.

Table 3.3 — Emission Coefficients (g Cd/ton lead) for Conventional and New Lead ProductionTechnologies by Different Authors.

	Conventional Lead Production		QSL-Process
	Primary Production	Secondary Production	
Güthner (1989)	1.3	n.a.	0.100
ERL-Report (1990)	3.0	2.2	n.a.
Metallgesellschaft (1990)	n.a.	n.a.	0.165
Pacyna (1990)	10.0	2.5	n.a.

Source: GÜTHNER (1989), ERL-REPORT (1990), METALLGESELLSCHAFT (1990), PACYNA (1991).

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 signifcant Cadmium emissions particularly in the case of primary production. However, the respective emission coefficients available from the literature vary considerably (see Table 3.3).

In contrast to the conventional technology there are some new "clean" technologies which 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 (Table 3.4). However, emission coefficients are only available for the so-called QSL-process (Table 3.3). These figures indicate that the replacement of the conventional technology by the QSL-process would reduce airborne Cadmium emissions per ton of primary lead by a factor of more than 10. In absolute terms this implies a reduction potential of about 1-2 tons of Cadmium per year.

Table 3.4 — Location and Capacity of New Lead Production Technologies

Process	Location of plant	Capacity (tons/year)
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).

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% lower compared to the conventional technology. Due to 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.

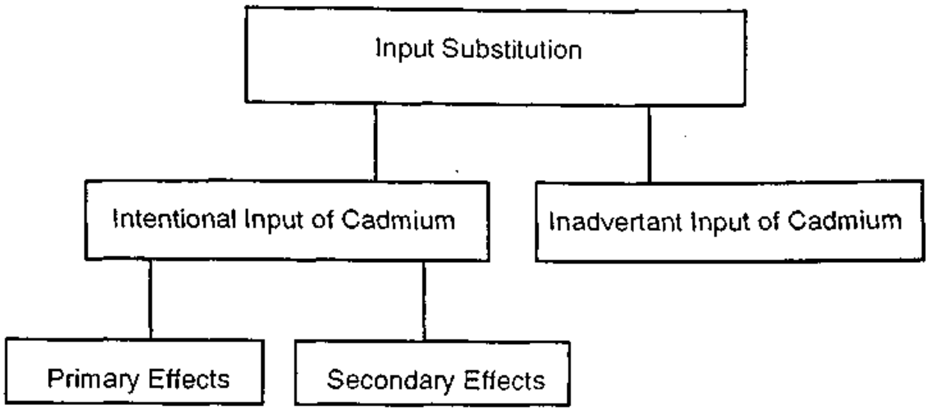
4. INPUT SUBSTITUTION

This chapter investigates the potential for reducing airborne cadmiun emissions through input substitution. In order to obtain a complete picture of all substitution posibilities which may have an impact on airborne Cadmium emissions, two different types of Cadmium input can be considered:

- 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.

Furthermore, the structure of the Cadmium flow through the economy (see KLEPPER/MICHAELIS 1991) indicates that the use of raw Cadmium or Cadmium-containing inputs may not only have 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 which are caused by the consumption and/or disposal of Cadmium containing products. Hence, the basic conceptual structure of the problem at hand can be represented by Figure 4.1.

Figure 4.1 — Possible Impacts of Substitution Activities on Airborne Cadmium Emissions



Before turning to a more detailed analysis of the potential for reducing airborne Cadmium emissions through input substitution it should be mentioned that 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 aims 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.

4.1 INTENTIONAL INPUT OF CADMIUM

Table 4.1 presents an estimate of the development of the Cadmium load in products which have entered German markets between 1974 and 1986. The most important product groups containing Cadmium as an intentional ingredient are stabilizers, pigments, batteries and plated commodities.

Table 4.1 — Cadmium in Products (tons)

	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			
Others	28	22	30	30	51	40	26	8	11	39			

Source: BÖHM/SCHÄFERS (1990).

4.1.1. CADMIUM-CONTAINING STABILIZERS

Cadmium containing stabilizers are used to protect products for outdoor use (mainly window frames) made from PVC 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 tons, of which corrected for exports about 219 tons did remain in Germany (see Table 4.2). In addition to the domestic production about 70 tons of Cadmium have been imported in 1986, so that total domestic consumption of Cadmium in stabilizers amounts to about 289 tons.

It should be noted, however, that these data on imports and exports include only international trade in Cadmium containing stabilizers themselves but no trans-frontier flows of manufactured products containing stabilizers which also contain Cadmium. Hence, the numbers on domestic consumption are subject to considerable uncertainty. RAUHUT (1987) conjectures 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.

Table 4.2 — Cadmium in Stabilizers (tons).

	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/RAUHUT(1987), RAUHUT (1990).

According to publications by BÖHM/TÖTSCH (1989) and BÖHM/SCHÄFERS (1990), which are the most recent studies on Cadmium substitution, three different options for substituting Cadmium containing stabilizers are available:

- a substitution of Cadmium containing stabilizers by Cadmium free stabilizers;
- a general renunciation of stabilizers in favour of the employment of additional surface coatings and
- a general substitution of PVC by other materials (mainly wood and aluminium) for the production of window frames and related commodities for outdoor use.

However, as BÖHM/TÖTSCH (1989) discuss in detail, each of these substitution possibilities has its own problems:

- At present, the only available cadmium-free stabilizer system relies on lead stabilization and requires the fivefold amount of lead compared to Cadmium stabilization. From an ecological point on view this trade-of between Cadmium and lead is hardly a sensible solution since lead also belongs to the class of high priority hazardous substances which are known to cause a major threat 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 impacts. 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 PVC by aluminium or wood is also problematic because window frames made of aluminium are expensive and the employment of wood

requires costly periodical upkeeping and maintenance activities. Furthermore, 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 PVC by wood or aluminium would yield a positive net environmental benefit.

Although the substitution of Cadmium containing stabilizers would lead to a decrease in Cadmium flows, the likely impact on airborne cadmium emissions is probably almost insignificant. Since the production of stabilizers and stabilized PVC-commodities accounts for less than 0.2% of total airborne Cadmium emissions in Germany (see UMWELTBUNDESAMT, 1990), a reduction of Cadmium flows through substitution in the stabilizer production would result 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 impact on airborne cadmium emissions. According to TÖTSCH/GAENSSLEN (1990) the annual flow of municipal waste[9] in Germany (without the new states) contains only about 30 tons of Cadmium which can be traced back to the use of Cadmium-containing stabilizers. Assuming that about 30% of municipal waste are incinerated and accounting for an end-of-pipe removal rate of about 98% with respect to Cadmium (see BÖHM/SCHÄFERS, 1990), the annual airborne Cadmium emissions from the incineration of stabilizers will be in the order of about 0.18 tons. Hence, even a total phasing-out of of Cadmium containing stabilizers would lead only to a very small decrease in airborne Cadmium emissions.

4.1.2 CADMIUM-CONTAINING PIGMENTS

Cadmium containing pigments are used to produce paints and to colour products made from plastics, ceramics, enamel and glass. According to BÖHM/TÖTSCH (1989) the colouring of plastics (mainly polyethylene, polypropylene, polystyrole and polyamide) is responsible for about 86% of the total use of Cadmium containing pigments in the FRG,

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

while the other areas of application are only of minor quantitative importance (paints 2%; ceramics and enamels 8%; glass 4%).

Table 4.3 shows that the Cadmium input in the domestic production of pigments amounted in 1986 to about 555 tons, of which about 301 tons did remain in Germany. Accounting for additional imports of about 35 tons total domestic consumption of Cadmium in pigments amounted to about 363 tons.

However, the above mentioned reservations (see Section 4.1.1) concerning the numbers on exports and imports also apply to the case of Cadmium containing pigments. The data presented in Table 4.3 do not include international trade in manufactured products that contain Cadmium in form of pigments and therefore the figures on total domestic consumption may be overestimated.

Table 4.3 —Cadmium in Pigments (tons)

	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 Comsumption	291	317	293	364	434	363

Source: BALZER/RAUHUT (1987), RAUHUT (1990).

For the colouring of plastics, the scope of available substitution possibilites strongly depends on the type of plastic, the required shade of colour and the characteristic features of the respective product under consideration (see BÖHM/TÖTSCH 1989). In some cases (e.g., the colouring of low density polyethylene) Cadmium-free substitutes are easily available, while in other cases (e.g., the colouring of polyamide) a phasing out of Cadmium containing pigments would imply that several shades of colour as well as some advantageous characteristics (in particular non-fade properties) are no longer available.

Moreover, even in those cases where suitable substitutes are available the problem often remains that the employment of these 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 detailled 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. During the last years the use of Cadmium in paint production has already been limited to these applications[10] and there are no significant potentials for further reductions in the Cadmium input.

A similar problems occurs with respect to the colouring of glass, ceramics and enamel: In most cases only Cadmium containing pigments are sufficiently resistant against the high temperatures prevailing during the process of colouring. A phasing-out of Cadmium containing pigments would imply that several shades of colour are no longer available. Hence, the scope of quantitatively significant substitutution possibilities seems to be limited to the colouring of plastics.

According to the UMWELTBUNDESAMT (1991), the production of Cadmium-containing pigments contributes less than 1% of the total airborne Cadmium in Germany. Hence, further reductions in Cadmium input would lead only to a very small primary effect on airborne cadmium emissions.

The reduction of airborne emissions caused by the industrial use of Cadmium containing pigments faces a dilemma. On the one hand, the colouring of glass and ceramics contributes significantly to airborne Cadmium emissions[11], but there are no substitution potentials. On the other hand, there seem to be significant substitution potentials in the colouring of plastics, but there are very little airborne Cadmium emissions from these activities.

Contrary to this rather pessimistic perspective concerning the reduction potential for Cadmium emissions there seem to be some scope for reducing emissions caused by the incineration of waste. According to TÖTSCH/GAENSSLEN (1990) the anual flow of municipal waste in Germany (without the new states) contains an amount of about 120 tons of Cadmium which is caused by the use of Cadmium containing pigments in the colouring of plastics. Given that about 30% of that waste is incinerated and that the incinerators have removal rates of about 98%, it is estimated that about 0.72 tons of airborne Cadmium emissions are caused by the incineration of scrapped plastics that are coloured with Cadmium containing pigments. Hence, a substitution of Cadmium in the colouring of

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[10] Cadmium input to the production of paints dropped from 20 tons in 1983 to 6 tons in 1987 (BÖHM/TÖTSCH, 1989, p. 49).

[11] According to the UMWELTBUNDESAMT (UBA) (1991) airborne Cadmium emissions caused by the manufacturing of glass and ceramics amount to more than 4 tons p.a. in Germany.

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 colouring of consumer-durables and only to a much smaller extend in the colouring of packaging materials (see BRAHMS et. al. 1989).

4.1.3 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 involve higher production costs, but they are superior to lead-accumulators in terms of their capacity/weigth-ratio, technical life-time and maintainance requirements.

Nickel/Cadmium-accumumlators are produced in two different variants: big vented accumulators that are mainly used for large-scale purposes (e.g., aircrafts) and small sealed accumulators which are mainly used in consumer durables (e.g., cordless vacuum cleaners).

Table 4.4 — Consumption of Cadmium in Accumulators (tons)

	1984	1985	1986	1987	1990 (forecast)
Sealed Accumulators	96	116	156	241	262
Vented Accumulators	n.d.	n.d.	59	51	50
Total	n.d.	n.d.	215	292	312

Source: FACHVERBAND BATTERIEN, quoted from BÖHM/TÖTSCH (1989).

Due to the higher production cost compared to lead-accumulators, the employment of big vented Nickel/Cadmium accumulators is almost completely restricted to those cases where the superior capacity/weigth-ratio is of crucial importance (mainly aircrafts, military and space technologies). As discussed by BÖHM/SCHÄFERS (1990) the amount of Cadmium used for vented accumulators is steadily declining due to the improved lead-accumulators (see also Table 4.4). Hence, there seems to be no scope and no need for additional policy measures aimed at stimulating the substitution of vented Nickel/Cadmium accumulators.

In contrast to the big vented accumulators, small sealed accumulators used in consumers durables have achieved increasing market shares during the last decade. As indicated in Table 4.4, the consumption of Cadmium in these accumulators has grown from

96 tons in 1984 to to 241 tons in 1987, and a further increase of this magnitude is expected. Moreover, as BÖHM/TÖTSCH (1989) and BÖHM/SCHÄFERS (1990) point out, the figures presented in Table 4.4 do not include imports of Nickel/Cadmium accumulators which are integrated in electrical appliances. They estimate that this trade effect leads to an additional net-inflow of about 100 tons of Cadmium per year.

According to BÖHM/TÖTSCH (1989) there is only little scope for substituting sealed Nickel/Cadmium-accumulators by other types of rechargeable batteries or by solar ceills. Hence, only two strategies for reducing the consumption of cadmium remain:

- a substitution of Nickel/Cadmium-accumulators by conventional (i.e. non-rechargeable) batteries, or
- a general reduction of cordless electrical appliance.

However, the former of these two options seems to be questionable from an ecological point since it implies a drastically increasing consumption of conventional batteries that 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 need 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 substitution would yield a positive net environmental benefit.

Concerning the scope for inducing primary effects on airborne Cadmium emissions by input substitution, the situation is similar to the cases of stabilizers and pigments. Since airborne Cadmium emissions caused by the production of Nickel/Cadmium accumulalators are almost insignificant (see KLEPPER/MICHAELIS 1991) only a very small primary effect could 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/SCHÄFERS 1990). Using the consumption data presented in Table 4.4 as a lower bound further more, assuming that the major part of sealed accumulators end up in municipal waste after an average time lag of about 5 years, accounting for a 30%-share of incineration and, finally, assuming a 98% end-of-pipe removal of Cadmium leads to an estimate of at least 0.9 tons of airborne Cadmium emissions caused by the incineration of scrapped Nickel/Cadmium accumulators in 1991. Furthermore, the sharp increase in consumption shown in Table 4.4 indicates that the magnitude of these emissions will grow considerably during the next years. Hence, a substitution of of Cadmium-containing accumulators would most likely lead to a decrease in airborne Cadmium emissions, but due to the time lag mentioned above the major part of the effect would occur only after several years.

4.1.4 CADMIUM-CONTAINING PLATINGS

The usual method to protect steel against corrosion is to apply a layer which inhibits any direct contact beween 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 an 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, due to the comparatively high price of Cadmium coatings and the resulting environmental risks, the use of Cadmium has is 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 Germany has declined from 420 tons in 1976 to 122 tons in 1986 (see Table 4.1)[12]. The strongest impact comes from the reduction of Cadmium-galvanized steel in the automobile industry. According to the *Advisory Board on Environmental Issues* (RAT VON SACHVERSTÄNDIGEN FÜR UMWELTFRAGEN 1990) one of the major German producers succeeded in reducing the Cadmium content per motor car from 500 grams to 1 gram. Similar reductions may be conceivable in military and aerospace technology, but as BÖHM/TÖTSCH (1989) and BÖHM/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.

Only the secondary effect is of importance for the likely impact on airborne Cadmium emissions since the coating of steel products with Cadmium is an aqueous chemical process ("electroplating") which does not contribute to airborne Cadmium emissions. In contrast to this, the major part of airborne Cadmium emissions caused by the production of iron and steel can be traced back to Cadmium contaminated scrap metals. Although Cadmium content of the scrap metals varies widely and the resulting emissions from iron and steel making can hardly be quantified, the close interrelationship 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/SCHÄFERS (1990) the

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[12] Data on international trade in Cadmium-galvanized products are not available, but RAUHUT (1987) estimates that there is a net-outflow of Cadmium induced by the particular trade structure of Germany.

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 approximatively 20 years. This effect has two implications concerning the possibility to reduce airborne Cadmium emissions through input substitution in surface plating:

- the Cadmium input into the production of iron steel through scrap metals will decrease anyway by a factor of more than three within the next 15 years (see Table 4.1) and
- in the case of further reductions in the intentional use of Cadmium for galvanization, the major reduction effect on the Cadmium input to the iron and steel production would occur only after about 20 years.

4.2 INADVERTANT INPUT OF CADMIUM

As discussed in KLEPPER/MICHAELIS (1991) the inadvertant entry of Cadmium to the production process through contaminated inputs leads to significant amounts of airborne Cadmium emissions from the following activities:

- production of non-ferrous metals,
- production of iron and steel,
- generation of energy by coal combustion.

4.2.1 PRODUCTION OF NON-FERROUS METALLS

Raw zinc ores, lead ores and copper ores contain certain amounts of Cadmium which are partly volatilized during the process of refining. The specific amount of Cadmium finally emitted to the air depends on three factors:

- the the Cadmium content of raw materials,
- the type of refining process,
- the efficiency of the employed end-of-pipe measures.

Table 4.5 shows that the Cadmium content of raw ores varies widely. 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 in the case of non-ferrous metals is hardly feasible.

4.2.2 PRODUCTION OF IRON AND STEEL

According to BÖHM/SCHÄFERS (1990) the Cadmium input to iron and steel production caused by the use of natural iron ore is negligible compared to the huge amounts of cadmium which enter the production process through scrap metal (see also Section 4.1.4). 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 due to the reduced Cadmium content of scrap metals (see Section 4.1.4) as well as tightened emission standards which have to be met by each plant until 1996 (see KLEPPER/MICHAELIS 1991). Hence, there seems to be no need and no rationale for reducing airborne Cadmium emissions through a reduction of the input of scrap metals.

Table 4.5 — Cadmium Content (ppm) of Fossile Fuels and Raw Materials

Fossil fuels:	
Hard coal	0.50 - 10.00 ppm
Brown coal	0.01 - 3.00 ppm
Heavy oil ("Heizoil S")	0.01 - 0.10 ppm
Natural gas	negligible
Raw materials:	
Iron ore	0.12 - 0.30 ppm
Dolomite, limestone	0.01 - 0.70 ppm
Sand, clay	0.03 - 3.00 ppm
Zinc ore concentr.	1000 - 12.000 ppm
Lead ore concentr.	3 - 500 ppm
Copper ore concentr.	30 - 1.200 ppm

Source: BÖHM/SCHÄFERS (1990).

4.2.3 COMBUSTION OF COAL

Hard coal and brown coal contain different amounts of Cadmium (see Table 4.5) which are partly released during the process of combustion. According to recent estimates, coal-fired utilities contribute about 5-10 % to total airborne Cadmium emissions in Germany (see UMWELTBUNDESAMT 1991). As discussed in Sections 2.1 and 3.1, these emissions can be reduced by end-of-pipe-measures or by new combustion technologies - e.g., fluidized-bed combustion. A third device for emission control is fuel-switching among coals or switching from coal to other fuels (natural gas, renewables or nuclear fuels).

Table 4.6 shows the widely varying Cadmium content of coal in the United States. Obviously, there is considerable scope for reducing airborne cadmium emissions by switching from high-Cadmium coals to low-Cadmium coals. However, such substitution processes require that there exists a systematic relationship between the coals' Cadmium content and all respective mining region. For the fuels which are burned in Germany, information on Cadmium contents and mining regions are not available and it is not clear at all if there exist any systematic relationship. However, empirical evidence from the United States (see Tables 4.6 and 4.7) suggests that there exist regional differences in Cadmium content which could be exploited in order to reduce airborne Cadmium emissions at comparatively low cost. Such an approach, however, could be in contradiction to the German energy policy that heavily relies on protecting the domestic suppliers of hard coal[13].

Table 4.6 — Average Cadmium Content (ppm) in U.S. Coals from Selected Mining Regions

Region	Cd-Content
Virginia	0.07 ppm
New Mexico	0.15 ppm
Gulf Coast	0.59 ppm
Washington	1.23 ppm
Illinois	3.27 ppm
Missouri	16.65 ppm

Source: CENTER FOR CLEAN AIR POLICY (1991, p.118).

Switching from coal to natural gas would yield a 100% reduction in emissions from presently coal-fired utilities[14]. As indicated by the empiricial estimates in Table 4.7 this kind of substitution would incur extremely high cost which may not be justifiable from a narrow perspective which focuses only the impact on Cadmium emissions. However, the combustion of coal contributes not only to airborne Cadmium emissions but also to a

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[13] In particular, the electricity sector in Germany is obliged to utilize certain amounts of domestic hard coal at administered prices (FELS/NEU 1990).

[14] Of course, switching to renewables or nuclear fuels would also yield a 100% reduction in emissions. However, renewable fuels will not be available on a large scale in the near fututure, and the use of nucelar fuels seems to problematic due to the well known reasons.

number of other environmental problems like, e.g., global warming and acid rain. Hence, from a broader perspective including all relevant environmental impacts, the substitution of coal by natural gas may be a sensible decision. Such a policy, however, would be incompatible with the above mentioned protection of domestic hard coal.

Table 4.7 — Relative Cost-Effectiveness of Cadmium Emission-Reduction Options for a 500 MW Model-Plant.

	Average Annual Cost ($ millions)	Cost Effectiveness ($ millions/ton cd)
Fuel-switching: low-cd coal	0 - 23	0 - 18
Fuel-switching: natural gas	120 - 147	84 -103
Baghouse filters	6 - 8	5 - 7

Source: CENTER FOR CLEAN AIR POLICY (1991, p.70).

5. POLICY CONCLUSIONS

The control of Cadmium emissions into the air provides a good example for the difficulties which environmental policies face because it combines many of those features where emissions 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 activites 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 period of time 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 only very few storage options exist which effectively remove Cadmium from the human environment.

These circumstances require a control of all processes involving Cadmium with the consequence that those 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. In this paper we have summarized the available information on airborne Cadmium emissions. In this concluding chapter, the results from the different sectors of the economy and the different abatement strategies will be evaluated from a policy perspective with the intention to identify the potential for further reduction. These reduction potentials can not only be assessed from a technological point of view, they also need to take into account the likely abatement costs as well as the likely benefits of reducing the respective emissions.

Todays abatement technologies and todays emissions are to some extent influenced by the current regulations of airborne emissions in the different sectors. German regulations usually require ambient emission standards leaving the choice of the emission control up to the firm. These regulations through the *TA-Luft* for industrial processes, the *Goßfeuerungsanlagenverordnung* for the combustion of fossil fuels, and the *Verordnung über Verbrennungsanlagen für Abfälle* for waste incineration (see Table 2.3) have led to the wide-spread introduction of the latest end-of-pipe dust arrester technologies since these are the only dust arresters which 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 such that older arresters - Cyclons 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 emissions charges may change these cost calculations and accelerate the diffusion of the ESP's and Fabric Filters.

The incentive based instruments, however, pose efficiency problems. The emission charge could be based on dust emissions. This would induce an efficient emission structure of dust but since the concentrations of Cadmium in the dust vary widely the control of Cadmium emissions would be far from efficient. On the other hand, an emission charge on Cadmium would ignore the other substances and the dust particles carrying these substances. For these are jointly produced emissions an efficient charge system can hardly be found.

The above mentioned regulations could also have some impact 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 with 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 emission of Cadmium into the air can only come from the clean technologies. In the non-ferrous metal production, 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 of emissions if this plant were shut down with the potential and costs of alternative emission reductions, the question can be raised whether this plant's negative environmental effects are worth the value added which 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% is indicated by the published emission coefficients.

Given the hierarchy of quantitatively significant reduction potentials, one can conclude that current regulations of airborne emissions 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 impact. 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 cost of abatement are just equal to the charge rate. Predictions about the likely reaction therefore need to rely on the approximate costs of abatement.

The information on the cost of different abatement technologies which we have found suggests that further end-of-pipe reduction measures are unlikely. Abatement costs per kilogram Cadmium removed in the range of DM 2,000 up to over DM 6,000 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 above mentioned clean technologies which have overall lower production costs and provide emission reductions practically free. The incentive character of market-like instruments would therefore increase the diffusion of new technologies, although they may not be sufficient to produce an efficient emission structure because of the above mentiond jointness of emissions.

Cadmium emissions into the air have relatively little negative environmental effects as long as they stay 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 such that optimal policies also need to integrate abatement policy options for other emitting sources. KLEPPER/MAHLAU (1992) have analyzed the different sources of Cadmium in the soil and found that 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 contamination of soils with Cadmium will not necessarily be found in the industrial sector but in other not yet regulated areas.

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