10 Case studies on emissions from single facilities

In the following, the Impact Pathway Approach which is extended by ingestion exposures according to the methodology developed in this work shall be applied to case studies. Two different kinds of case studies will be performed. The first kind addresses the derivation of marginal external costs due to the operation of single power plants (this Chapter). The other assesses the overall quantifiable external costs due to pan-European emissions into air for the situation in 1990 which will be presented in a separate Chapter (11).

10.1 Definition of marginal emission-related case studies

The marginal emission-related case studies investigate the influence of the location of point sources on the marginal external costs due to the exposure towards the trace elements under study. The resulting, quantifiable marginal external costs will be put into perspective by comparing them to those caused by the emission of the classical air pollutants such as SO_2, NO_x, NH_3, NMVOC and primary particles previously reported.

In order to define the scope of the respective case studies, one needs to specify (European Commission, 1999a):

- the technology to be assessed,
- the location of emissions (e.g., at the power plant, supporting activities), and
- the fuel (type, source and composition).

According to the context in which this study is conducted, the techniques of prime interest are related to energy conversion (European Commission, 1999a). Generally, the combustion of hard coals and lignite leads to the highest emissions of heavy metals when compared to oil and natural gas used in the energy sector (Joint Research Centre of the European Commission, 2003). While most trace elements are emitted at amounts several orders of magnitude higher for coal than for the other fossil fuels, the combustion of heavy fuel oil may lead to

Table 10-1: Characteristics of the investigated power plants

Characteristic	Belgium	France	Germany	UK
Location	Genk-Langerlo	Cordemais, near Nantes	Lauffen	West Burton
Latitude [°]	50.97	47.18	49.08	53.38
Longitude [°]	5.50	-1.48	9.18	-1.50
Stack height [m]	140	220	240	230
Net efficiency [%]	37	38	43	38
Electricity generation [GWh_{el}/yr]	1472	2100	3900	11700

releases of nickel and vanadium in larger quantities. However, these elements are not subject of the analysis due to data availability constraints primarily related to the impact assessment (cf. section 7.3).

Consequently, the technology to be assessed are coal-fired power plants. The investigated trace elements are mostly released into air in association with particles (Joint Research Centre of the European Commission, 2003). The amounts emitted depend to a large extent on the flue gas treatment in use and the coals employed (e.g., Rentz and Martel, 1998; Joint Research Centre of the European Commission, 2003). For instance, the reduction rates from flue gas of high performance electrostatic (dust) precipitators and fabric filters lie above 99.9 %. Principally one can distinguish between three groups of trace elements in terms of their mass balance during combustion and flue gas cleaning (Joint Research Centre of the European Commission, 2003). Chromium belongs to one of these groups whose elements leave the stack to 0.1 %. Arsenic, cadmium and lead being part of another group are lost to air with the cleaned flue gas to 0.07 %. These values will be used to determine the amounts of trace elements emitted by power plants equipped with Best Available Techniques (BAT). Further information needed in order to determine the total emissions of trace elements into air during a one year period are the total annual electricity sent-out and the efficiency of the power plant the concentrations of the trace elements in the coals burnt and their lower heating value.

Four sites have been selected for the investigation that are taken from the recently completed EC-funded NewExt project (Number: ENG1-2000-00129). All facilities are coal-fired power plants. The locations and some characteristics of the power plants are given in Table 10-1.,According to the stack heights, only

Table 10-2: Ranges of trace element concentrations in coals of different origin as quoted in Joint Research Centre of the European Commission (2003) [mg/kg]

Trace element	Minimum value	Maximum value
Arsenic	1.4	18.5
Cadmium	0.06	0.73
Chromium	7.4	40
Lead	4.8	32

Table 10-3: Theoretical emission ranges of the investigated trace elements for the respective facilities [t/yr]

Plant	Estimate	Arsenic	Cadmium	Chromium	Lead
Belgium	minimum	$4.13 \cdot 10^{-4}$	$1.77 \cdot 10^{-5}$	$3.12 \cdot 10^{-3}$	$1.42 \cdot 10^{-3}$
	maximum	$6.87 \cdot 10^{-3}$	$2.71 \cdot 10^{-4}$	$2.12 \cdot 10^{-2}$	$1.19 \cdot 10^{-2}$
France	minimum	$5.73 \cdot 10^{-4}$	$2.46 \cdot 10^{-5}$	$4.33 \cdot 10^{-3}$	$1.97 \cdot 10^{-3}$
	maximum	$9.54 \cdot 10^{-3}$	$3.77 \cdot 10^{-4}$	$2.95 \cdot 10^{-2}$	$1.65 \cdot 10^{-2}$
Germany	minimum	$9.41 \cdot 10^{-4}$	$4.03 \cdot 10^{-5}$	$7.11 \cdot 10^{-3}$	$3.23 \cdot 10^{-3}$
	maximum	$1.57 \cdot 10^{-2}$	$6.18 \cdot 10^{-4}$	$4.84 \cdot 10^{-2}$	$2.71 \cdot 10^{-2}$
UK	minimum	$3.19 \cdot 10^{-3}$	$1.37 \cdot 10^{-4}$	$2.41 \cdot 10^{-2}$	$1.10 \cdot 10^{-2}$
	maximum	$5.32 \cdot 10^{-2}$	$2.10 \cdot 10^{-3}$	$1.64 \cdot 10^{-1}$	$9.20 \cdot 10^{-2}$

so-called 'high' emissions, i.e., those above 100 metres have been considered. No plant-specific information on the coals burnt are available which is why default values will be used. Table 10-2 gives the ranges of trace element concentrations in coal stemming from different mines of the world. The lower heating values of hard coals are assumed to range from 27 to 34 MJ per kilogram (Beitz and Küttner, 1995).

The upper and lower bound in terms of trace element emissions are given in Table 10-3 for the respective power plants. The minimum and maximum values are obtained by combining the upper bound lower heating value with the trace element contents of the less contaminated coals and vice versa.

Table 10-4: Effective Intake Fractions due to inhalation of selected trace elements for a one year pulse emission into air at different sites [$kg_{inhaled}$ per $kg_{released}$]

Trace element	Belgium	France	Germany	UK
Arsenic	$8.7 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$7.2 \cdot 10^{-6}$	$4.6 \cdot 10^{-6}$
Cadmium	$8.7 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$7.2 \cdot 10^{-6}$	$4.6 \cdot 10^{-6}$
Chromium	$8.7 \cdot 10^{-7}$	$4.8 \cdot 10^{-7}$	$7.2 \cdot 10^{-7}$	$4.6 \cdot 10^{-7}$
Lead	$8.7 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$7.2 \cdot 10^{-6}$	$4.6 \cdot 10^{-6}$

Default emission scenarios have been run with the help of the EcoSense model for all facilities by assuming that 1000 kilogram of a trace element are emitted during a one year period. The effective Intake Fractions for inhalation and ingestion exposures are derived separately based on these pulse emission scenarios. The properties of the investigated contaminants are given in Appendix C.

10.2 Impacts due to inhalation exposure

The impact assessment due to inhalation is based on the respective (effective) Intake Fraction. Its contribution to the quantifiable overall Intake Fraction ceases after one year for substances that are short-lived in air under pulse emission conditions of the same duration. The respective values due to inhalation exposures are given in Table 10-4. It can be noted that all elements emitted at one site show the same environmental dispersion. This is due to the way the trace elements are assumed to be distributed on the different particle size classes in air (Table 4-1 and Lee, 2003). Note that lead stemming from an emission source other than traffic also follows the same particle size distribution scheme in air like the other trace elements in this case. The difference by one order of magnitude between the values for arsenic, cadmium and lead on the one hand and for chromium on the other is due to the assumption that 10 % of the chromium amounts emitted are in the hexavalent state (cf. Table C-2). The Intake Fractions for the power plant in Belgium are the highest indicating that more people are affected. This is due to the prevailing westerly winds which lead to a higher exposure of the Ruhr catchment in Germany, an area with a high population density (agglomeration). A higher population density of the area affected also applies to the German emission scenario, however, to a lesser extent.

The Disability Adjusted Life Years (DALYs) due to cancer and non-cancer effects related to the release of one kilogram of the respective trace element are

Table 10-5: Disability Adjusted Life Years (DALYs) per kilogram of selected trace elements released due to cancer and non-cancer effects upon inhalation exposure caused by a one year pulse emission from selected power plant sites [years lost-equivalents per $kg_{released}$]

Trace element	Type of effect	Belgium	France	Germany	UK
Arsenic	cancer	$5.95 \cdot 10^{-4}$	$3.26 \cdot 10^{-4}$	$4.94 \cdot 10^{-4}$	$3.15 \cdot 10^{-4}$
	non-cancer	n/a	n/a	n/a	n/a
Cadmium	cancer	$2.49 \cdot 10^{-4}$	$1.37 \cdot 10^{-4}$	$2.07 \cdot 10^{-4}$	$1.32 \cdot 10^{-4}$
	non-cancer	n/a	n/a	n/a	n/a
Chromium	cancer	$1.66 \cdot 10^{-4}$	$9.11 \cdot 10^{-5}$	$1.38 \cdot 10^{-4}$	$8.79 \cdot 10^{-5}$
	non-cancer	$2.43 \cdot 10^{-6}$	$1.33 \cdot 10^{-6}$	$2.02 \cdot 10^{-6}$	$1.29 \cdot 10^{-6}$
Lead	cancer	n/a	n/a	n/a	n/a
	non-cancer	n/a	n/a	n/a	n/a

given in Table 10-5. No non-cancer effect information for inhalation exposures is available for arsenic, cadmium and lead (cf. section 7.3). The same applies to cancer effects due to inhalation of lead which means that no inhalation-related effects for lead can be assessed at present. The cancer-related DALYs per kilogram released are about in the same order of magnitude for all trace elements, owing to comparable slope factors and associated DALYs. The steeper slope factor for cancer due to inhalation of chromium is counterbalanced by the lower amount of hexavalent chromium assumed to be present in air. The non-cancer effect caused by inhalation of hexavalent chromium is classified as a category 3 effect with little years lost-equivalents associated (cf. Table 7-7) leading to a reduced contribution to the overall impact. As discussed in section 9.3.1, the assumption of a linear exposure-response function without thresholds is still a matter for debate with respect to non-cancer effects at least at the individual level. However, the non-cancer associated DALYs caused by chromium are smaller by about two orders of magnitude than those due to cancer. Also the contribution of the non-cancer effects to the overall damage costs caused by inhalation exposures are negligible (see Table 10-6).

Valuing the substance-specific inhalation-caused impacts leads to damage factors in external costs per kilogram of pollutant emitted (Table 10-6). The monetary values used are given in section 8.2.4. The external costs yielded are smaller by up to a factor of about seven when compared to those provided by European

Commission (2004). The discrepancy can be attributed to the different concentration-response model, to the different monetary values chosen and partly the different air quality models used. The effect information employed differs by a factor of two corresponding to the modification of the 95th upper limit estimate to become a maximum likelihood slope factor according to Eq. (7-14). The monetary valuation of cancer cases at a discount rate of 3 % is also different by a factor of two, using $2 \cdot 10^6$ €$_{2000}$ per generic cancer case (European Commission, 2004) and 819552 €$_{2000}$ per lung cancer case in this study (cf. Table 8-6), respectively. This means that the contribution of the trace elements investigated to the overall external damage costs due to the operation of power plants is even less substantial than according to European Commission (2004).

The damage factors for classical air pollutants such as NO_x, SO_2 and primary particles may range from 3 to 27 €$_{2000}$ per kilogram emitted (discounted at 3 %, European Commission, 2004). These values are about in the same order of magnitude as those estimated here, noting that the classical air pollutants are emitted in much larger quantities.

Ranges of annual external costs due to the operation of the four facilities investigated are obtained by scaling the damage factors (Table 10-6) with the theoretical minimum and maximum annual emission values (Table 10-3). The resulting figures in Euro per year are given in Tables 10-7 and 10-8 for a discount rate of 0 and 3 %, respectively. The external costs indicate that the use of different coals with variable degrees of contamination and (lower) heating values may have a pronounced effect of more than one order of magnitude on the external costs assessed to occur. However, usually the characteristics of the coals employed at a given plant can be known exactly so that this source of variability of the results can substantially be reduced. It shows, furthermore, that the plant with the largest electricity generation is situated in the UK leading to the highest external costs due to a one-year operation. This reflects the highest annual emissions (cf. Table 10-3) despite its smallest damage factors among the facilities analysed (cf. Table 10-6). The ranking of the other facilities is Germany, Belgium and France in descending order.

The external costs per kilowatt hour of electricity generated are also given in Tables 10-7 and 10-8. The external costs of the classical air pollutants per kilowatt hour are in the €-cent range according to European Commission (2004) whereas those computed for the trace elements in total are about five orders of magnitude smaller which is due to them being emitted to a lesser extent.

Table 10-6: Damage factors due to inhalation for a one year pulse emission from different sites discounted at a rate of 0 and 3 % [$€_{2000}$ per $kg_{released}$]

Trace element[a]	Type of effect	Type of monetary value	Belgium		France		Germany		UK	
			0 %	3 %	0 %	3 %	0 %	3 %	0 %	3 %
Arsenic[b]	cancer	WTP	44.6	23.8	24.5	13.1	37.1	19.8	23.6	12.6
		COI	11.8	6.3	6.5	3.4	9.8	5.2	6.2	3.3
Cadmium[b]	cancer	WTP	18.7	10.0	10.2	5.5	15.5	8.3	9.9	5.3
		COI	4.9	2.6	2.7	1.4	4.1	2.2	2.6	1.4
Chromium	cancer	WTP	12.4	6.6	6.8	3.6	10.3	5.5	6.6	3.5
		COI	3.3	1.8	1.8	0.96	2.7	1.5	1.7	0.93
	non-cancer	WTP	0.182	0.097	0.100	0.053	0.152	0.081	0.097	0.052
		COI	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

a. No effect information available for lead.

b. No non-cancer effect information available.

Table 10-7: Ranges of quantifiable external costs discounted at 0 % due to inhalation of selected trace elements and in total caused by a one year pulse emission from different sites (variable units, base year 2000)

Trace element[a]	Type of effect	Type of monetary value	Belgium		France		Germany		UK	
			[€/ yr]	[10^{-9} €/ kWh$_{el}$]	[€/ yr]	[10^{-9} €/ kWh$_{el}$]	[€/ yr]	[10^{-9} €/ kWh$_{el}$]	[€/ yr]	[10^{-9} €/ kWh$_{el}$]
Arsenic[b]	cancer	WTP	18-306	13-208	14-234	6.7-111	35-581	8.9-149	75-1256	6.4-107
		COI	4.9-81	3.3-55	3.7-62	1.8-29	9.2-153	2.4-39	20-331	1.7-28
Cadmium[b]	cancer	WTP	0.33-5.1	0.22-3.4	0.25-3.9	0.12-1.8	0.63-10	0.16-2.5	1.4-21	0.12-1.8
		COI	0.087-1.3	0.059-0.91	0.066-1.0	0.032-0.48	0.17-2.5	0.042-0.65	0.36-5.5	0.031-0.47
Chromium	cancer	WTP	39-264	26-179	30-201	14-96	74-501	19-128	159-1082	14-93
		COI	10-70	7.0-47	7.8-53	3.7-25	19-132	5.0-34	42-285	3.6-24
	non-cancer	WTP	0.57-3.9	0.39-2.6	0.43-3.0	0.21-1.4	1.1-7.3	0.28-1.9	2.3-16	0.20-1.4
		COI	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Sum			*73-731*	*50-497*	*56-558*	*27-265*	*139-1390*	*36-355*	*300-3000*	*26-256*

a. No effect information available for lead.

b. No non-cancer effect information available.

Table 10-8: Ranges of quantifiable external costs discounted at 3 % due to inhalation of selected trace elements and in total caused by a one year pulse emission from different sites (variable units, base year 2000)

Trace element[a]	Type of effect	Type of monetary value	Belgium		France		Germany		UK	
			[€/ yr]	[10^{-9} €/ kWh$_{el}$]	[€/ yr]	[10^{-9} €/ kWh$_{el}$]	[€/ yr]	[10^{-9} €/ kWh$_{el}$]	[€/ yr]	[10^{-9} €/ kWh$_{el}$]
Arsenic[b]	cancer	WTP	9.8-163	6.7-110	7.5-125	3.6-59	19-310	4.8-79	40-670	3.4-57
		COI	2.6-43	1.8-29	2.0-33	0.94-16	4.9-82	1.3-21	11-177	0.91-15
Cadmium[b]	cancer	WTP	0.18-2.7	0.12-1.8	0.13-2.1	0.064-0.98	0.33-5.1	0.086-1.3	0.7-11	0.062-0.95
		COI	0.046-0.7	0.032-0.48	0.035-0.54	0.017-0.26	0.088-1.3	0.023-0.35	0.19-2.9	0.016-0.25
Chromium	cancer	WTP	21-141	14-96	16-107	7.5-51	39-267	10-68	85-577	7.2-49
		COI	5.5-37	3.7-25	4.2-28	2.0-13	10-70	2.7-18	22-152	1.9-13
	non-cancer	WTP	0.30-2.1	0.21-1.4	0.23-1.6	0.11-0.75	0.57-3.9	0.15-1.0	1.2-8.5	0.11-0.72
		COI	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Sum			*39-390*	*27-265*	*30-297*	*14-142*	*74-739*	*19-190*	*160-1600*	*14-137*

a.No effect information available for lead.

b.No non-cancer effect information available.

10.3 Impacts due to ingestion exposure

The assessment of the ingestion-related human exposures is performed based on the environmental settings of the 'food removal' scenario (see section 9.3.3). The four trace elements analysed show marked differences in terms of both the absolute value of the effective Intake Fraction due to ingestion exposures and the temporal development of this measure (Fig. 10-1 and Fig. 10-2, note the logarithmic scale). The amount of cadmium taken in is highest for releases from all sites reaching 0.25 % of the overall amount released in the Belgian case. Arsenic and chromium show effective Intake Fractions due to ingestion of about one order of magnitude less than cadmium in the long run. The effective Intake Fraction due to ingestion of lead is about one third of that for cadmium. According to the present assessment, there will be a relatively and absolutely higher exposure of cadmium and lead within the next 100 years upon release of the trace elements. This means that 23.2-25.6 %, 9.6-10.6 %, 1.4-2.1 % and 1.0-1.3 % of the time-integrated effective Intake Fraction due to ingestion will have been reached within this period of time for cadmium, lead, chromium and arsenic, respectively. These figures are substantially smaller for the first 10 year period (4.3-5.0 %, 1.4-2.1 %, 0.2-0.5 % and 0.12-0.14 %, respectively). The contribution of the inhalation-related Intake Fraction is insignificant in the long run (when performing non-zero discounting, Fig. 10-1 and Fig. 10-2). This also holds for the short and intermediate term, except for arsenic. This indicates that the exposure through the media soil and water are most significant at least in the intermediate to long term.

The differences between the sites in terms of the absolute time-integrated Intake Fractions due to ingestion are within a factor of 1.3 for chromium to 2.6 for arsenic, with Belgian emissions leading to the highest specific ingestion exposures investigated and those from the UK site to the lowest. This ranking is equal to that of the inhalation Intake Fractions. Also the variation between sites is similar to the inhalation Intake Fractions despite the homogenizing effect of food concentrations due to trade. This homogenizing effect of trade has especially been postulated by Spadaro and Rabl (2004) which is demonstrated not to be the case to the extent expected by these authors. It is reflected in all subsequently derived measures such as damage costs per contaminant emitted (see below). Moreover, the dynamics for the different trace elements vary for the different sites. For instance, the development of the ingestion exposure with respect to cadmium is quickest in the UK (25.6 % of the time-integrated situation reached after 100 years) that of chromium is about the slowest at the same site (1.5 %).

Not only the total amounts taken in vary considerably in time and space but also the most contributing food items (Fig. 10-3 and Fig. 10-4). This variation may even lead to entirely different patterns in terms of the dominating food items at different integration times. For instance, the long-term exposure towards arsenic is dominated by dairy products (more than 74 %) while in the short term the composition of the ingestion exposure is more balanced. Also, the exposure through aboveground exposed produce such as spinach contributes more substantially in the near future alongside with the occurring emissions while in the long run its contribution to the effective Intake Fraction may be insubstantial (top vs. bottom for a given site in Fig. 10-3 and Fig. 10-4). The contribution of aboveground exposed produce through interception of atmospheric deposition, thus, appears to be similar to inhalation-related exposures in terms of their intertemporal significance for human exposure towards pulse emissions.

The ingestion of cadmium and lead primarily occurs contained in cereals (more than 77 % in the long run) while dairy products are also important for chromium and even more so for arsenic. Beef only constitutes a significant share of chromium's Intake Fraction in the long run according to this assessment (Fig. 10-3 and Fig. 10-4). Freshwater fish and other animal products such as pork, poultry and eggs contribute less than one percent of the Intake Fraction due to ingestion, partly owing to non-available substance-specific transfer data (Table C-5). Depending on the place of emission, the shares of the different food items contributing to the aggregated ingestion exposure also vary. For instance, cereals are more important for emissions taking place in France and in the UK while the exposure through potatoes grows in importance for emissions occurring in Belgium and Germany. This is mainly explainable by differences in the intensity of the cultivation of these two staple food products in different countries (cf. Table B-16). Differences between aboveground protected and belowground produce in terms of the bioconcentration factors are insubstantial except for arsenic (cf. Table C-4).

In the long run, the impacts due to ingestion in terms of DALYs per emitted amount of trace element tend to be larger than those due to inhalation for a one year pulse emission except for chromium (Table 10-9 vs. Table 10-5). These impacts are assessed by employing the approach described in section 7.3.1 which is based on the Intake Fractions presented above. Generally, non-cancer effects dominate the DALYs assessed via ingestion exposures (Table 10-9). Only non-cancer effect information is available for cadmium and chromium through this exposure route according to Crettaz (2000). While the DALYs due to non-cancer effects are about one order of magnitude larger than due to cancer for arsenic, this discrepancy amounts to more than two orders of magnitude for lead (refer to section 9.3.1 with respect to a discussion on the uncertainty of the effect assessment for both effect types).

Valuing the impacts assessed to occur via ingestion yields the damage factors expressed in external costs per kilogram of pollutant emitted (Table 10-10 through to Table 10-13). These are given for two different discount rates. The highest specific damage costs are estimated for emissions stemming from the Bel-

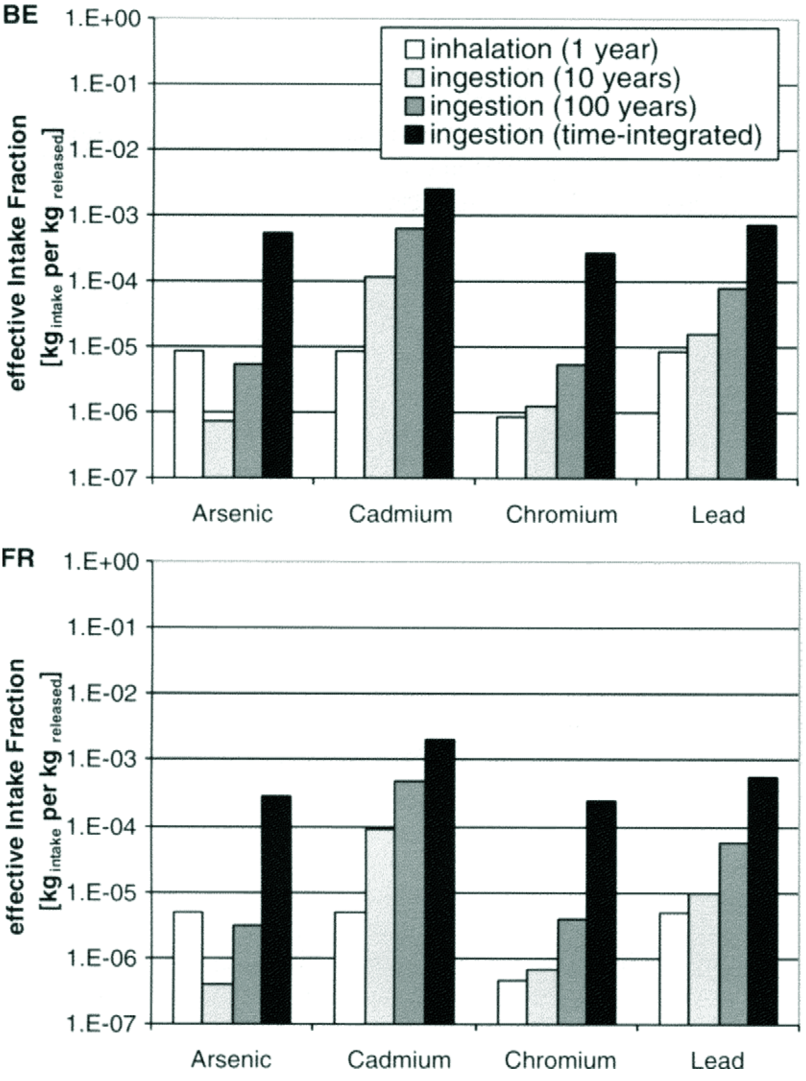

Fig. 10-1: Effective Intake Fraction of selected trace elements via inhalation after one year and via ingestion of food after 10 and 100 years, and time-integrated for a one year pulse emission from the Belgian ('BE', top) and French site ('FR', bottom); note the logarithmic scale [kg_{intake} per $kg_{released}$]

gian power plant followed by the facilities in Germany, France and the UK in descending order. In all cases, the highest damage factors are estimated to be caused by non-cancer effects due to cadmium and lead ingestion ranging from 3488 to

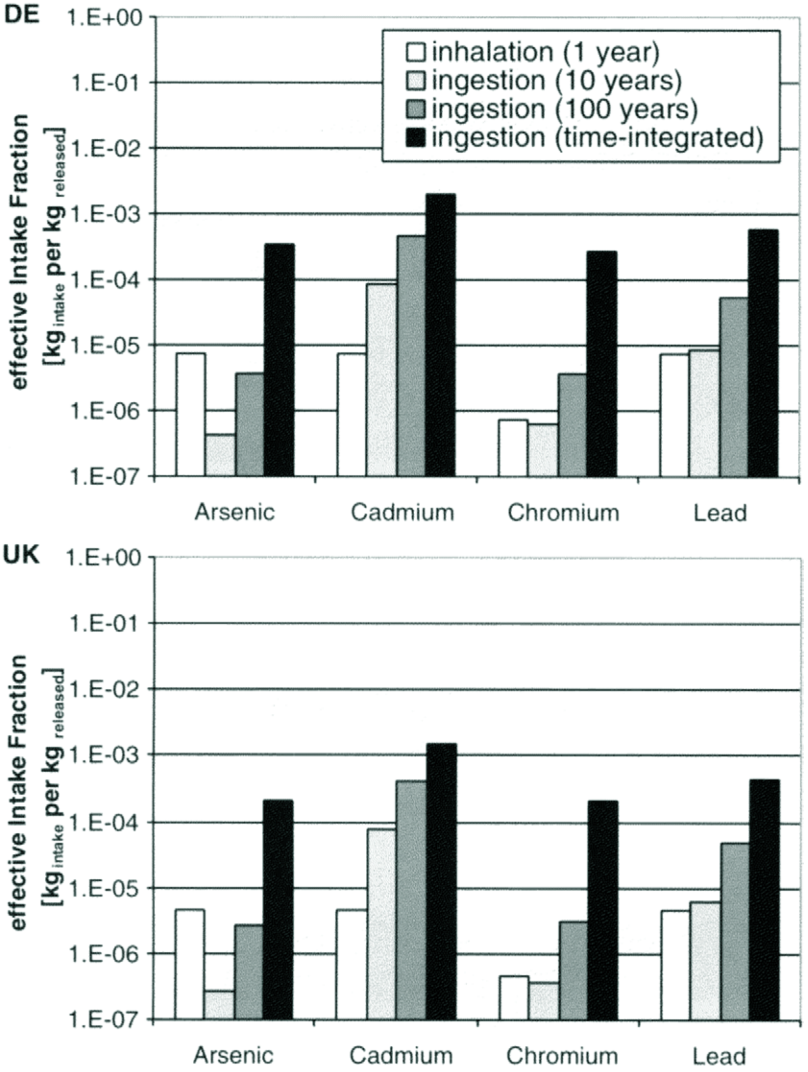

Fig. 10-2: Effective Intake Fraction of selected trace elements via inhalation after one year and via ingestion of food after 10 and 100 years, and time-integrated for a one year pulse emission from the German ('DE', top) and UK site ('UK', bottom); note the logarithmic scale [kg_{intake} per $kg_{released}$]

5642 €$_{2000}$ per kilogram of cadmium released and from 3500 to 5658 €$_{2000}$ per kilogram of lead released, respectively, when discounting at a rate of 0 %. The corresponding costs for arsenic amount to some ten percent of those for lead or

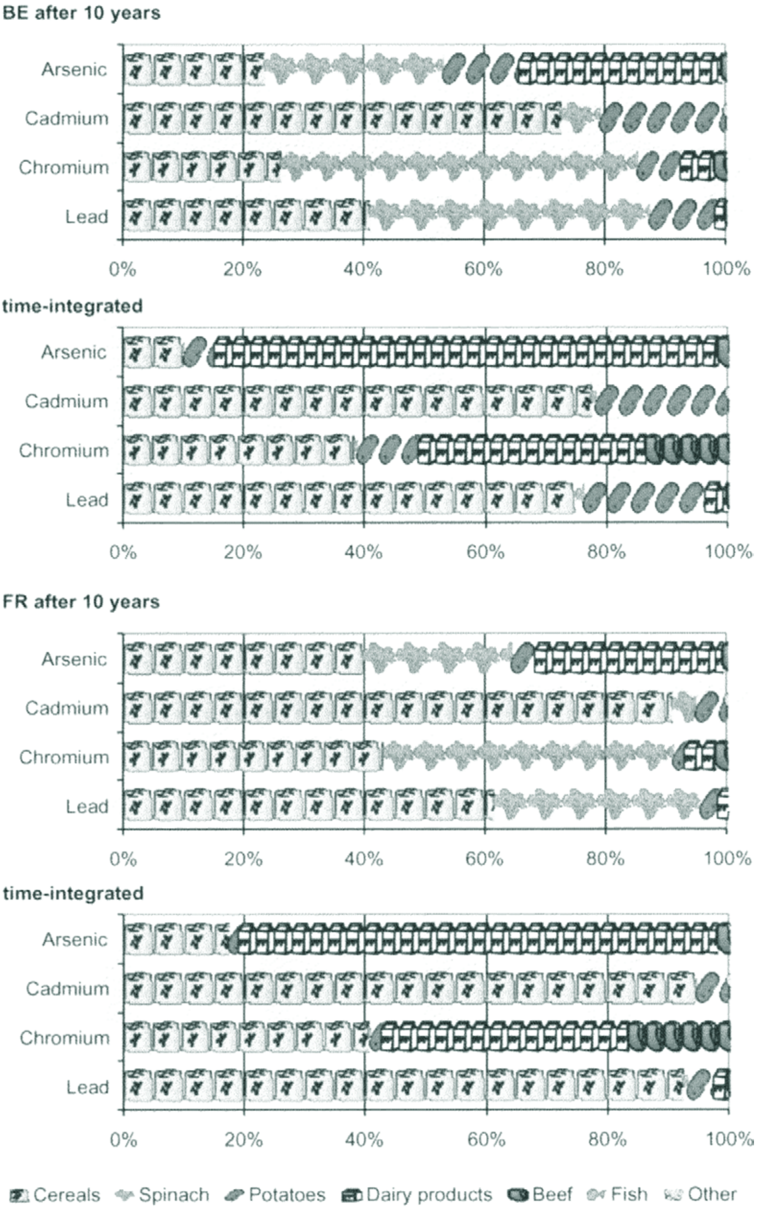

Fig. 10-3: Relative contribution of the different food items to the effective Intake Fraction (ingestion) of selected trace elements after 10 years and time-integrated for a one year pulse emission from the Belgian ('BE', top) and French site ('FR', bottom, cliparts by Corel Corporation, 2002)

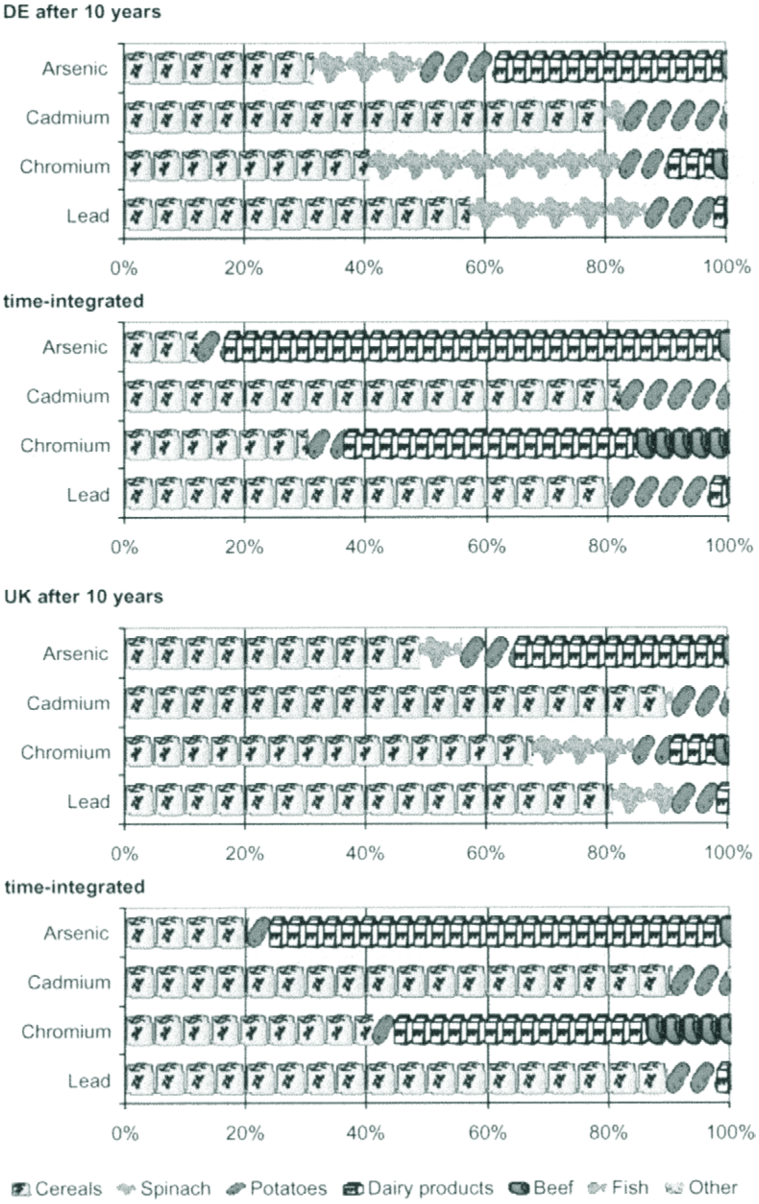

Fig. 10-4: Relative contribution of the different food items to the effective Intake Fraction (ingestion) of selected trace elements after 10 years and time-integrated for a one year pulse emission from the German ('DE', top) and the UK site ('UK', bottom, cliparts by Corel Corporation, 2002)

Table 10-9: Time-integrated Disability Adjusted Life Years (DALYs) per kilogram of trace element released due to cancer and non-cancer effects upon ingestion exposure caused by a one year pulse emission from single sites [years lost-equivalents per $kg_{released}$]

Trace element	Type of effect	Belgium	France	Germany	UK
Arsenic	Cancer	$1.39 \cdot 10^{-3}$	$7.41 \cdot 10^{-4}$	$9.12 \cdot 10^{-4}$	$5.36 \cdot 10^{-4}$
	Non-cancer	$2.94 \cdot 10^{-2}$	$1.57 \cdot 10^{-2}$	$1.94 \cdot 10^{-2}$	$1.14 \cdot 10^{-2}$
Cadmium	Cancer	n/a	n/a	n/a	n/a
	Non-cancer	$7.52 \cdot 10^{-2}$	$5.98 \cdot 10^{-2}$	$6.02 \cdot 10^{-2}$	$4.65 \cdot 10^{-2}$
Chromium	Cancer	n/a	n/a	n/a	n/a
	Non-cancer	$2.89 \cdot 10^{-5}$	$2.53 \cdot 10^{-5}$	$2.90 \cdot 10^{-5}$	$2.23 \cdot 10^{-5}$
Lead	Cancer	$2.04 \cdot 10^{-4}$	$1.58 \cdot 10^{-4}$	$1.59 \cdot 10^{-4}$	$1.26 \cdot 10^{-4}$
	Non-cancer	$7.54 \cdot 10^{-2}$	$5.85 \cdot 10^{-2}$	$5.86 \cdot 10^{-2}$	$4.67 \cdot 10^{-2}$

cadmium at the respective site. The analogous relation for chromium is below the per mill range.

There is only one ingestion-related damage factor available in the literature for the trace elements analysed (European Commission, 2004). It is given for arsenic and amounts to a value of 33.6 $€_{2000}$ per kilogram of arsenic emitted by taking only cancer effects into account and discounting at a rate of 3 %. This value is larger by two orders of magnitude and more when only comparing it to the cancer effect-related damage costs of arsenic in the present assessment. It needs to be noted that (a) no distinction is made in European Commission (2004) with respect to the toxicity of different arsenic species via ingestion exposures (only 3 % of the contents in food is assumed to be in the toxic inorganic form here, cf. Table C-2), (b) the monetary value assigned to cancers caused by ingestion of (inorganic) arsenic is different in the two studies ($2 \cdot 10^6$ $€_{2000}$ per generic cancer case according to European Commission (2004) and 422200 $€_{2000}$ per skin cancer case in this study, cf. Table 8-6, discounting at 3 %), and (c) the slope factor for ingestion exposures related to undifferentiated arsenic species is larger in European Commission (2004) by a factor of two according to Eq. (7-13). All of these issues, thus, lead to lower external costs by a factor of about 0.003 only due to the assessment and valuation of cancers per kilogram of arsenic released when following the methodology proposed in the present study. This is, however, modified by the use

Table 10-10: Damage factors due to ingestion for a one year pulse emission according to emissions from the Belgian power plant [$€_{2000}$ per $kg_{released}$]

Trace element	Type of effect	Type of monetary value	Discount rate	
			0 %	3 %
Arsenic	cancer	WTP	104	0.19
		COI[a]	71	0.13
	non-cancer	WTP	2207	4.1
		COI	n/a	n/a
Cadmium[b]	non-cancer	WTP	5642	337
		COI	n/a	n/a
Chromium[b]	non-cancer	WTP	2.2	0.0095
		COI	n/a	n/a
Lead	cancer	WTP	15	0.34
		COI[a]	5.1	0.12
	non-cancer	WTP	5658	128
		COI[c]	209	4.7

a.COI for average cancer.
b.Cancer effect information not available.
c.COI for hypertension.

of an environmental fate and exposure assessment model that differs from the Uniform World Model employed in European Commission (2004) leading to less pronounced discrepancies between the two approaches than the factor of 0.003. Additionally, also non-cancer effects can be valued according to the approach taken here. The consideration of these effects substantially increases the damage costs due to the ingestion of inorganic arsenic. This is also the case for lead. No impact assessment would have been possible for cadmium and chromium via ingestion exposures towards these heavy metals without non-cancer effects according to the approach followed. The significance of the non-cancer impacts stems from the steeper slope factors despite the smaller severity in terms of DALYs per person (Table 7-7) as compared to the cancer impacts (Table 7-6).

Table 10-11: Damage factors due to ingestion for a one year pulse emission according to emissions from the French power plant [$€_{2000}$ per $kg_{released}$]

Trace element	Type of effect	Type of monetary value	Discount rate 0 %	Discount rate 3 %
Arsenic	cancer	WTP	56	0.11
		COI[a]	38	0.075
	non-cancer	WTP	1180	2.3
		COI	n/a	n/a
Cadmium[b]	non-cancer	WTP	4483	255
		COI	n/a	n/a
Chromium[b]	non-cancer	WTP	1.9	0.0061
		COI	n/a	n/a
Lead	cancer	WTP	11.9	0.24
		COI[a]	4.0	0.080
	non-cancer	WTP	4388	89
		COI[c]	162	3.3

a.COI for average cancer.
b.Cancer effect information not available.
c.COI for hypertension.

The damage factors are significantly smaller when non-zero discounting is performed, owing to the long-lived nature of these pollutants (cf. Hellweg, 2000; van den Bergh et al., 2000; Huijbregts et al., 2001; de Vries et al., 2004). Depending on the dynamics of the respective pollutant (cf. Fig. 10-1 and Fig. 10-2), the effect is more (e.g., arsenic) or less (e.g., cadmium) pronounced.

Multiplying the damage factors due to ingestion exposures with the theoretical annual emission ranges given in Table 10-3 yields the annual external costs in Euro per year via this exposure route (Tables 10-14 through 10-17). The ranking of the facilities according to the resulting values for a one year pulse emission is the same as for inhalation: UK, Germany, Belgium and France in descending

Table 10-12: Damage factors due to ingestion for a one year pulse emission according to emissions from the German power plant [$€_{2000}$ per $kg_{released}$]

Trace element	Type of effect	Type of monetary value	Discount rate 0 %	3 %
Arsenic	cancer	WTP	68	0.13
		COI[a]	47	0.086
	non-cancer	WTP	1452	2.7
		COI	n/a	n/a
Cadmium[b]	non-cancer	WTP	4516	250
		COI	n/a	n/a
Chromium[b]	non-cancer	WTP	2.2	0.0059
		COI	n/a	n/a
Lead	cancer	WTP	12	0.23
		COI[a]	4.0	0.077
	non-cancer	WTP	4397	85
		COI[c]	163	3.1

a.COI for average cancer.
b.Cancer effect information not available.
c.COI for hypertension.

order. Generally, one can note that the quantified external costs due to lead by far exceed those caused by the other trace elements. A more thorough discussion on the absolute values will be done for the pan-European emission scenario which is to be presented in Chapter 11.

The external costs are also provided related to a kilowatt hour of electricity produced in Tables 10-14 through 10-17 by dividing those per year by the annual electricity sent-out as given in Table 10-1. When comparing these costs to those for the classical air pollutants as given in European Commission (2004), the conclusion is the same as for inhalation in that the external costs of the classical air pollutants exceed those of the trace elements investigated here by at least four orders of magnitude when equally discounting at 3 %.

Table 10-13: Damage factors due to ingestion for a one year pulse emission according to emissions from the power plant in the UK [$€_{2000}$ per $kg_{released}$]

Trace element	Type of effect	Type of monetary value	Discount rate	
			0 %	3 %
Arsenic	cancer	WTP	40	0.090
		COI[a]	27	0.061
	non-cancer	WTP	854	1.9
		COI	n/a	n/a
Cadmium[b]	non-cancer	WTP	3488	222
		COI	n/a	n/a
Chromium[b]	non-cancer	WTP	1.7	0.013
		COI	n/a	n/a
Lead	cancer	WTP	9.5	0.19
		COI[a]	3.2	0.065
	non-cancer	WTP	3500	71
		COI[c]	129	2.6

a.COI for average cancer.
b.Cancer effect information not available.
c.COI for hypertension.

Some general concluding remarks on the estimated DALYs and external costs for both case studies will be given in sections 12.3.2 and 12.4.

Table 10-14: Ranges of quantifiable external costs due to ingestion caused by a one year pulse emission of selected trace elements and in total according to theoretical minimum and maximum emission values from the Belgian power plant (variable units)

Trace element	Type of effect	Type of value	Discount rate			
			0 %		3 %	
			[€$_{2000}$/yr]	[10^{-9} €$_{2000}$/ kWh$_{el}$]	[€$_{2000}$/yr]	[10^{-9} €$_{2000}$/ kWh$_{el}$]
Arsenic	cancer	WTP	43-714	29-485	0.080-1.3	0.054-0.90
		COI[a]	29-486	20-330	0.054-0.91	0.037-0.62
	non-cancer	WTP	911-15160	619-10299	1.7-28	1.2-19
		COI	n/a	n/a	n/a	n/a
Cadmium[b]	non-cancer	WTP	100-1529	1582-26328	6.0-91	95-1574
		COI	n/a	n/a	n/a	n/a
Chromium[b]	non-cancer	WTP	6.8-46	0.61-10	0.029-0.20	0.0027-0.044
		COI	n/a	n/a	n/a	n/a
Lead	cancer	WTP	22-182	4.3-71	0.49-4.1	0.097-1.6
		COI[a]	7-61	1.4-24	0.16-1.4	0.032-0.54
	non-cancer	WTP	8008-67224	1587-26402	181-1515	36-595
		COI[c]	296-2486	59-976	6.7-56	1.3-22
Sum			*9420-87900*	*3902-64926*	*196-1700*	*133-2214*

[a] COI for average cancer.

[b] Cancer effect information not available.

[c] COI for hypertension.

Table 10-15: Ranges of quantifiable external costs due to ingestion caused by a one year pulse emission of selected trace elements and in total according to theoretical minimum and maximum emission values from the French power plant (variable units)

Trace element	Type of effect	Type of value	Discount rate			
			0 %		3 %	
			[$€_{2000}$/yr]	[10^{-9} $€_{2000}$/ kWh_{el}]	[$€_{2000}$/yr]	[10^{-9} $€_{2000}$/ kWh_{el}]
Arsenic	cancer	WTP	32-530	15-252	0.063-1.0	0.030-0.50
		COI[a]	22-361	10-172	0.043-0.71	0.020-0.34
	non-cancer	WTP	677-11258	322-5361	1.3-22	0.64-11
		COI	n/a	n/a	n/a	n/a
Cadmium[b]	non-cancer	WTP	110-1688	1224-20368	6.3-96	70-1160
		COI	n/a	n/a	n/a	n/a
Chromium[b]	non-cancer	WTP	8.2-56	0.52-8.6	0.026-0.18	0.0017-0.028
		COI	n/a	n/a	n/a	n/a
Lead	cancer	WTP	23-196	3.2-54	0.47-4.0	0.065-1.1
		COI[a]	8.0-65	1.1-18	0.16-1.3	0.022-0.36
	non-cancer	WTP	8628-72432	1198-19940	174-1464	24-403
		COI[c]	319-2679	44-737	6.4-54	0.90-15
Sum			*9827-89266*	*2819-46912*	*189-1643*	*96-1591*

a.COI for average cancer.
b.Cancer effect information not available.
c.COI for hypertension.

Table 10-16: Ranges of quantifiable external costs due to ingestion caused by a one year pulse emission of selected trace elements and in total according to theoretical minimum and maximum emission values from the German power plant (variable units)

Trace element	Type of effect	Type of value	Discount rate			
			0 %		3 %	
			[€$_{2000}$/yr]	[10^{-9} €$_{2000}$/ kWh$_{el}$]	[€$_{2000}$/yr]	[10^{-9} €$_{2000}$/ kWh$_{el}$]
Arsenic	cancer	WTP	64-1071	17-275	0.12-2.0	0.030-0.51
		COI[a]	44-729	11-187	0.081-1.3	0.021-0.34
	non-cancer	WTP	1367-22741	350-5831	2.5-42	0.65-11
		COI	n/a	n/a	n/a	n/a
Cadmium[b]	non-cancer	WTP	182-2791	1090-18133	10-154	60-1003
		COI	n/a	n/a	n/a	n/a
Chromium[b]	non-cancer	WTP	15-105	0.52-8.7	0.042-0.28	0.0014-0.024
		COI	n/a	n/a	n/a	n/a
Lead	cancer	WTP	38-322	2.9-48	0.74-6.2	0.055-0.92
		COI[a]	13-108	0.96-16	0.25-2.1	0.018-0.31
	non-cancer	WTP	14189-119117	1061-17658	274-2299	20-341
		COI[c]	525-4406	39-653	10-85	0.76-13
Sum			*16437-151389*	*2573-42809*	*298-2592*	*82-1369*

a.COI for average cancer.
b.Cancer effect information not available.
c.COI for hypertension.

Table 10-17: Quantifiable external costs due to ingestion caused by a one year pulse emission of selected trace elements and in total according to theoretical minimum and maximum emission values from the power plant in the UK (variable units)

Trace element	Type of effect	Type of value	Discount rate 0 %		Discount rate 3 %	
			[€$_{2000}$/yr]	[10^{-9} €$_{2000}$/ kWh$_{el}$]	[€$_{2000}$/yr]	[10^{-9} €$_{2000}$/ kWh$_{el}$]
Arsenic	cancer	WTP	129-2138	11-183	0.29-4.8	0.025-0.41
		COI[a]	88-1456	7.5-124	0.20-3.3	0.017-0.28
	non-cancer	WTP	2729-45407	233-3881	6.1-102	0.52-8.7
		COI	n/a	n/a	n/a	n/a
Cadmium[b]	non-cancer	WTP	478-7317	952-15849	30-466	61-1009
		COI	n/a	n/a	n/a	n/a
Chromium[b]	non-cancer	WTP	40-275	0.46-7.6	0.32-2.2	0.0036-0.060
		COI	n/a	n/a	n/a	n/a
Lead	cancer	WTP	104-870	2.6-43	2.1-18	0.053-0.88
		COI[a]	35-291	0.86-14	0.71-5.9	0.018-0.29
	non-cancer	WTP	38340-321866	956-15904	782-6568	20-325
		COI[c]	1418-11904	35-588	29-243	0.72-12
Sum			*43359-391525*	*2199-36594*	*851-7413*	*81-1356*

a.COI for average cancer.

b.Cancer effect information not available.

c.COI for hypertension.