

*A model for waste-specific
life cycle inventories of
open burning of waste*



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1 Introduction

The LCA waste incineration model in Doka (2003-II, 2013) is based on modern waste incinerator plants in Switzerland and Germany, with extensive flue gas purification. Here a process inventory model for open burning of waste is presented. As with the previous instalments, the model focuses on the emission of pollutants from specific waste materials. This model can be used to obtain emission figures for specific waste materials when they are burned in the open without any kind of flue gas cleaning. A first model of open burning was already developed in (Doka 2000).

The present tool was developed 2016–2017 by Gabor Doka in a project for Sustainable Recycling Industries SRI, financed by the Swiss State Secretariat for Economic Affairs SECO, commissioned by the Swiss Federal Laboratories for Materials Science and Technology EMPA, mandated by theecoinvent Association. The reports were reviewed by Ivan Muñoz of 2.-0 LCA consultants.

2 Basic concept

The present model for open, uncontrolled burning is conceptually based on a previous model elaborated for controlled municipal incineration. The municipal waste incineration model in Doka (2003-II, 2013) basically calculates waste-specific emissions by applying *transfer coefficients* for chemical elements to the content of those elements in a specific waste material. The elemental waste composition describes the *input* to the plant and the transfer coefficients describe the *behaviour* of elements in the plant. In very basic terms this can be formulated in the following way:

$$\text{Waste input}_{\text{Element}} \times \text{Transfer Coefficient}_{\text{Element,Output}} = \text{Emission}_{\text{Element,Output}}$$

A distinction is made in the incineration model between burnable and unburnable waste. This concept is also applied for the open burning model. Unburnable materials are assumed to go to the solid residue, while burnable materials can also lead to air emissions. For the user of the model it is therefore important to keep unburnable and burnable materials separate. The model allows for inventories of *mixtures* of unburnable and burnable materials. The functional unit is always 1 kg waste input.

A modern waste incinerator has several output streams, each of which are described with a set of transfer coefficients. The outputs in the municipal incinerator model are bottom ash, boiler ash, ESP ash, scrubber sludge, water emissions, and air emissions. Scrubber sludge and water emissions contains the pollutants removed from flue gas by scrubber columns. For the open burning model the transfer coefficients are reduced to two outputs: emissions to air and emissions to solid residues (Fig. 2.1). The transfer coefficients to air are obtained by summing up the transfer coefficients for scrubber sludge, water emissions, and air emissions. These are the streams that would remain airborne without scrubbers. The transfer coefficients to residues are the remaining transfer coefficients for bottom ash, boiler ash, and ESP ash. These are the streams that will sink to the ground after incineration. Transfer coefficients for burnable materials in open burning are shown in Tab. 7.1 on page 14.

Some recyclable metals might be separated from the residues. No further treatment is assumed after recycling: the remaining residues stay on site and are inventoried as emissions to soil. The user can choose if this shall be industrial soil (default) or agricultural soil (for agricultural biomass burning).

The air emissions are inventoried unfiltered and unchanged. From the non-gaseous compounds in the flue gas a figure for total particulate mass is calculated. From this, waste-specific emissions are derived for three particulate matter classes ($\text{PM}_{>10}$; $\text{PM}_{2.5-10}$; $\text{PM}_{<2.5}$). The heavy metals and other

elements are additionally inventoried as emissions in accordance to methodological choices in the ecoinvent database.

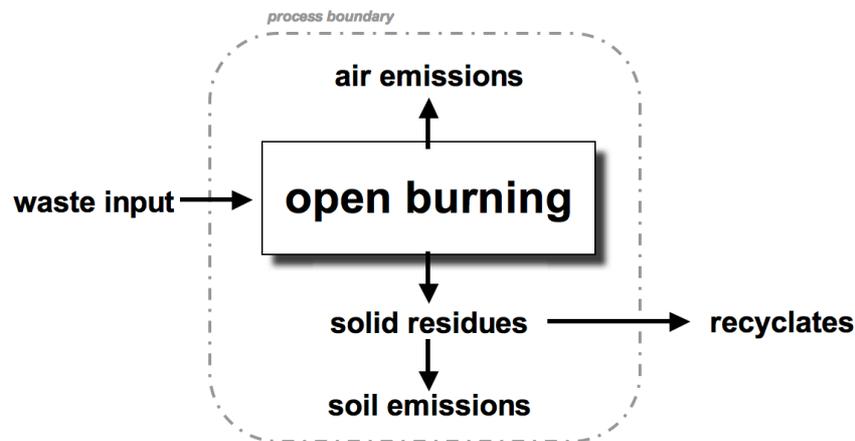


Fig. 2.1 Flows and boundaries for the open burning process

3 Waste composition

3.1 Waste-specificity and burnability

The open burning model is waste-specific, which means that the elemental waste composition to a large degree influences the inventoried emissions. Waste compositions should be divided into burnable and unburnable parts by the user, since they have distinctly different behaviour. For instance electronic waste should be divided into burnable parts (mostly plastics) and unburnable parts (bulk metals, bulk minerals, ceramics, glasses etc.). Chemical elements contained in a burnable matrix, for instance copper traces in plastics, belong to the burnable material and shall not be classified by the user as being unburnable. A borderline case may be thin layers of unburnable material on burnable materials. Here the user has to decide which fate seems most likely, or devise a burnable/unburnable mixture.

3.2 Assistant fuels



Fig. 3.1 Roasting of printed wiring boards over an open fire in Guiyu, China. Credit: Step Initiative / EMPA Source: <http://ewasteguide.info/images/4333>

Sometimes open burning employs some assistant fuels, e.g. roasting of printed wiring boards on open coal stoves. If the emissions of the fuel are to be included in the inventory, two methods can be employed:

- 1) Two separate inventories are created for the waste and the assistant fuel.
- 2) Waste and fuel are defined as a mixture of materials and inventoried in one inventory.

In either case the elemental composition of the fuel must be specified. Also if the fuel is commercial (e.g. coal, fuel wood) and not a waste itself, its upstream production chain should be included by adding an appropriate fuel supply input in the inventory.

3.3 Recycled materials

Sometimes open burning is performed to isolate recyclables from a composite material, e.g. burning off of cable insulation from copper cables (cf. title page). In such cases some target recyclables are removed from the burn residues.

For iron, aluminium and copper the user can specify the recycling rate of these metals from waste residues (cf. chapter 6.5 'Recycling rates' on page 12). The actually recycled fractions are then subtracted before calculating the emissions to soil. The rates refer only to *bulk metallic* parts of these elements, not to their oxides etc. nor the complete elemental content.

In case any other materials than iron, aluminium or copper are removed, e.g. metallic lead, it is advised that the effectively recycled amounts are already excluded in the waste composition definition, otherwise they would cause soil emissions, which actually do not occur.

4 Particulate emissions

A waste-specific figure for total particulate mass emitted to air is derived from the waste-specific masses transferred to air. For each element an oxidation and an according weight increase is assumed.

The oxides of following elements emitted to air are summed up to obtain total particulate mass: phosphor, boron, chlorine, bromine, fluorine, iodine, silver, arsenic, barium, cadmium, cobalt, chromium, copper, mercury, manganese, molybdenum, nickel, lead, antimony, selenium, tin, vanadium, zinc, beryllium, scandium, strontium, titanium, thallium, tungsten, silicon, iron, calcium, aluminium, potassium, magnesium, and sodium. For example for average municipal waste this yields a total particulate mass of 6500 mg/kg waste, which is close to a value found in literature (7300 mg/kg in World Bank 2008).

Ecoinvent requires inventory of particulate mass in three size classes. Information in (Downard et al. 2015) on particulate emissions in open burning of tires is used there to obtain a particulate profile:

PM_{>10}: 20.0w%

PM_{2.5-10}: 28.0w%

PM_{<2.5}: 52.0w%

This tentative profile is applied to the waste-specific amount of total particulate mass.

5 Incomplete combustion products

From a literature survey¹ various emission factors for open burning of municipal waste were compiled. Tab. 5.1 shows the geometric mean of the found literature values. From the literature only values which represent a municipal waste mixture were heeded. In the following, the way these factors were used in the inventory are described.

For most pollutants simply a constant emission factor per kilogram of waste input is assumed. For these pollutants it is assumed that it is less waste composition, but more the characteristics of combustion (temperature, oxygen supply, burn reaction heterogeneities etc) that determine their magnitude, which were called "process-specific" emissions in (Doka 2003-II) to contrast them to the waste-specific emissions, which depend strongly on waste input composition.

Tab. 5.1 Geometric mean of literature survey of emission factors for open burning of municipal waste

Pollutant	unit	Emission to air
Nitrogen oxides	mg/kg waste	2'700
Carbon monoxide	mg/kg waste	38'600
Methane	mg/kg waste	5'900
Dinitrogen monoxide	mg/kg waste	116
Benzene	mg/kg waste	980
Phenol	mg/kg waste	15
Styrene	mg/kg waste	528
Toluene	mg/kg waste	372
Formaldehyde	mg/kg waste	444
Acetaldehyde	mg/kg waste	428
Benzene, ethyl-	mg/kg waste	327
PAH, polycyclic aromatic hydrocarbons	mg/kg waste	344
Polychlorinated biphenyls	mg/kg waste	0.112

¹ Gullett et al 2000, Costner 2006, UNEP 2005, EPA 1992, Gullett and Touati 2003, Lemieux 2002, Leung et al 2006, Doka 2000, Lemieux et al. 2003, World Bank 2008, Downard et al. 2015, IPCC 2006-5

5.1 Nitrogen emissions

A simplified model of NO_x formation is applied here. The total NO_x emissions to air have three contributions:

- Fuel- NO_x , which originates from the oxidation of nitrogen in the fuel.
- Thermal- NO_x , which originates from N_2 in combustion air, oxidised at high temperatures $>1000^\circ\text{C}$
- Prompt- NO_x , which originates from N_2 in combustion air reacting with free hydrocarbon radicals ($\text{CH}\cdot$).

Fuel- NO_x

For this model the user-specified waste is the fuel. The fuel- NO_x is therefore the part of nitrogen in the waste that ends up as NO_x in flue gas. According to the incineration model in (Doka 2003) 37.38% of fuel nitrogen in *untreated* incineration (without DeNO_x) is in NO_x , the rest mostly in N_2 . The air-bound nitrogen in a waste composition is converted with this factor to NO_x .

Thermal- NO_x

Formation of thermal NO_x depends on a range of combustion parameters, most importantly temperature and air excess, and not on the nitrogen content in fuel. Even in controlled incineration there is ambiguous information of the share of thermal NO_x on total NO_x emissions, ranging from 20% to 100% (Doka 2003-II:40). A value of 50% was used in the controlled incinerator model. No literature information of thermal-to-total- NO_x ratios could be found for the present open burning model. It can be surmised that for open burning, combustion temperatures are lower and that the ratio is lower than for controlled incineration. A tentative default value of 30% is chosen as a default value. The user can set other values. The literature survey suggests a value of 2700 mg per kg waste for *total* NO_x emissions (Tab. 5.1). With the chosen default share of thermal NO_x of 30%, an average emission of 810 mg thermal NO_x per kg waste results. The contribution from thermal NO_x is added to the contribution from fuel NO_x in the inventory. Each waste composition receives an emission from thermal NO_x regardless of its nitrogen content (process-specific emission).

Prompt- NO_x

No special modelling of prompt NO_x is attempted, as information is even more scarce than for thermal NO_x . Also this is a process-specific emission depending more on the details of the combustion process than on waste composition. Any forthcoming knowledge on prompt- NO_x in open burning can be covered by adjusting the thermal- NO_x -share parameter accordingly.

Nitrous oxide N_2O

The small amount of N_2O from Tab. 5.1 is inventoried as process-specific, constant emission.

5.2 Carbon monoxide and methane

Constant process-specific emissions of CO and CH_4 are inventoried for each kilogram of waste, regardless of composition. The formation of carbon dioxide from waste is corrected by the amounts of carbon in CO and CH_4 .

5.3 Organic carbon compounds

The range of emissions of benzene, phenol, styrene, toluene, formaldehyde, acetaldehyde, ethylbenzene, and polycyclic aromatic hydrocarbons are inventoried as constant process-specific emissions for each kilogram of waste, regardless of composition.

The incineration model is focussed on fate of chemical elements and fate of individual compounds is not modelled. Compounds are only inventoried in a summary fashion as process-specific emissions. If there is reason to believe the burning could release significant amounts of specific compounds like flame retardants or plasticizers these emissions should be estimated additionally.

5.3.1 Dioxin

Dioxin to air

Gullett et al. (2000) performed open burning tests on various municipal waste mixtures and found that their total chlorine content is a fair predictor for emissions of dioxin, regardless of the forms of chlorine.

	Chlorine content in burnt mixture mg/kg	Dioxin emission factor ng TEQ /kg waste
MSW baseline	2'000	71
MSW with 0% PVC	2'000	14
MSW with 1% PVC	8'000	201
MSW with 7.5% PVC	47'000	4916
MSW with 7% CaCl ₂ added	46'752	734

These measurements are used here to derive a power-law regression formula to coarsely estimate waste specific dioxin generations based on chlorine content:

$$\text{Eq. 5.1} \quad O_{\text{dioxin,air}} = 0.001683 \cdot I_{\text{Cl}}^{1.296881}$$

where,

$O_{\text{dioxin,air}}$ Output of dioxin in flue gas, in [ng/kg waste]

I_{Cl} Input of chlorine in waste, in [mg/kg waste]

Please note that this formula is only valid for uncontrolled open burning. In proper incinerators temperatures are higher, dioxin formation is lower and generally less dependent on chlorine content, but more on incinerator design (Doka 2003-II:44).

In an LCA framework the dioxin emissions show not to be very relevant when compared to other pollutants. For this reason the coarse estimations of dioxin emissions made here – including neglecting to heed the exact form of chlorine – are of little overall importance. By comparison, emissions of benzene from open burning are about five orders of magnitude more damaging than dioxin emissions, or particulate emissions are about nine orders of magnitude more damaging than dioxin emissions (weighted with ReCiPe'08 HA). Dioxin emissions are therefore inventoried only for completeness, but they will likely not be relevant, but this depends on the applied Impact Assessment method.

Dioxin in residues

Costner (2006) lists ranges of dioxin releases from open burning of municipal waste to air and to solid residues. For a medium MSW composition average dioxin emissions to air are approximately 3.6 larger than average dioxin emissions to residues. This relation is used here to estimate dioxins in residues (ultimately to soil) from the emissions of dioxins to air derived above.

$$\text{Eq. 5.2 } O_{\text{dioxin, residue}} = O_{\text{dioxin, air}} / 3.6$$

where,

$O_{\text{dioxin, residue}}$ Output of dioxin in solid residues, in [ng/kg waste]

$O_{\text{dioxin, air}}$ Output of dioxin in flue gas, in [ng/kg waste]

5.4 Properties of exchanges

In Ecospol2 each exchange can – besides a name and an amount – have several properties describing the exchange in more detail, like dry mass, water content, fossil carbon content etc. The tool adjusts also some properties of exchanges. An overview is given in the following.

5.4.1 Waste input

The specific waste composition is a core aspect of these calculation tools and thus an extensive range of properties are defined for the waste input, including trace amounts. The waste is however not described in full, as for waste consisting of more fraction (complex wastes) detail is lost. This is important to understand especially for complex wastes with heterogeneous fractions, i.e. mixtures of burnable and inert waste or mixtures of degradable and less degradable fractions. It not possible to back-engineer the composition of individual fractions from a given complex mixture's composition alone. New waste fractions shall therefore be clearly documented in an accompanying report.

5.4.2 Emissions

Also elementary exchanges possess properties, describing their characteristics. Commonly this information is constant (e.g. an emission of copper has a dry mass of 100%, a fossil carbon content of zero etc.). For carbonaceous emissions, the distinction between fossil and non-fossil carbon can become relevant for some purposes. In the ecoinvent database this issue is dealt with in two different ways:

1. Different exchanges for fossil/non-fossil emissions: CO₂, CH₄, CO each have two different exchanges with different names, e.g. "Carbon dioxide, fossil" and "Carbon dioxide, non-fossil". This allows to assign different characterisation factors in LCIA, e.g. giving biogenic CO₂ a GWP of zero.
2. Different properties for fossil/non-fossil carbon within an exchange. The carbon content property is split up in two variants, which must be set separately (the total carbon property does exist in ecoinvent, but cannot be changed by a normal user). For instance an emission of ethylene can be of fossil or non-fossil origin, or a mixture of both. All exchanges possess these properties as defaults. The figures for the defaults were defined when the exchanges themselves were defined. Currently (Jan 2017) the default properties of ecoinvent's emissions are chiefly set to contain 100% fossil carbon, though for some emissions a 50/50 split was employed (e.g. for NMVOC or methanol).

The previous waste tools of 2003 already discerned different emissions according to (1) like fossil and non-fossil CO₂, and this is maintained in the present models. For instance burning of plastic will lead to fossil CO₂ emissions, while burning of biomass waste will lead to non-fossil CO₂. The prerequisite

for this is that the used waste material has a properly defined share of biogenic carbon in the waste definition, cf. Calculation Manual, point 148.

Additionally in the tools of the current project also carbonaceous emissions like benzene or dioxins receive adjusted properties, according to (2) above. E.g. the benzene emission associated with burning paper will have its fossil carbon content property set to zero, while the benzene emission associated with burning common plastic will receive a zero biogenic carbon content property. This is calculated automatically from waste input properties and transfer coefficients. For the open burning model following procedures are employed.

Share of non-fossil carbon in air emissions is derived from the mass of non-fossil carbon in the burnable waste fraction(s) over total carbon in the burnable waste fraction(s), see Eq. 5.3. The denominator is the sum of all carbon present in burnable waste fraction(s) and is calculated from carbon content and the burnability flag of the employed waste fraction(s). The numerator is the sum of all non-fossil carbon in the burnable waste fraction(s) and is calculated from carbon content, share of non-fossil carbon and the burnability flag of the employed waste fraction(s). If a chosen waste composition does not contain any carbon, a default share of 60.7% non-fossil carbon is used for carbonaceous air emissions (see chapter 5.3 'Organic carbon compounds' on page 9).

$$\text{Eq. 5.3 } \%b_{\text{air}} = \left(\sum_{\text{fraction } i} f_i \times m_{C,i} \times B_i \times \%b_i \right) / \left(\sum_{\text{fraction } i} f_i \times m_{C,i} \times B_i \right)$$

where,

$\%b_{\text{air}}$ Fraction of non-fossil, biogenic carbon in air emissions, [weight-%]

f_i Share of fraction i in selected waste (mixture), [weight-%]

$m_{C,i}$ Mass of all carbon in fraction i , [kg carbon/ kg wet waste]

B_i Indicator of burnability of fraction i , [0 or 1]

$\%b_i$ share of biogenic carbon in fraction i , [weight-%]

Soil emissions derive from the ash residues of open burning. In the model these residues have two sources: inert, unburnable waste materials which are assumed to go directly to ash, and the parts of burnable waste which end up in ash according to the transfer coefficients. Also here the share of non-fossil carbon is calculated by relating the sum mass of all non-fossil carbon ending up in residues to the total mass of carbon in residues is calculated. Either is calculated from waste composition, the burnability flag of the waste fraction(s) and the transfer coefficient for carbon into residues of 0.5% (cf. Tab. 7.1 on page 14). If a chosen waste composition does not contain any carbon, a default share of 30.32% non-fossil carbon is used for soil emissions, based on average municipal waste.

$$\text{Eq. 5.4 } \%b_{\text{soil}} = \left(\sum_{\text{fraction } i} f_i \times m_{C,i} \times (B_i \times TK_C + (1 - B_i)) \times \%b_i \right) / \left(\sum_{\text{fraction } i} f_i \times m_{C,i} \times (B_i \times TK_C + (1 - B_i)) \right)$$

where,

$\%b_{\text{soil}}$ Fraction of non-fossil, biogenic carbon in soil emissions, [weight-%]

f_i Share of fraction i in selected waste (mixture), [weight-%]

$m_{C,i}$ Mass of all carbon in fraction i , [kg carbon/ kg wet waste]

B_i Indicator of burnability of fraction i , [0 or 1]

TK_C Transfer coefficient for carbon to soil in burnable materials, = 0.5%

$\%b_i$ share of biogenic carbon in fraction i , [weight-%]

Note that the term $(B_i \cdot TK_C + (1-B_i))$ is equal to TK_C for burnable materials (when B_i is 1) and equals 1 for unburnable materials (when B_i is 0).

6 Modelling parameters

The model includes several parameters which characterise the open burning process. These are informations that are more associated with a certain site or location, than a particular waste material.

6.1 Geography code

The open burning model is geographically independent, apart from the user-defined waste input composition which can be dependent on location. The geographic code will be incorporated in the Ecospol2 inventory.

6.2 Subcategory of air emissions

The user can choose if the air pollutants are released in high-population (urban) air, or in low-population (rural) air. A choice of high-population air will *not* depict health burdens imposed on workers in close proximity to the open burning site.

Entering the code "hi" chooses high-population air, anything else the default low-population air.

6.3 Subcategory of soil emissions

The user can choose if the soil pollutants are released to industrial soil, or in agricultural soil. Agricultural soil can – depending on the Impact Assessment method – lead to larger human health burdens.

Entering the code "agri" chooses agricultural soil, anything else the default industrial soil.

6.4 Share of thermal NO_x

For the attribution of thermal NO_x emissions, a ratio of (thermal NO_x to total NO_x) must be given. A default of 30% is suggested. The function of this parameter in this model is explained in section 'Thermal-NO_x' on page 8.

6.5 Recycling rates

For iron, aluminium and copper the user can specify how much of the metal in the waste will actually be recycled from burn residues. A figure of 100% signifies that all of the element *in bulk metallic form* is separated. The recycling rate defines how much of the maximally recyclable bulk metal is actually recycled. The maximally recyclable bulk metal is part of the waste material definition.

An example: a waste has a *total* copper content of 1 gram per kg. Of that copper only 50% is in bulk metallic form.² The rest is in oxides and distributed in traces of materials. So *maximally* only 0.5 gram of copper metal can be gained from this waste. Recycling rates are usually not perfect and small bits or

² This figure is part of the *waste material definition* and refers to the make-up of the material, and not to its treatment.

devalued items cannot be recycled. If the recycling rate is set for instance at 70% it means that in this case 0.35 gram of copper metal will be separated from residues ($=0.5 \text{ g} \cdot 70\%$). The emissions to soil will be corrected by this amount.

The user can define recycling rates for iron, aluminium and copper. For other recyclables see chapter 3.3 'Recycled materials' on page 6.

7 Annex A: Transfer Coefficients

The transfer coefficients for elements in *burnable* materials are shown in Tab. 7.1. The transfer coefficients for elements in *unburnable* materials are 100% to residue.

The waste-specific transfer coefficients for a particular waste *mixture* of burnable and unburnable components depend on the relative distribution of elements in burnable and unburnable materials and is calculated from the previous two statements.

Uncertainty of transfer coefficients

The results from the open burning model must be taken as rough estimates for open burning. Open burning is by its very nature largely uncontrolled can include a wide possible range of different combustion conditions – from agricultural burning of straw on fields to smouldering waste fires. Large differences in conditions can even occur within one burning event. The present model is intended for open burning of municipal waste fractions and due to the large possible variability in burning conditions the results bear considerable uncertainties. In (Doka 2003-II) the uncertainty of transfer coefficients was derived from a generic formula, giving large uncertainties to small transfer coefficients.

$$\text{Eq. 7.1} \quad GSD_{TK} = N \cdot \ln(m_{TK}) + 1$$

where,

GSD_{TK} Geometric standard deviation of the transfer coefficient

m_{TK} Mean value of transfer coefficient, in [kg/kg]

N constant

In (Doka 2003) the value for N was chosen so that the GSD^2 value for the smallest m_{TK} values (metals to air) are 200%. I.e. at most the confidence interval for the transfer coefficient is assumed to stretch from double to half of the mean value. This resulted in a value for N of -0.022.

For open burning it is assumed that due to burn condition heterogeneities the transfer coefficients tend to be even more uncertain than in controlled municipal incineration. The value of N is decreased to -0.0546, which results in maximal GSD^2 values of 300%, i.e. for small transfer coefficients the confidence interval stretches from one third to thrice the mean value. As always, for emissions the uncertainty of transfer coefficients is combined with the uncertainties of waste composition.

Tab. 7.1 Mean transfer coefficients for elements in burnable materials (rounded to 5 digits)

	Emissions to residues g/kg waste	Emissions to air g/kg waste
O	38.343	961.66
H	0	1000
C	5.0151	994.98
S	856.43	143.57
N	10.012	989.99
P	993.13	6.8707
B	999.6	0.39996
Cl	332.89	667.11
Br	679.32	320.68
F	893.39	106.61
I	332.89	667.11
Ag	994.87	5.1321
As	991.48	8.5229
Ba	958.78	41.216
Cd	994.34	5.6578
Co	959.67	40.333
Cr	998.51	1.4912
Cu	998.9	1.0991
Hg	393.94	606.06
Mn	991.49	8.5121
Mo	995.01	4.9918
Ni	998.57	1.4267
Pb	991.6	8.4033
Sb	1000	0.0024032
Se	913.33	86.668
Sn	1000	0.0019596
V	922.79	77.209
Zn	992.56	7.4399
Be	998.11	1.89
Sc	999	1
Sr	999	1
Ti	989.4	10.603
Tl	998	2
W	1000	0
Si	1000	0.0046726
Fe	998.19	1.8119
Ca	976.39	23.61
Al	999.18	0.82428
K	985.18	14.822
Mg	997	2.9959
Na	975.37	24.631

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Web addresses indicate the source of electronic documents. The subsequent (date in brackets) refers to the date of retrieval.

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