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

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Author

Gabor Doka

Doka Life Cycle Assessments, Zurich

Author Gabor Doka, Doka LCA, Zurich, do@doka.ch

Title picture Burning of electronic waste and refrigerator insulation foam for informal metal recycling, in the Agbogbloshie landfill, Accra, Ghana. © Fabian Blaser, EMPA St.Gallen, source: http://ewasteguide.info/location/ghana

Significant digits Figures in this report often feature several digits. This is not to imply that all the shown digits are really significant or that the data displayed is very precise. Showing several digits helps to minimise the avoidable accumulation of rounding mistakes along the chain of calculations performed here, and in possible future studies referring to this data.

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Contents

1 Introduction

The LCA waste incineration model in Doka (2003-II, 2013) are 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.

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.

A distinction is made in that 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. 8.1 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 ($PM_{>10}$; $PM_{2.5\text{-}10}$; $PM_{<2.5}$). The heavy metals and other elements are additionally inventoried as emissions in accordance to methodological choices in the ecoinvent database.

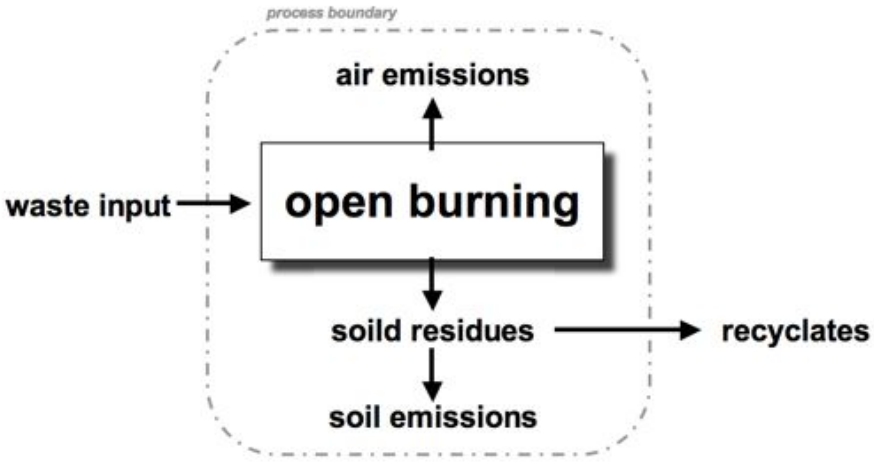

Fig. 2.1 Flows and boundaries for the open burning process

3 Waste composition

3.1 Waste-specifity 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, since they have distinctly different behaviour. I.e. electronic waste should be divided into burnable parts (mostly plastics) and unburnable parts (bulk metals, bulk minerals, ceramics, glasses etc.). Chemical elements embedded in a burnable matrix, for instance copper traces in plastics, belong to the burnable material and shall not be separated. 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 10). 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%

$PM_{2.5\text{-}10}$: 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 survey[1] 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	2700
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

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°C
- Prompt-NO_x, which originates from N_2 in combustion air reacting with free hydrocarbon radicals (CH·).

Fuel-NO_x

For this model the user-specified waste is the fuel. The fuel-NOx 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) 37.8% 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.

[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

Thermal-NOx

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, ethyl-benzene, 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	**Dioxin emission factor**
	mg/kg	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 estimate waste specific dioxin generations based on chlorine content:

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

$O_{dioxin,air}$ = 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 estimations of dioxin emissions made here are of little overall importance. Emission 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 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.

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

$O_{dioxin,residue}$ = Output of dioxin in solid residues, in [ng/kg waste]
$O_{dioxin,air}$ = Output of dioxin in flue gas, in [ng/kg waste]

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 user can enter a two-letter country code or a three letter region code which will be incorporated in the Ecospold 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 NOx

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-NOx' 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 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 g · 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.

[2] Both these figures are part of the waste material definition and refer to the make-up of the material, not to its treatment.

6.6 Sets of parameters

The user can compile various sets of parameter values for various sites and record them in a list on the right side of the sheet 'para'. A certain set can then conveniently be chosen by choosing the site number.

7 Calculation Manual

Setting up

1. Open the Excel file 'MSWI 2016.xls' that contains the centralised waste definitions.
2. Open the file 'Open Burning 2016.xls' to create inventories for wastes to open burning.
3. Do not update links to other sheets. There is no need. Choose 'No' in the dialog.
4. On slower machines you might want to disable automatic calculation. Choose the menu command 'Extras/Preferences', choose 'calculation' and set the calculation to 'manual'.
5. In 'MSWI 2016.xls' go to the sheet 'waste input'. If you want to calculate inventories of (un)sanitary landfills set the 'disposal code' in cell B4 to 'R' (the 'R' signifying the German 'Reaktordeponie').
6. Go to the waste composition database (located on the same sheet 'waste input') starting at the range K9:K66. Headers are in A9:A66. Examine the waste compositions listed there. If you find something suitable for you go to 'Choosing the waste fractions' further below. If not, you need to define a new waste composition.

Enter a new waste fraction

7. Find an empty column in the waste composition database in the sheet 'waste input' e.g right of column K. **You can only enter data in the white cells.** You can also overwrite existing columns, but this is not advised for consistency's sake. In case you need to insert new, additional columns, make sure the functionality of the formulas in columns H, I and J is retained, i.e. the SUMPRODUCTs must refer the complete database area. To do that, enter new columns starting on the *left* of the last column in the database (then copy the contents/formulas of an existing data column, to retain sheet functionality). Also the formulas in rows 68, 69 and 79 should be copied when inserting new columns.
8. In a suitable column, enter your data for the waste. If you have waste that is heterogeneous in burnability, e.g. insulated copper cables, you need to divide the waste up into burnable part (e.g. insulation) and a unburnable part (e.g. copper) and enter them in two separate columns. In row 13 enter a 1 for a burnable fraction and 0 for an unburnable fraction. For waste with metal parts, fill in the recyclable metallic iron (row 63) and recyclable metallic aluminium and copper (rows 76 & 77). This refers to the metallic and *theoretically recyclable* part of an element, not to the part *actually* recycled on site (see chapter 6.5 'Recycling rates' on page 10 for this, and chapter 3.3 'Recycled materials' on page 6).
9. For identification enter a name for the waste in row 15 of the free column.
10. Enter heating values, composition data and other characteristics in rows 18 to 65 of the free column. Use the correct units (MJ/kg and kg/kg) as given in column D. All figures are per kilogram wet waste. More information and guidance in (Doka 2003-III) chapter 5.7 'Necessary waste-specific data' on page 39. An error message appears in row 14, if the entered composition is not reasonably close to 100%. Please note that unnecessary rounding to significant digits at

this stage can lead to 'mass gaps', resulting in an error message. Degradability in landfill can be skipped for burning, but you might want to fill it in anyway, if you plan to create inventories for this material in landfills. More information on degradability of different materials can be found in (Doka 2003-III) chapter 6.1.1 'Waste-specific degradability in sanitary landfills' on page 46.

12. Save the sheet.

Choosing the waste fraction(s)

13. To calculate a new inventory go to the rows below cell C84 of the sheet 'waste input'. In a free row enter the following information: In column C the name of the waste (in row D a local name for Ecopsold1). These names will be used to generate module names in the sheets 'X-Process' and 'X-Exchange'. On the same row starting on column K you can enter the percentages for the waste fractions you want to be present in the waste of this inventory (waste fractions were defined above in rows 16:66). These shares make up the final waste in your process inventory. Usually you just select one column, i.e. one waste fraction with 100%. You can also enter any combination of fractions as long as the sum total of all fractions is 100%. With this mechanism you recombine the fractions of different burnabilities you separated at point 8, and it also allows you to integrate complex waste mixtures or waste/fuel mixtures into one single inventory. The functional unit is fixed at 1 kg material burned. Check if the burnabilities of the chosen waste fractions in row 13 are entered correctly.

14. Go to column A and the row you just entered your fraction information. Here is the number that identifies the waste (mixture) composition you just defined. Enter the number, e.g. '118' in cell A82. This selects this waste (mixture) composition as the input for the model.

Setting the landfill site characteristics

15. Goto the workbook 'Open Burning 2016.xls' and to the sheet 'Para'. In cell E5 enter a value to choose one of the parameter sets compiled on the right (columns I etc). You can also alter any of the white cells, or enter a new parameter set to characterise a specific landfill site. The various parameters are explained in chapter 6 'Modelling parameters' on page 9f.

Ecospold calculation

16. Force Excel to recalculate the workbook(s) by pressing 'Alt - =' on Windows machines or '⌘ - =' on Mac machines or by choosing the menu command 'Extras/Preferences', 'calculation' and clicking on 'Calculate now'. Important: wait until calculation is complete. Excel's status bar comment in the lower left corner of your screen shows you the progress of the calculation.

17. For disposal of your waste in a sanitary landfill: Go to the sheets 'X-Process' and 'X-Exchange' in ' Open Burning 2016.xls' from where you can copy the inventory data in ECOSPOLD format. Paste the tables *as values* to another sheet (press '⌘–Shift–V' and choose 'values').

8 Annex A: Transfer Coefficients

The transfer coefficients for elements in *burnable* materials are shown in Tab. 8.1. 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.

Eq. 8.1 $$GSD_{TK} = N \cdot \ln(m_{TK}) + 1$$

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. 8.1 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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