Life Cycle Inventory data of mining waste: Emissions from sulfidic tailings disposal

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Picture on title page:
Rehabilitated tailings impoundment of the Martha Gold Mine, Waihi, New Zealand http://www.marthamine.co.nz/graphics/dam.jpg (accessed 19. July 2003)

1 Introduction

Tailings are a slurry waste produced during metal ore refining (beneficiation). Tailings are usually poured into tailings impoundments. The water is largely decanted from the impoundments and recycled to the beneficiation plant (ore mill), while the slurry solids remain within the developing impoundments. Tailings can contain sulfides, which are biochemically oxidised to sulfuric acid. The acidic pH then promotes washout of many metals (Acid Rock Drainage, ARD). Large masses of tailings are produced per kilogram metal, especially if ore grades are low. Tailings impoundments represent a considerable environmental burden in the primary metal process chain, because tailings contain large amounts of toxic metals and large masses of tailings are produced: the current annual worldwide production of all types of tailings is estimated to be several hundred million metric tonnes per year, which surpasses the mass naturally eroded from the earths surface by rivers (Gardner & Sampat 1998, Aswathanarayana 2003).

Life Cycle Assessment studies often neglect to quantify the burdens from tailings disposal for lack of data. As tailings disposal is considered one of the major impacts of metal ore mining, this is a significant data gap. In this study, first generic estimates on the burden from disposal of sulfidic tailings are derived from a dedicated tailings deposit model. The results were used in a study commissioned by FOEN, the Swiss EPA, on resource management and recycling, and are to be included in the Swiss Life Cycle Inventory database ecoinvent v2.2 (to be published early 2009). This dataset should provide a first informed estimate of the full magnitude of sulfidic tailings burdens for non-ferrous metal products and encourage further research and more detailed models for subsequent versions of ecoinvent. In order to avoid overestimations, the modelling assumptions – within the framework of Life Cycle Assessment – were chosen to be conservative.

2 Tailings landfill model

The tailings landfill model was based on the modelling framework applied in exisiting landfill process models used in ecoinvent, see ecoinvent report 13 (Doka 2003). These models are based on a top-down approach. Literature data on measurements of deposited compositions and currently measured concentrations in landfill leachate are used to calculate the currently occurring emissions of the landfill. Heeding chief parameters like hydrology and pH development these emissions are then projected into the future. Thus these models incorporate physical and chemical conditions, while being rooted in the currently observed emission behaviour. More details on general modelling assumptions of these models can be taken from (Doka 2003). The resulting tailings model and its transfer coefficients are not applicable to other waste types.

2.1 Tailings and leachate composition

A large database with literature data on tailings composition and measured tailings leachate concentrations mainly from copper, zinc, lead, nickel and molybdenum mining sites is assembled[1]. The geometric mean of established data is taken to represent a global average sulfidic tailings composition and leachate composition[2]. The results of this survey are presented in and . The relation between leachate concentration and tailings composition quantifies how easily this particular element is transferred to the aqueous phase and thus how mobile it potentially is. Heeding water availability and water exchange rates it is possible to estimate how much of a particular element is removed from

[1] Data was taken from ATSDR 1997; ATSDR 2006; Boulet & Larocque 1998; Dorronsoro et al. 2002; Downing & Gravel 2006; EPA 1994; Garcia-Meza et al. 2006; Hadjibiros et al. 2005; Hernandez et al. 2007; IAEA 2003; IPPC 2004; Koerth 2002; Laliberte & Tremblay 2002; Lazar 2002; Matheis et al. 1998; McLemore et al. 2006; MIMI 2004; Muwanga 1997; Nash 2000; OK Tedi 2002; Robinson et al. 2004; Thoms 2006; Tyler et al. 2004; Van Zyl 2002; Wels et al. 2000; Ye et al. 2002

[2] This is the standard procedure in establishing waste compositions in ecoinvent.

the landfill over time. The fraction of removed pollutant is expressed in transfer coefficients. Transfer coefficients also allow comparisons with other landfill models. Roughly 2600 individual data points are used to create the model of tailings emissions for 39 chemical elements.

2.2 Development of leachate pH

Acid-base balances for the average tailings composition suggest that no pH-induced changes in leachate concentrations occur. I.e. the *currently observed* emission behaviour is – on average – taken to represent the *average long-term* situation. This is a conservative approach, since the literature data includes data from impoundments that have not, or not yet developed an acidic pH, which is a likely fate for sulfidic tailings. The long-term mobility of metals tends therefore to be underestimated.

Chemical weathering of tailings depends on climate conditions. In wet climates large volumes of downward leaching through the tailings body are possible. In arid climates leaching is slow or in reverse direction, because water evaporation transports soluble tailings materials to the surface. Surface erosion by wind is accordingly a relevant emission pathway in arid climates (cf. Fig. 2.1). In this study, however, only emissions via bottom leaching are considered.

2.3 Hydrology and leachate generation

While the landfill models in (Doka 2003) were based on Swiss climate, for the tailings model the climate and precipitation that is relevant to tailings sites is heeded. Based on the location of the world's largest producers of sulfidic tailings, a weighted average precipitation rate of 770 mm/a was calculated (Spiess 2002, FAO 2000). In a global average situation, tailings deposits are rarely vegetated due to the extreme type of ground. Evapotranspiration of precipitated water is therefore neglected. It is assumed that tailings deposits are ideally constructed in such a way that mechanical erosion by surface runoff is excluded. All precipitation water therefore infiltrates the landfill body. All major mining sites are outside permafrost regions, so that a normal water circulation is possible. The height of the tailings landfill is assumed to be 50 meters. With a tailings density of 2200 kg/m^3 a mass of 110'000 kg tailings is deposited per square meter tailings landfill surface. Thus, an amount of 0.007 litres precipitation water per kilogram tailings infiltrates annually.

Fig. 2.1 Wind blown tailings in Clayton mine, Idaho, USA (Hammarstrom et al. 2002)

Fig. 2.2 Nickel Tailings in Sudbury Ontario, Canada (Burtynsky 1996)

A part of the infiltrated water flows preferentially through the tailings. Due to the fine grain size of tailings, the amount of preferentially flowing water is assumed to be only 5%, and the residence time of preferential water is assumed to be 18 weeks (=T_p)[1]. The water content (*v%*) of stabilised tailings is assumed to be 30 w-%. It is assumed that preferentially flowing water has little contact with the tailings materials and carries no pollutants from the landfill[2]. Based on model formulas given in Doka (2003:III.30ff.) it follows that the amount of effective, i.e. polluted annual leachate volume is 0.0067 litres per kilogram tailings (=V_{eff}).

2.4 Modelling time horizon

Transfer coefficients are calculated for two time horizons, 100 years (short-term) and 60'000 years (long-term). In Doka (2003) a long-term time frame of 60'000 years was chosen to represent an 'ecological planning horizon': by that time the Swiss midlands will probably be covered again with glaciers, that remodel the Swiss landscape. At that time the Swiss ecosphere will be redefined, creating new boundary conditions for environmental goals. The emissions over 60'000 years therefore represent a coarse mean expectation value of the burden inflicted by landfills on the ecosphere as we know it now and are concerned about. In other regions this ecological planning horizon might be dissimilar. Especially in tropical regions very long periods of climatic stability can be expected[3]. For simplicity a long-term time frame of 60'000 years for all tailings sites was chosen. Many metal mines are in tropical regions and hence substantially longer timeframes were justifiable. The adherence to 60'000 years as a long-term timeframe is justified as a conservative approach, as outlined in the introduction.

Also no deterioration of the physical structure of the impoundment is assumed. No mechanical erosion or rupture through flooding is assumed. Such incidents do occur and it is probable that over 60'000 years the physical and mechanical integrity of a tailings impoundment is compromised. Only chemical weathering of the impoundment contents is considered. This again is a conservative approach in order not to overestimate expected burdens for this as yet quite coarse model.

The calculated transfer coefficients for the short term (100 years) and the long term (60'000 years) are presented in Tab. 3.3. Due to lack of data, certain transfer coefficients are estimated by chemical similarity. Transfer coefficients for halogens are based on data from fluorine. Transfer coefficients for nitrogen are based on sulfur. Transfer coefficients for scandium are based on the arithmetic mean of antimony and selenium. Transfer coefficients for tungsten are based on the arithmetic mean of molybdenum and selenium. All these proxies are for completeness only and make up only very minor contributions to the LCIA results for this dataset (less than 0.1 percent).

3 Tailings impoundment land use

Land use is based on a generic final height of a tailings impoundment of 50 meters. Thus, per kilogram tailings with a density of 2200 kg/m^3 a land area of $9.1 \cdot 10^{-6}$ m^2 is necessary. The land is assumed to be converted from unknown origin to dump site. After an operational phase of 30 years, spontaneous restoration of a consolidated state is assumed to be reached after one hundred years. The total occupation time is therefore 130 years and the land occupation per kilogram tailings $1.18 \cdot 10^{-3}$ m^{2}a.

[1] All variables are introduced in (Doka 2003, part III).

[2] If landfills dry out periodically, then preferential water might wash out evaporites and be significantly burdened. This effect is not heeded here, leading to conservative emission figures.

[3] In such regions ecological planning horizons might be defined by very rare events like climate changes after meteorite impact (cf. Cretaceous-Tertiary impact winter 65 million years ago) or by very slow processes (glaciation after continental drift). For example, about 400 million years ago most regions that are tropical today were close to the south pole. However, currently tropical regions drift towards the equator and not towards the poles.

Tab. 3.1 Average initial sulfidic tailings composition from literature survey

Element	Tailings composition (geom. mean) mg/kg	Data points	Geometric Standard deviation %
S	14600	57	267%
N	23.1	3	147%
P	493	85	384%
B	310	1	n.a.
Cl	2	1	n.a.
Br	0.229	3	208%
F	826	30	376%
I	n.a.	0	n.a.
Ag	14.4	54	688%
As	284	87	919%
Ba	460	107	290%
Cd	7.16	84	617%
Co	18.6	62	404%
Cr	42.6	114	234%
Cu	277	142	540%
Hg	0.882	62	757%
Mn	875	109	426%
Mo	7.02	61	371%
Ni	22.8	96	487%
Pb	468	139	857%
Sb	79.2	44	812%
Se	6.81	13	661%
Sn	11.6	35	402%
V	57	69	255%
Zn	791	140	762%
Be	1.45	18	355%
Sc	6.13	76	166%
Sr	112	92	302%
Ti	6.29	52	11500%
Tl	2.6	10	736%
W	10.9	19	414%
Si	154000	24	306%
Fe	45400	70	323%
Ca	11900	63	423%
Al	27800	60	262%
K	9600	56	229%
Mg	7400	55	455%

Tab. 3.2 Average initial leaching concentrations from sulfidic tailings from literature survey

Element	Tailings leachate (geom. mean) mg/kg	Data points	Geometric Standard deviation %
S	2790	1	-
N	n.a.	0	-
P	291	4	427%
B	42.7	1	-
Cl	n.a.	0	-
Br	n.a.	0	-
F	2.42	6	147%
I	n.a.	0	-
Ag	0.000986	5	2036%
As	0.0283	16	6511%
Ba	0.00682	12	331%
Cd	0.0234	18	1935%
Co	0.0514	13	1339%
Cr	0.00572	13	604%
Cu	0.139	32	4040%
Hg	0.0000418	9	1797%
Mn	2.09	20	739%
Mo	0.245	14	1867%
Ni	0.0223	16	1394%
Pb	0.0137	19	2614%
Sb	0.00913	4	781%
Se	0.026	14	232%
Sn	0.0161	2	171%
V	0.008	5	1593%
Zn	0.941	33	5499%
Be	0.00615	5	309%
Sc	n.a.	0	-
Sr	0.879	18	598%
Ti	0.0126	1	-
Tl	0.00166	2	204%
W	n.a.	0	-
Si	2.110	11	558%
Fe	6.49	17	3575%
Ca	225	20	291%
Al	2.27	19	2624%
K	13.5	107	1422%
Mg	62.9	18	511%

Na	1460	42	507%

Na	14.8	17	851%

Tab. 3.3 Modelled short- and long-term transfer coefficients for the sulfidic tailings deposit given as "kg emitted per kg deposited"

Element	Short-term transfer coefficients (100a)	Long-term transfer coefficients (60'000a)
Sulfur	12.7%	100%
Nitrogen	12.7%	100%
Phosphor	39.4%	100%
Boron	8.77%	100%
Chlorine	0.195%	69%
Bromium	0.195%	69%
Fluorine	0.195%	69%
Iodine	0.195%	69%
Silver	0.00457%	2.74%
Arsenic	0.00666%	3.92%
Barium	0.000991%	0.595%
Cadmium	0.218%	100%
Cobalt	0.185%	100%
Chromium	0.00898%	5.24%
Copper	0.0335%	20.1%
Mercury	0.00317%	1.9%
Manganese	0.159%	95.5%
Molybdenum	2.3%	100%
Nickel	0.0653%	39.2%
Lead	0.00195%	1.17%
Antimony	0.0077%	4.51%
Selenium	0.255%	78.4%
Tin	0.0923%	55.4%
Vanadium	0.00937%	5.47%
Zinc	0.0795%	47.7%
Beryllium	0.283%	100%
Scandium	0.131%	41.4%
Strontium	0.524%	100%
Titanium	0.134%	80.3%
Thallium	0.0426%	25.6%
Tungsten	1.28%	89.2%
Silicon	0.000913%	0.548%
Iron	0.00955%	5.73%
Calcium	1.27%	100%
Aluminium	0.00546%	3.28%
Potassium	0.0941%	43.2%
Magnesium	0.568%	100%
Sodium	0.676%	98.3%

4 Results

According to the calculated long-term transfer coefficients even after 60'000 years only a part of the deposited tailings are leached, e.g. only 4 w-% of the arsenic content is emitted. When looking at the total toxic potential in deposited tailings roughly 8% is emitted and 92% are retained in the impoundment after 60'000 years. Tab. 4.5 lists the life cycle inventory for the disposal of one kilogram average sulfidic tailings.

If the environmental burdens are valuated with the Eco-indicator'99(HA) LCIA method, an impact of 0.034 EI99HA-points results. To put this in perspective the contributions of tailings disposal to the production of some primary metals is given in Tab. 4.4.

Tab. 4.4 LCIA results for some primary metals and contributions from tailings according to Eco-indicator'99(HA).

Primary metal	**Specific tailings generation** kg tailings per kg primary metal	**Total LCIA impact for primary metal** EI99HA-points / kg primary metal	**Impact contribution from tailings**
Copper	351	0.635	66%
Zinc	12	0.199	29%
Nickel	72.5	0.214	40%
Lead	15.8	0.188	27%

The impact from tailings as measured by Eco-indicator'99(HA) are dominated by emissions of *arsenic*, which make up 56% of the total impact of 0.034 EI99HA-points/kg. Another large part are *cadmium* emissions (40%) so that these two elements account for the lion share of the impact. Eco-indicator'99(HA) has a limited extent of characterisation factors for inorganic pollutants. Assessed are only As, Cd, Cr, Cu, Hg, Ni, Pb and Zn. Using other LCIA methods other important elements ensue. With the CML'01 human toxicity potential HTP 500a, *fluorine* is the largest contributor with 29% of the total toxicity, followed by *thallium* (22%), *selenium* (17%), *antimony* (8%) and *cobalt* (6%). However CML'01 HTP 500a features no characterisation factor for arsenic, which highlights the still incomplete scope of LCIA methods. It is remarkable though that oxianions seem to play a considerable role in the toxicity of tailings emissions.

4.1 Comparison with residual material landfill

The transfer coefficients of the tailings landfill can be compared with the transfer coefficients of a residual material landfill[1] from (Doka 2003), as shown in Fig. 4.3.

It is apparent that oxianions have reduced relative mobility in the tailings deposit (red area). Oxianions are more mobile at high pH values. Since residual landfills have high pH values, but tailings deposit often have low pH values, the modelled behaviour is realistic. On the other hand there is a cluster of elements with higher mobility in tailings deposits (blue area). These are elements that are known to be more soluble at low pH values. While the uncertainties in these coarse models are high, it is an encouraging fact that they succeed in depicting *chemically reasonable mobility behaviour*, without any information on such mobility characteristics being entered into the models beforehand. The results of the model are sensible and not overly dependent on the variable nature of the fundamental data. Otherwise such clustering of elemental types could not be distinctly observed. It is a sign that the sample size of the applied literature data is large enough to represent *typical* tailings.

[1] The Swiss residual material landfill is for inert, inorganic waste materials sometimes solidified with cement.

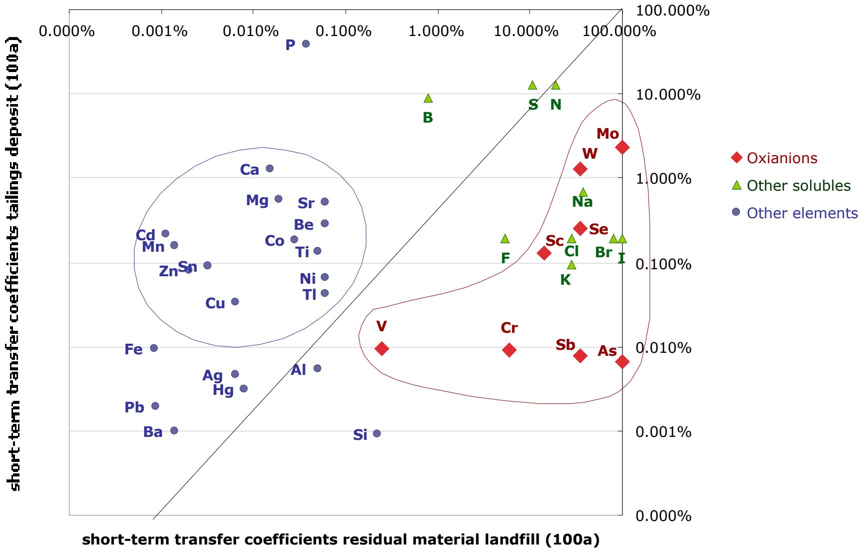

Fig. 4.3 **Comparison of short-term transfer coefficients for residual material landfill (x axis) and tailings deposit (y axis)**

4.2 Data quality

Uncertainty in this dataset is high, but not only due to a high aggregation level resulting from a worldwide average. The subject matter is inherently uncertain due to the stochiastic processes in the earth's crust, leading to very diverse ore bodies, and thus to very variable data relating to tailings even for one single mining site. Hence, the level of uncertainty is high and likely to remain high, even if in the future more differentiated tailings models are created. The sample sizes for almost all relevant (toxic) elements are in the range of 80 – 140 data points. Presuming the literature data is representative, these sample sizes are large enough to yield significant LCIA results for the observed data variability.

The uncertainty range for the emission data is derived according to the procedures applied in Doka (2003). A mean value for emissions is derived from the leaching model described above. As a *worst case*, all tailings material will be weathered or eroded within 60'000 years. This worst case is taken to represent the upper confidence value of a lognormal distribution. Together with the inventoried mean value, the geometric standard deviation is defined.

Rehabilitation and tailings management as it is done in certain parts, can alter the ecological impacts greatly at least in the short term. Due to the lack of reliable data, no deliberate rehabilitation is assumed here.

Tab. 4.5 Unit process raw data for the disposal of sulfidic tailings.

Name	Location	Category	SubCategory	Infrastructure	Unit	disposal, sulfidic tailings, off-site
					Location	GLO
					Infrastructure	0
					Unit	kg
Sulfate		water	ground-		kg	0.00559
Nitrate		water	ground-		kg	0.000013
Phosphate		water	ground-		kg	0.000595
Boron		water	ground-		kg	0.0000272
Chloride		water	ground-		kg	3.91E-09
Bromine		water	ground-		kg	4.47E-10
Fluoride		water	ground-		kg	0.00000161
Silver, ion		water	ground-		kg	6.59E-10
Arsenic, ion		water	ground-		kg	1.89E-08
Barium		water	ground-		kg	4.56E-09
Cadmium, ion		water	ground-		kg	1.56E-08
Cobalt		water	ground-		kg	3.44E-08
Chromium VI		water	ground-		kg	3.82E-09
Copper, ion		water	ground-		kg	9.29E-08
Mercury		water	ground-		kg	2.79E-11
Manganese		water	ground-		kg	0.00000139
Molybdenum		water	ground-		kg	0.000000162
Nickel, ion		water	ground-		kg	1.49E-08
Lead		water	ground-		kg	9.14E-09
Antimony		water	ground-		kg	6.1E-09
Selenium		water	ground-		kg	1.74E-08
Tin, ion		water	ground-		kg	1.07E-08
Vanadium, ion		water	ground-		kg	5.35E-09
Zinc, ion		water	ground-		kg	0.000000629
Beryllium		water	ground-		kg	4.11E-09
Scandium		water	ground-		kg	8.05E-09
Strontium		water	ground-		kg	0.000000587
Titanium, ion		water	ground-		kg	8.41E-09
Thallium		water	ground-		kg	1.11E-09
Tungsten		water	ground-		kg	0.00000014
Silicon		water	ground-		kg	0.00000141
Iron, ion		water	ground-		kg	0.00000434
Calcium, ion		water	ground-		kg	0.000151
Aluminum		water	ground-		kg	0.00000152
Potassium, ion		water	ground-		kg	0.00000904
Magnesium		water	ground-		kg	0.000042
Sodium, ion		water	ground-		kg	0.00000985
Sulfate		water	ground-, long-term		kg	0.0383
Nitrate		water	ground-, long-term		kg	0.0000893
Phosphate		water	ground-, long-term		kg	0.000916
Boron		water	ground-, long-term		kg	0.000283
Chloride		water	ground-, long-term		kg	0.00000138
Bromine		water	ground-, long-term		kg	0.000000158
Fluoride		water	ground-, long-term		kg	0.000569
Silver, ion		water	ground-, long-term		kg	0.000000395
Arsenic, ion		water	ground-, long-term		kg	0.0000111
Barium		water	ground-, long-term		kg	0.00000273
Cadmium, ion		water	ground-, long-term		kg	0.00000714
Cobalt		water	ground-, long-term		kg	0.0000186
Chromium VI		water	ground-, long-term		kg	0.00000223
Copper, ion		water	ground-, long-term		kg	0.0000556
Mercury		water	ground-, long-term		kg	1.67E-08
Manganese		water	ground-, long-term		kg	0.000835
Molybdenum		water	ground-, long-term		kg	0.00000686
Nickel, ion		water	ground-, long-term		kg	0.00000893
Lead		water	ground-, long-term		kg	0.00000547
Antimony		water	ground-, long-term		kg	0.00000357
Selenium		water	ground-, long-term		kg	0.00000532
Tin, ion		water	ground-, long-term		kg	0.00000643
Vanadium, ion		water	ground-, long-term		kg	0.00000311
Zinc, ion		water	ground-, long-term		kg	0.000377
Beryllium		water	ground-, long-term		kg	0.00000145
Scandium		water	ground-, long-term		kg	0.00000253
Strontium		water	ground-, long-term		kg	0.000111
Titanium, ion		water	ground-, long-term		kg	0.00000504
Thallium		water	ground-, long-term		kg	0.000000664
Tungsten		water	ground-, long-term		kg	0.00000961
Silicon		water	ground-, long-term		kg	0.000843
Iron, ion		water	ground-, long-term		kg	0.0026
Calcium, ion		water	ground-, long-term		kg	0.0117
Aluminum		water	ground-, long-term		kg	0.000911
Potassium, ion		water	ground-, long-term		kg	0.00414
Magnesium		water	ground-, long-term		kg	0.00735
Sodium, ion		water	ground-, long-term		kg	0.00142
Transformation, from unknown		resource	land			9.09091E-06
Transformation, to dump site		resource	land			9.09091E-06
Occupation, dump site		resource	land			0.001181818
disposal, sulfidic tailings, off-site	GLO	waste mai	residual material lan	0	kg	1

5 Outlook

A first Life Cycle Inventory model of sulfidic tailings disposal was presented here. Representation of sulfidic tailings disposal is still very coarse: there is only one single generic dataset for *any* sulfidic tailings deposit. Future refinements, which were not possible here due to time and money constraints, may include a differentiation according to the mined metal, the tailings site climate and other important conditions.

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