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RISK MANAGEMENT OF HAZARDOUS SOLID WASTES BY HAZARDOUS PROPERTY INCLUDING MERCURY CONTAINING WASTES

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ABSTRACT

The classification of waste is complex. Once detailed chemical composition, and in some cases speciation testing has been completed, the chemicals present are identified either as hazardous chemicals or persistent organic pollutants (POPs). However, detailed waste characterisation data can be used to support onward management of wastes, including hazardous wastes. A process management flowchart has been compiled using data from twelve waste streams. Specifically, for hazardous waste, the proposed approach can be used to firstly identify how a potential hazard may be eliminated using specific treatment. Secondly risk mitigation strategies are provided to reduce risks during short-term management of transportation, preparation and processing of wastes. Finally, the approach highlights how waste characterisation data can be used to guide the long-term management of hazardous waste. For non-hazardous waste a risk approach generates case specific permissible concentration limits. Using a risk-based approach for hazardous waste management can be used for both short-term operations and during recovery loops. Wastes containing "legacy" banned substances must be phased out. But the wastes with hazardous compounds at hazardous concentration should be recovered in controlled recovery loops. They should be managed during the loop by a risk approach, like the products they were and the products that they can become, according to REACH. A worked example of this approach for a mercury containing waste both by hazard and risk is presented, using leaching data (risk) to prevent groundwater contamination from mine tailings using a reverse modelling approach, as proposed to the conference of the UN Minamata Convention.

1. INTRODUCTION

Hazardous wastes have the potential to undergo chemical and biological reactions and for some wastes these properties have beneficial secondary uses. Applications include: the recovery of specific elements from the waste, production of energy, the ability to mitigate hazards in other waste due to their acidic or alkaline capacity (i.e neutralization reactions) or reducing or oxidizing capacity (to react with other wastes). An example is the neutralization of ashes and alkaline bauxite residue by carbonation and eventual addition of soluble calcium (Young-Hoo et al. 2016, Hennebert et al. 2016, Tiefieng et al. 2021, Nguyen et al. 2021). Some hazardous wastes can be recovered or valorised (Wang et al 2021). In the European Union end-of-waste status may then be appropriate (if they can be used for a specific purpose, if there is a market, if they meet technical specifications, and finally if the intended use will not result in overall negative impact on the environment or human impacts on health) (EC 2008, EU 2018).

Hazardous wastes can be recovered but are subject to important legal obligations in terms of handling, transport and management to minimise risks to human health and the environment. Logical frameworks for management have previously been proposed. Yang et al. 2020, produced a system based on the synthesis of accident in waste management facilities. Saeidi-Mobarakeh et al. 2020 produced a mathematical approach for tackling the fluctuation of medical hazardous waste generation rates, and Yu et al. 2020 a method for optimizing the location and sizes of hazardous waste facilities.

Waste transfer stations which collect and group wastes are subject to demanding regulatory requirements as soon as the quantity of hazardous waste exceeds a certain quantity (one ton in France). These requirements apply even when they receive solid and stable wastes and present a

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low risk. When a waste processing site holds non-hazardous and hazardous waste, this will require separate collection, transportation and processing systems. Examples may include:

- plastics which may or may not contain POPs which would restrict onward recovery (Vencowsky et al. 2021); or
- washed packaging waste containing pesticides at concentrations >250 mg/kg (Eras et al. 2017, Jin et al. 2018), making them ecotoxic chronic level 1 (multiplying M-factor of concentration = 1 000) or 2 (multiplying M-factor = 100) in the product classification, if recovered (Hennebert 2019).

The novel approach presented in this paper is to use the information acquired during the characterization and classification of waste (EU 2014, EU 2018, Hennebert 2019) (i) in some cases to eliminate the hazard, (ii) to assess and mitigate the risk(s) during temporary hazardous waste transit, grouping and sorting, and (iii) to choose the management of the hazardous waste on the long-term. A flowchart is presented that can be used for solid and liquid waste. Liquid hazardous wastes are typically treated to become solid waste before long-term landfill disposal. Hazardous waste management by risk was proposed by Bodar et al (2018). Waste could be treated as products, per risk according to REACH (Friege et al. 2021). The interface between chemicals legislation and waste legislation should be as closed as possible to achieve a circular economy.

A brief summary of the requirements for the classification of waste as either hazardous or non-hazardous in the EU are provided in the context of the proposed suggested management approaches for the three scenarios identified above. These include: elimination of the hazard linked to specific hazard properties (HPs), actions to control risks during short-term transit, sorting, grouping and treatment of hazardous waste and finally tested procedures for the long-term management of hazardous waste. These later procedures are commonly used by industry on a day-to-day basis but not within the structure of an overall structured approach.

The flowchart proposed in the study combines:

- fifteen hazard properties and POPs, with three targets and several routes of exposure;
- actions to eliminate seven specific hazards;
- actions for short-term management to control risk, and long-term waste management (7 actions) of hazardous waste; and
- management of non-hazardous wastes for specific recovery opportunities through a risk approach, as it is currently undertaken in practice in many regulations.

It appears that the management of hazardous waste could be structured in a general framework with the removal of the hazard, actions to control risk during short-term transit, grouping and processing, and actions to control risk during long-term end-of-life.

The management of non-hazardous waste for recovery or valorisation is specific to each couple waste/recovery. It includes the setting of concentration limits for every contaminant trough specific risk assessment for every intended use, in a much larger spectrum than for hazardous waste. This aspect is covered by numerous pieces of legislation for each waste: battery, tyres, parts of end-of-life vehicles, of waste of electrical and electronic equipment, paper, metals and more, including end-of-waste status, every case being potentially a chapter of a book not treated here… This is illustrated in this paper only in the part devoted to mercury, with the case of mine tailings stockpiling explained below.

These methods have been suggested by EU experts working in two technical groups of the UNEP 4th Conference of Parties of the Minamata Convention on Mercury (COP-4), to set up concentration limits ("thresholds") for "environmentally sound management" (treatment and confinement) of waste containing mercury (hazard approach), and for the leaching concentration of mine tailings (with a total concentration below the hazardous one) to protect the groundwater below the impoundments. A worked example for mercury is presented with some details of modelling to illustrate a practical case of risk assessment for the long-term storage of these wastes.

2. MATERIALS AND METHOD

2.1 A flowchart for management of hazardous waste

Data and information have been used from twelve documented case studies of hazardous waste or "mirror" entry wastes (wastes which could be hazardous depending on the presence or absence of hazardous substances at relevant concentrations) according to the European List of Waste. The twelve case study wastes were 1.) treated wood for infrastructure, 2.) bottom ash from the incineration of municipal waste, 3.) air pollution control residue from the incineration of municipal waste, 4.) waste containing asbestos, 5.) contaminated excavated soil, 6.) contaminated household waste, 7.) brominated flame retardants in waste electrical and electronic equipment plastics, 8.) empty and rinsed packaging of phytosanitary products, 9.) cigarette butts, 10.) a residue from metallurgical mineral processes, 11.) fly ash from coal-fired power stations and 12.) waste containing mercury. These studies are not presented in detail in this article. These wastes were analysed and classified for relevant hazardous properties. The potential emissions of hazardous substance(s) during present short- and long-term management actions of these waste were evaluated. Depending on the hazard, the actions avoiding exposure of the mankind, the environment, and the infrastructures during short- and long-term management were listed. The list of relevant actions has been built using general knowledge of waste management, specific requirements in France for mitigating risks during transportation (ME 2002), and the list of treatment options for "environmentally sound management" of waste listed in the Basel Convention and the Minamata Convention (UNEP 2015). The different actions were organised in classes for hazard removal, risk mitigation and final treatment of hazardous waste. It was found in the working groups on mercury waste (see 4.7) that it helped the understanding

of waste management to organise the different options in an organised structure.

2.2 Waste sampling, analysis and classification

The stages of waste classification include: representative sampling (Hennebert and Beggio 2021, Beggio and Hennebert 2022); detailed testing and total analysis (Hennebert et al. 2012); speciation of elements to provide information on compounds present (Hennebert 2019, Bishop and Hennebert 2020); and then the assessment and classification with respect to each hazard property HP 1 to HP 15 (synthetic table in Hennebert 2019) and the content of persistent organic pollutants (POPs). The hazard classification is based on intrinsic properties of substances, and their concentrations in the waste. If a waste contains POPs above a specific threshold concentration the waste cannot be recovered unless the POPs can be removed and the POPs content must be irreversibly destroyed or transformed according to Annex IV of the POP regulation - EU 2019a). The concentration limits are presented in Table 1. Some POPs may be present at concentrations that make the waste making hazardous (EU 2014). All the hazardous properties must be evaluated to be able to declare a waste to be non-hazardous.

3. RESULTS

3.1 Flowchart of management of hazardous and non-hazardous waste

From the twelve hazardous waste scenarios a structured approach for the management of hazardous and non-hazardous wastes based on risk has been developed into a flowchart. Risk is an exposure of a target to a hazard. For products: risk = hazard x exposure or transfer (depending on use) x target (depending on use). For waste: risk = hazard x relevant exposure (depending on the management method) x relevant target (depending on the management method).

The different options of the waste treatment hierarchy (EU 2018) are reutilization, valorisation by material recycling (), recovery / combustion with energy recovery, and finally disposal to landfill. These correspond to different regulatory frameworks. For recycling, exposure and targets are framed by regulations specific to each product family. For landfilling, exposure and targets are regulated by landfill regulations (2003/33/EC). For the two other modes that may present exposure to targets, namely reutilisation and recovery, the treatment operations can be grouped into three main types of actions: (i) hazard elimination (if possible), (ii) short-term handling, grouping and processing, and (iii) long-term treatment. The flowchart is presented at Figure 1. The different actions are presented in Table 2. The targets and exposure routes from hazard properties can be organized as in Table 3. The substances considered must include those that can be produced as a result of chemical reactions and evolution like hazardous gases (property HP 15). The characteristics of space consumption and visual impact are not considered because they are not specific to hazardous waste.

TABLE 1: Wastes which may contain POPs and concentration limits in recycled materials.

Uses, materials	Substances	Concentration limit for recycled material	Concentration classifying the waste as hazardous
Unwanted by-products of incineration or combustion, and chlorinated substances processing	Dibenzo-p-dioxines et dibenzofuranes polychlorés (PCDD/PCDF)	15 µg TEQ/kg	15 µg TEQ/kg
Waxes	Polychlorinated naphthalenes	10 mg/kg	
Pesticides	DDT (1,1,1-trichloro-2,2-bis (4-chlorophenyl)ethane), Chlordane, Hexachlorocyclohexanes, including lindane, Dieldrin, Endrin, Heptachlor, Hexachlorobenzene, Chlordecone, Aldrin, Pentachlorobenzene, Mirex, Toxaphene, Hexabromobiphenyl	50 mg/kg	50 mg/kg
Electric transformer heat-resistant fluid, rubbers and seals	Polychlorinated Biphenyls (PCB)	50 mg/kg	50 mg/kg
Brominated flame retardants in plastics	Hexabromobiphenyl	50 mg/kg	50 mg/kg
Anti-stain, waterproof coatings, fire-fighting foam	Perfluorooctane sulfonic acid and its derivatives (PFOS)	50 mg/kg	
Solvent in the chemical industry (mainly for chlorine)	Hexachlorobutadiene	100 mg/kg	
Brominated flame retardants in plastics	Sum of the concentrations of tetrabromodiphenyl ether, pentabromodipheny lether, hexabromodiphenyl ether, heptabromodiphenyl ether and decabromodiphenyl ether	1 000 mg/kg	
	Hexabromocyclododecane	1 000 mg/kg	
Conveyor belts for mine and quarries, flame retardant in plastics, plasticizer, coatings	Alkanes C10-C13, chloro (short-chain chlorinated paraffins) (SCCPs)	10 000 mg/kg	

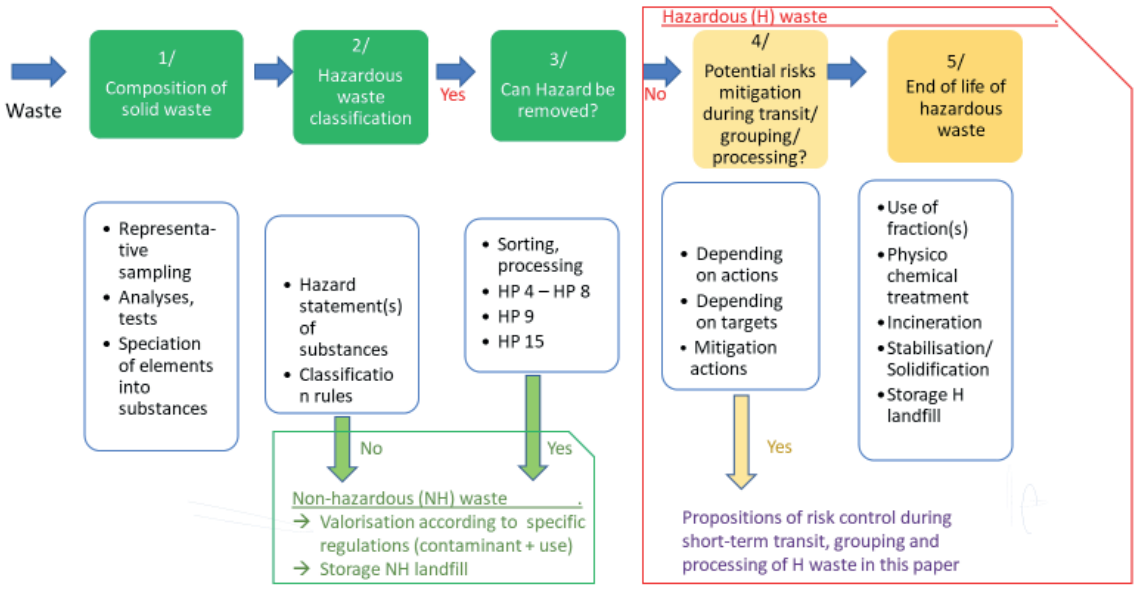


FIGURE 1: Information flow for the management of hazardous and non-hazardous waste through removal of the hazard, through actions to control risk during short-term transit, grouping and processing, and through actions to control risk during long-term end-of-life.

3.2 Actions removing the hazard (RA) of hazardous waste

One route for hazardous waste management is to remove the fraction which contains the hazard when the contaminant is not uniformly distributed among the particles of the waste (shredded). Examples include the selective dismantling of waste of electrical and electronic equipment (WEEE) and end-of-live vehicles (ELV), sorting of metallic non-ferrous (copper, zinc, nickel) fraction, sorting of plastics of WEEE for banned flame retardants.

Actions specific to remove some HPs are:

- HP 4 'Irritant' and HP 8 'Corrosive' by acidity or alkalinity. In case of acidity, neutralization can be achieved by controlled preparation with an alkaline waste. In case of alkalinity, neutralization can be obtained by acid waste or by carbonation by CO_2 (passive or active: Young-Hoo et al. 2016, Hennebert et al. 2016, Tiefieng et al. 2021, Nguyen et al. 2021);
- Reducing or oxidizing waste: neutralization can be obtained with oxidizing or reducing waste;
- HP 9 'Infectious': the infective parts can be deactivated by sterilization;
- HP 15 'Waste capable of exhibiting a hazardous property not directly displayed by the original waste' : For example, if use of the material as a backfill as part of landfilling is required and organic matter is present, a prior sorting of the biodegradable fraction should be done to obtain a low organic matter content (total organic carbon TOC <3% for inert waste landfill, EC 2003). The backfilling should be permeable to air and water, to avoid the emission of methane, hydrogen sulphide and leachate with organic matter. In the event of the presence of sulphides (mining residues, tailings, sediments): addition of alkalinity in a quantity greater than the potential acidity to neutralise the sulfuric acid produced by the biological oxidation of sulphides (Petrignet et al. 2018).

For the other hazardous properties, suitable widely available treatments include: the incineration of organic substances; chemical and physical treatments specific to organic or mineral substances in the dedicated industrial installation; and the stabilization / solidification with cement or waste having hydraulic or pozzolanic activity. These treatments remove the hazard (frequent cases of incineration of non-halogenated low-ash organic waste) or produce a new hazardous waste (frequent cases of initially mineral waste, and air pollution control residues of incinerators) which must be characterized either before use or before storage according to the storage rules. For this reason, incineration is included in the long-term treatment actions. All these actions are presented in Table 2.

3.3 Actions of short-term transit, grouping and processing (PA) of hazardous waste

The different actions identified for this temporary phase of waste management are presented in Table 2. All these actions are specific to given HP(s) and given exposure route(s) (Table 3). Precise information about every waste batch is essential to correctly identify the relevant hazards and exposure routes, in order to avoid accident or damages.

3.4 Actions of long-term treatment (TA) of hazardous waste

Some of these actions (Table 2) are unspecific to a given HP: physico-chemical treatment, incineration of organic substances, stabilization/solidification of the mineral substances to reduce the leaching fraction and storage in engineered landfills (Table 3).

Other actions are specific to HPs: for explosives (weap-

TABLE 2: Removing, short-term processing and long-term treatment management actions for solid hazardous waste to minimize the risk during waste management operations.

Actions	Code used in Table 3	Operations
Actions removing the hazard (from hazardous waste to non-hazardous waste)	RA1	Separation of the hazardous fraction
	RA2	Acid or alkaline waste: neutralization with alkaline or acid waste
	RA3	Alkaline waste: passive or active carbonation by CO_2
	RA4	Reductive or oxidative waste: neutralization with oxidative or reductive waste
	RA5	Sterilization (water vapor 120°C 20 minutes or equivalent)
	RA6	Pre-treatment to sort out organic matter
	RA7	Sulphide wastes (mining residues, sediments): avoidance of contact with O_2, addition of alkalinity greater than the potential for acid generation
Actions of short-term transit, grouping, processing of hazardous solid waste*	PA1	Specialized handling
	PA2	No contact with metals or organic matter
	PA3	General actions against fire, ventilation, surveillance
	PA4	Limitation of quantities per batch
	PA5	Avoidance of human contact: mechanical handling, packaging, containment, humidification, misting
	PA6	No contact with water or an acid
	PA7	Avoidance / minimization of environmental contact: containment, watertight area, shelter, misting
	PA8	Organic matter: avoidance of anaerobic degradation (without oxygen) producing CH_4, NH_3, amines and H_2S
	PA9	Organic matter: avoidance of animal products in composting in an open environment
Actions of long-term treatment of hazardous solid waste	TA1	Physico-chemical treatment
	TA2	Incineration of organic substances
	TA3	Stabilization/solidification of the mineral substances to reduce the leaching fraction
	TA4	Storage in engineered landfills
	TA5	Explosives (weapons): Destruction on site or in military installations
	TA6	Asbestos, Mercury: Storage in specially engineered landfills
	TA7	POP substances: Mandatory destruction by incineration or combustion, or irreversible transformation

** these actions concern waste and not people*

ons), destruction on site or in military installations; for asbestos and mercury, storage in specially engineered landfills; for POP substances, mandatory destruction by incineration or combustion, or irreversible transformation (EU 2019a) (Table 3).

Backfilling of hazardous waste and by extension final disposal in an open environment cannot be carried out in Europe (EU 2018): "17 a. "backfilling" means any recovery operation where suitable non-hazardous waste is used for purposes of reclamation in excavated areas or for engineering purposes in landscaping. Waste used for backfilling must substitute non-waste materials, be suitable for the aforementioned purposes, and be limited to the amount strictly necessary to achieve those purposes".

3.5 Removal actions, treatment actions and handling actions by hazard property and exposure routes to humans, the environment and the infrastructures

The results are presented in Table 3. The abbreviations RA (removing actions), PA (short-term processing actions) and TA (long-term treatment actions) are detailed in Table 2.

Examples: A flammable waste (HP 3) can be handled by separation of the hazardous (flammable) fraction (hazard removing action RA1), should be managed by general actions against fire, ventilation, surveillance (processing action PA3), limitation of quantities per batch (processing action PA4), and incinerated (long-term treatment action TA2). A POP waste (POP) can be handled by separation of the hazardous (POP) fraction (hazard removing action RA1), should be managed by avoidance of human contact: mechanical handling, packaging, containment, humidification, misting (processing action PA5), avoidance / minimization of environmental contact: containment, watertight area, shelter, misting (processing action PA7), and physico-chemically treated or incinerated (long-term treatment action TA1 or TA2).

3.6 Risk method for reuse or storage of non-hazardous waste

Contaminants are frequently present in non-hazardous waste, with concentrations below thresholds which make the waste hazardous. These non-hazardous wastes are commonly in practice managed by a risk approach, although specific concentration limits may need to be met for the intended storage or recovery route. An example is the use of sewage sludges or compost or digestates in agriculture. The limits may apply to the total concentration, be linked to bioavailability (as determined by a mild extractant

TABLE 3: Actions removing the hazard (RA), actions of short-term transit, grouping, processing (PA) and actions of long-term treatment (TA) of hazardous waste. For non-hazardous waste, a risk assessment for the intended management action is recommended (see 4.6).

Actions	Unspecific Removing Action (RA)	HP Specific actions: Hazard Removing actions (RA), Short-term risk of transit, grouping and Processing mitigating actions (PA) and, Long-term Treatment actions (TA)											Unspecific Long-term Treatment Actions (TA)
		Targets → Man			Environment				Facilities, infrastructure, neighborhood				
Hazard Property ↓	Routes →	Heat & Pressure	Skin, eye contact: Dermal	Inhalation	Air: Dust, gas	Water: Leaching	Soil: Storage	Organisms	Heat & Pressure	Dust, gas	Odor	Vermin (rat, fly, parasite, etc.)	
HP 1 Explosive		PA1 TA5							PA1 TA5				TA1 to TA4
HP 2 Oxidizer	RA1	PA2							PA2				TA1 to TA4
HP 3 Flammable	RA1	PA3							PA3 PA4				TA1 to TA4
HP 4 Irritant	RA1		RA2 RA3 PA5			PA7	PA7	PA7					TA1 to TA4
HP 5 Specific toxic	RA1		PA5	PA5									TA1 to TA4
HP 6 Toxic	RA1		RA4 PA5	PA5									TA1 to TA4
HP 7 Carcinogenic	RA1		PA5	PA5 TA6*									TA1 to TA4
HP 8 Corrosive (skin)	RA1		RA2 RA3 PA5			PA7	PA7	PA7					TA1 to TA4
HP 9 Infectious	RA1		RA5 PA5	RA5 PA5	RA5	RA5	RA5	RA5				PA5 PA9	TA1 to TA4
HP 10 Reprotoxic	RA1		PA5 TA6**	TA6**									TA1 to TA4
HP 11 Mutagenic	RA1		PA5										TA1 to TA4
HP 12 Toxic gas	RA1			PA6 PA8	PA6 PA8			PA6 PA8		PA6 PA8			TA1 to TA4
HP 13 Sensitizing	RA1		PA5	PA5									TA1 to TA4
HP 14 Ecotoxic	RA1				PA7	PA7	PA7	PA7					TA1 to TA4
HP 15 Generating another HP	RA1				PA8	RA6 RA7 PA8	RA6 RA7 PA8				TGPA8		TA1 to TA4
POP	RA1		PA5	PA5	PA7	PA7	PA7	PA7					TA1 to TA4

TA6 = asbestos, TA6** = mercury, RA1-7, PA1-9, TA1-7: see Table 2*

or biotest), or a leachable concentration (with deionised water), as per the waste acceptance criteria for landfill disposal in the EU (EC 2003). A specific example of bespoke concentration limits for mercury in recycled waste is discussed below and presented in Table 4.

3.7 Hazard and Risk approach for waste containing mercury compliant with the Minamata Convention

The approach presented in this paper has been applied by EU experts to mercury-containing wastes in the framework of a working group of the UN Minamata Convention (the motto of which is "make mercury history") and is submitted to the fourth Conference of the Parties of this convention, in 2021 and 2022. The first step is the determination of the concentration of mercury that makes waste hazardous. These wastes must be treated in industrial installations and confined in engineered landfills (TA6** in Table 2 and 3). Below this value, a case by case (waste/use) risk approach is proposed. The approach could be used for mine tailings.

3.7.1 Hazard approach: ≥ 25 mg Hg/kg

The EU proposes a threshold for waste of category C "Contaminated with mercury or mercury compounds" to be disposed of (Article 11 of the Minamata Convention), using the Globally Harmonized System of classification and labelling of chemicals of the United Nations (GHS - UNEP, 2017). Mercury and mercury compounds are classified as substances for the physical, health and environmental hazards categories. The thresholds of mercury and mercury compounds classifying a mixture as hazardous for the different hazard categories (physical, health, environmental) are "Presence" of some organic substances with mercury, >0.3% of reprotoxic elemental mercury, and >0.0025% (25 mg mercury/kg of waste) for mercury and all the substances containing mercury, respectively (Hennebert 2019). Calculated M-factors from published acute and chronic ecotoxicological data of algae, invertebrate and fish of fresh water and marine water were used for the environmental hazard. The acute and chronic M-factors for mercury-containing substances are 100. M-factors are concentration

multipliers that are used to calculate if a limit is exceeded, to account for the higher degree of ecotoxicity of certain substances. The M-factors range from 1 (little ecotoxic substances) to 1,000,000 (certain pesticides). It should be noted that the abandonment of the M-factors in EU waste classification gives a concentration limit 100 times higher in a waste to be classified as hazardous in the EU (= 0.25%). That concentration of 25 mg Hg/kg has an international status since it is calculated with the UN GHS.

According to the Convention, waste of category "C" with a concentration above a given threshold must be submitted to the "Environmentally Sound Management" of the Basel Convention and the Minamata Convention Guidance (UNEP 2015):

"*The following disposal operations, as provided for in Annex IV, parts A and B, of the Basel Convention, should be permitted for the purpose of environmentally sound management of mercury wastes:*

- *D5 Specially engineered landfill;*
- *D9 Physico-chemical treatment;*
- *D12 Permanent storage; mixing*
- *D13 Blending or prior to submission to operations D5, D9, D12, D14 or D15;*
- *D14 Repackaging prior to submission to operations D5, D9, D12, D13 or D15;*
- *D15 Storage pending operations D5, D9, D12, D13 or D14;*
- *R4 Recycling/reclamation of metals and metal compounds;*
- *R5 Recycling/reclamation of other inorganic materials;*
- *R8 Recovery of components from catalysts;*
- *R12 Exchange of wastes for submission to operations R4, R5, R8 or R13;*
- *R13 Accumulation of material intended for operations R4, R5, R8 or R12."*

These management recommendations correspond to the last column "Unspecific Treatment actions" without transfer and exposure to targets of Table 3. As a consequence, the EU proposes a threshold of 25 mg total Hg/kg dry matter for the category C: every waste containing mercury above that threshold should be "environmentally sound managed" by the actions mentionned here above.

3.7.2 Risk approach: risk mitigation between 1 and 25 mg Hg/kg

EU experts have proposed the use of a case-by-case risk-based approach for waste with mercury concentrations below 25 mg/kg, for the reuse of waste in defined scenarios in circular economy. A risk approach is much more complex than a hazard approach: the effect of the waste on human health and ecosystems, the environment and eventually the infrastructures must be quantitatively assessed, and an acceptable level of impact must be defined. Scientists are aware that an impact accepted three decades ago cannot now be accepted at the present time. Additionally, the present baseline of impact (the initial situation) is not always well defined. As risk depends on natural and human factors, that approach is best developed at a national level. Some national documented cases of thresholds derived from risk assessment of waste in defined reuses are given in Table 4. The concentration range is between 25 and 0.8 mg Hg/kg: the national risk-based concentrations in countries where wastes are properly managed are all <25 mg/kg and are thus coherent with the proposed hazard-based

TABLE 4: Some national concentration limits for reuse of waste with low Hg contamination in circular economy sorted by decreasing concentration of Hg.

Waste, Use	Country	Hg concentration (mg/kg)	Hg summary range mg/kg	Source
Sewage sludge in agricultural land	European Union	16 to 25 mg/kg; revision to 1 mg/kg considered	16-25 1	EEC 1986. Directive of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (86/278/EEC) (OJ L 181, 4.7.1986, p. 6)
Artificial soil used for ecological restoration and greening, Use as filling materials for land and Cover materials in landfill site	Republic of Korea	Area 1: 4 mg/kg, Area 2: 10 mg/kg, Area 3: 20 mg/kg	4 -20	Note of Rep. of Korea Expert Seung-Whee RHEE, 08/04/2021
Reuse for cement, ceramic and fuel	Republic of Korea	Reuse slag in cement: 2 mg/kg, ceramic: 16 mg/kg, other waste in cement: 2 mg/kg, fuel for cement: 1.2 mg/kg, fuel: 1 or 1.2 or 1 mg/kg, solid refuse fuel: 1 or 1.2 mg/kg	1-16	Note of Rep. of Korea Expert Seung-Whee RHEE, 08/04/2021
Sewage sludge in agricultural land	France	10 mg/kg	10	RF 1998. Arrêté du 8 janvier 1998 épandages de boues sur les sols agricoles
Sewage sludge land spreading	Denmark, Germany, Australia	0.8 - 5.0 mg/kg	0.8-5	Oral communication to the group
Fertilizers from circular economy	European Union	1 mg/kg and in one case 2 mg/kg	1-2	EU 2019b. Regulation (EU) 2019/1009 … the making available on the market of EU fertilising products EC 2016. Circular Economy Package - Proposal for a Regulation … on the market of CE marked fertilising products
Threshold for certain reuses	Switzerland	1 mg/kg	1	Swiss Confederation 2015

global concentration of ≥25 mg/kg. In practice, a panel of contaminants (not only Hg), specific to each couple (waste / reuse), are monitored before the reuse of waste.

3.7.3 Risk approach: no risk at concentrations ≤ 1 mg Hg/kg

Toxicological risk assessment of Hg shows that there is no risk for use/reuse product or waste that contain less than 1 mg Hg/kg, as for instance, the concentration limit in skin whitening cosmetics (WHO 2019).

3.7.4 Two specific issues of hazard and risk for mercury waste in the working groups of the Minamata Convention

High exposure from hazardous chemicals due to inappropriate waste management practices in less developed countries should be of high concern. For example, waste pickers working at uncontrolled landfills are exposed at close quarters to a wide variety of wastes containing a wide spectrum of contaminants present at unknown concentrations, including mercury. This example of unethical and unsustainable waste management could be improved by reducing the levels of exposure. This could be managed by improved landfill management practices, increasing the selective collection of mercury containing waste (lamps, batteries, thermometers etc.), and ensuring that any following treatment undertaken in local specialist or industrial facilities with appropriate health and safety measures rather than setting a low concentration permissible concentration limit for mercury waste (which would then need to be monitored).

Low mercury concentrations and a lack of appropriate disposal facilities is not a reason for choosing the maximum risk scenario and therefore the minimum threshold for mercury. A maximum risk approach would require increased quantities of waste being incinerated with proper air pollution control and/or landfilled in controlled landfills. However, these facilities can be lacking in more disadvantaged countries. Improvements to basic waste management will achieve the desired exposure reduction.

Representative waste sampling where mercury concentrations are under 25 mg/kg and particularly 1 mg/kg: the correct sampling of these low concentrations is really challenging for heterogeneous (granular) waste (like unsorted household waste). A representative sample must include the particles containing mercury in the same proportion as the waste heap or flow. Where mercury is present as rare but discrete high concentration individual pieces, for example a battery, require a very large samples to be taken (calculated mass between 20 tonnes for 25 mg/kg to 500 tonnes for 1 mg/kg for rare button batteries of 2 grams in household waste) and costly crushed before taking a smaller sub-sample. Size reduction must be repeated in steps to produce the laboratory sample, and then repeated in the laboratory to produce a test portion of one gram that is analysed. In these specific cases, the task is in practice impossible or will be too expensive to be done. The "true" low concentrations of mercury in granular heterogeneous waste cannot be known with certainty. Sampling is easier for wastes that have been treated and thus homogenized (for instance in wastewater treatment plant, plastic shreds sorting installation, municipal solid waste incinerator). Sampling standards must be strictly applied (EN 14899, EN 15002, Hennebert and Beggio 2021).

3.7.5 A hazard and risk approach for non-sulphidic mine tailings

The Minamata Convention considers a two-tiered approach for the concentration threshold of mercury in mine tailings. The technical group "mine tailings" agreed with a first threshold of a total concentration for mercury of 25 mg/kg. Mine tailings from non-Hg mining activities may have a concentration of Hg >25 mg/kg. In a brief survey of scientific literature, 3 data out of 10 tailings have a concentration of Hg >25 mg/kg: 36 mg/kg (Canada), 41 mg/kg (Russia) and 97 mg/kg (Portugal) (Hennebert 2020), depending on the composition of the rock that is mined.

The second threshold considered is based on the risk of Hg contamination of groundwater. Looking at leaching specifically, the mercury can move in the leachate to the surrounding soil and to groundwater. In the context of an environmentally sound management of wastes containing mercury for the Minamata Convention, the question posed was what concentration of mercury in the leachable fraction of mining wastes is the limit to avoid contamination of groundwater above limits set for potable water?

The method developed for the EU acceptance of waste at landfills (without an impermeable layer) (EC 2003) was proposed to the working group and accepted. That procedure includes an integrated model of emission of elements and some compounds by waste, the vertical transport of these contaminants though the unsaturated soil layer by vertically draining water and their interaction with that soil. This is followed by mixing and horizontal transport and adsorption/desorption within the saturated zone by horizontally moving ground water (Hjelmar et al. 2001, Hjelmar 2012). Only the results for the scenario without an impermeable layer (for inert waste) will be modelled here, as it seems to be the most frequent case for legacy abandoned mining waste.

The principle is that from the release of contaminants in leachate from a waste (by column percolation tests), the expected concentration at the point of compliance (POC) can be assessed. Using the target concentration of elements and substances in the groundwater, the corresponding maximum leaching concentration of elements and substances from waste can be calculated by "reverse modelling". This is simple, because a linear Kd-based transport model is used (Hjelmar et al. 2001). The partition coefficient K_d is the ratio of the concentration of an element that is adsorbed to the soil and the concentration of that element in solution in equilibrium with the soil. Its unit is (mg/kg) / (mg/L) = L/kg.

Release from waste: Using multiple sets of data from column percolation tests (EN 14405), the concentration of many elements in the leachate from many waste shows, along with increasing liquid to solid "L/S" ratio an initial highest concentration, C0, followed by a logarithmic decrease, down to near zero concentration for the largest water quantities (Aalbers et al, 1996). The rate of the decrease can for many substances be expressed by a factor K that is experimentally measured for each element. The compo-

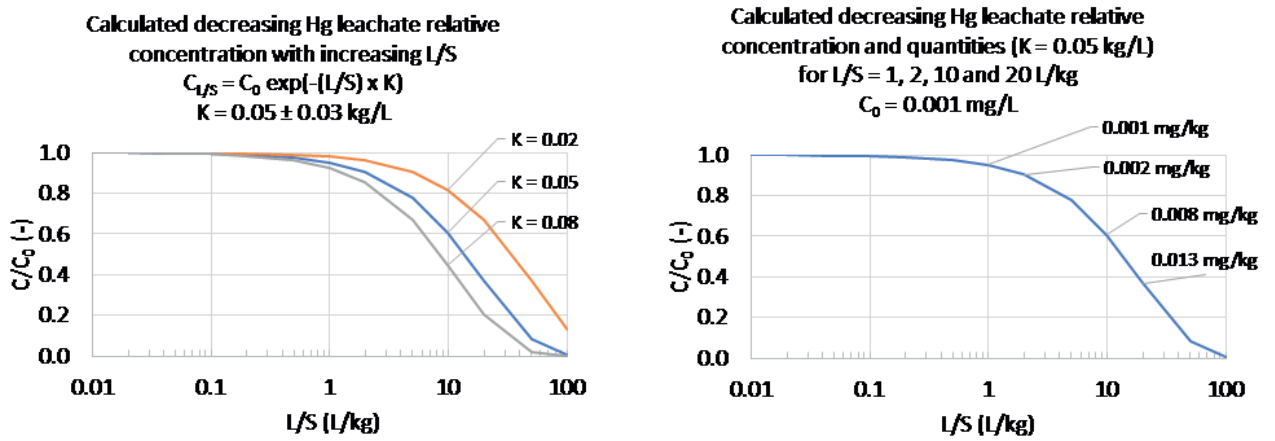


FIGURE 2: Calculated concentration of Hg in leachate from a waste as a function of K and L/S ratio (logarithmic scale) in a column percolation test (this paper). C0 is the initial concentration. C/C0 is the concentration relative to C0. Emission concentration for different values of K (left). Emission concentration for K = 0.05 l/kg and emitted quantities (labels, mg Hg/kg waste) for C0 = 0.001 mg/l and for L/S = 1, 2, 10 and 20 l/kg.

nent-specific experimental constant K is a factor describing the magnitude of the decrease in the concentration of a component at the exit of a unidirectional flow when it is rinsed with water without this component. For the emission by waste, the concentration (mg/L leachate) as a function of liquid to solid ratio L/S (L/kg) is approximated as CL/S = C0 exp((-L/S) x K). The cumulated quantity (mg/kg waste) emitted as a function of L/S is then EL/S = (C0/K) (1-exp((-L/S) x K)). The K factor for Hg has been found experimentally to be 0.05 (± 0.03) kg/L for five wastes (Hjelmar 2012 quoting Aalbers et al. 1996). In a percolation test with K = 0.05 kg/L, the cumulative emission is one time the maximum initial concentration at L/S = 1 L/kg, eight times (and not ten times) the maximum concentration at L/S = 10 L/kg and thirteen times (and not twenty times) the maximum concentration at L/S = 20 L/kg (Figure 2, right).

Reactive transport modelling: Calculations have been undertaken using three different 2D and 3D models (CXTFIT/ECOSAT and HYDRUS 2D for the unsaturated zone and MODFLOW and MT3D for the saturated zone, Hjelmar 2012). A mild reversible adsorption by Kd has been used for Hg (1 L/kg from literature for medium grain-size soil). The annual drainage is assumed to be 300 L/m². For a 20 m high stockpiling, with an assumed density of 1500 kg/m³, that volume of drainage water corresponds to 0.01 L kg^{-1} $year^{-1}$: 1 L/kg corresponds to 100 years of drainage in the hydraulic model and in Figure 2. The size of the landfill was 150 m x 150 m. High dispersivity values were deliberately used to ensure a total vertical mixing and equal vertical concentrations in the aquifer of 6 m thickness. The drainage water dilutes in a moving groundwater with a velocity of approximately 20 m/year corresponding to a fixed hydraulic head of 4.1 m at the downstream boundary of the model area. The mean concentration at the point of compliance along time is calculated.

Expression of results: The results are synthetically expressed by a dilution attenuation factor (DAF) fa , which is the ratio of the maximum leachate concentration relatively to the maximum groundwater concentration at the point of compliance (Hjelmar et al. 2001). That factor is the ratio of the maximum leaching concentration and the maximum calculated concentration in the groundwater (taking into account time and soil adsorption and desorption and dilution by moving groundwater) and is not a simple (hydraulic) dilution factor. The maximum leachate concentration is:

$$C0\ target\ leachate = Ctarget\ groundwater\ POC * fa \quad (1)$$

The corresponding target cumulated quantity (mg/kg waste) emitted as a function of L/S is:

$$EL/S = (C0\ target\ leachate/K)\ (1\text{-}exp\ ((\text{-}L/S) \times K) \quad (2)$$

In the EU calculations for Hg and inert waste, the dilution attenuation factor fa was found to be 2.03 L/L (with K_d = 1 L/kg and a point of control 20 m after the landfill) (recalculated from Hjelmar 2012). The attenuation factor depends on the soil and climate of every country or even area within a country. With the drinking water maximum concentration of 0.001 mg Hg/L in the EU, the calculated maximum emission for inert waste is 0.016 mg leachable Hg/kg at L/S = 10 L/kg, using the decreasing exponential emission with L/S. That value rounded to 0.01 mg/kg has been adopted in the EU landfill acceptance criteria for inert waste (EC 2003).

The International Council on Mining and Metals has asked the consulting company Ecometrix to simulate what might be the emission concentration of mine tailings, to protect groundwater, with a maximum concentration of 0.006 mg Hg/L (World Health Organization) (Barbanell 2021, Haack and Nicholson 2021a,b). For waste release and for hydraulic transport, the same values than the EU calculations were used. For adsorption/desorption by soil, 83 K_d literature data representative of the sub-soil of the impoundments were gathered. The 5th percentile is 133 L/kg, the median is 2 164 L/kg, and the 95th percentile is 35 168 L/kg (minimum 20 L/kg, maximum 60 000 L/kg) (Haack and Nicholson 2021a).

For the 5th percentile K_d (95% of the literature cases will have a higher Kd and DAF), for the 2-D model, the calculated $C_{max\ underground\ water}$ / $C_{0\ leachate}$ = 0.047 with a point of con-

trol 200 m after the impoundment (Haack and Nicholson 2021a, b), and the corresponding DAF is the reverse, namely 21.4 L/L. The maximum concentration in the groundwater C_{max} will be reached after about 38 000 years. To simplify and make the result understandable and usable at any L/S of the different tests, the decreasing exponential emission from waste with L/S has not been used. To not exceed the drinking water value of 0.006 mg Hg/L, the maximum leaching concentration is = 0.006 mg Hg/L underground water x 21.4 L underground water/L leachate of waste = 0.15 mg Hg/L leachate of waste.

The result is expressed in mg/L leachate of waste. As various leaching tests are used across the world, this value can be converted into a release E (or emission E) in mg leachable Hg/kg dry matter by multiplying by the L/S ratio of the test (not taking into account the exponential decrease observed in percolation test, see above). With L/S = 10 L/kg (EN 12457-2, EN 14405) and a maximum leaching concentration Cmax = 0.15 mg Hg/L leachate, E(Hg) = Cmax x L/S = 0.15 mg/L x 10 L/kg = 1.5 mg Hg/kg dry mass.

In conclusion for mine tailings, after two years of work, the thresholds for a 2-Tier approach are proposed by the expert group. The first tier informs what is the acceptable maximal total concentration in impoundments. The group proposes a hazard approach: the concentration that makes the waste ecotoxic. Mine tailings with total Hg concentration >25 mg/kg cannot be stored in impoundments in contact with the environment. The second tier identifies what is the maximum leachable concentration required to protect the groundwater in the vicinity of the impoundment. The group proposes a risk approach: the maximum leachable concentration derived from reactive transport reverse modeling from mine tailings, based on published parameters for modeling. Mine tailings with leaching concentration >0.15 mg Hg/L leachate cannot be stored in impoundments in contact with the environment. This corresponds to the risk method for reuse or storage of non-hazardous waste developed in this paper. That approach of hazard and assessed risk is suggested to the COP-4 of the Minamata Convention.

4. CONCLUSIONS

The information acquired during the characterization and classification of waste (EU 2014, EU 2018, Hennebert 2019) can be used to inform the future management of wastes. This paper provides a procedure to (i) eliminate the hazard of some wastes where this is possible, (ii) to assess and mitigate the risk(s) during temporary hazardous waste transit, mixing and sorting, and (iii) to choose the management of the hazardous waste in the long-term. This study proposes an over-arching flowchart which combines hazard properties and POPs (16), potential targets (3 types with several routes of exposure), the actions of elimination of the hazard (7), the actions of short-term waste management (9 actions) to control the risk, and long-term waste management (7 actions) of hazardous waste, as well as the management of non-hazardous waste for each specific reuse through a risk approach, as it is done in practice in many regulations.

The flowchart was developed from twelve practical waste cases and this approach has been used successfully by two working groups on mercury waste and mine tailings of the UNEP Minamata Convention. According to the experience acquired in these technical groups, it helps to organize hazard, risk and short- and long-term management in a clear scheme that can be adopted by all stakeholders of waste generation and management and their potential reuse in the circular economy.

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