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Leachability Assessment and Material Characterization of Toxic Metals from Obsolete Mobile Phones

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Abstract: Mobile Phones (Cellular) have become a necessary electronic device used across the globe. The rapid advancement of technology has created cycles of replacement that have resulted in a growing and significant source of hazardous waste from the numerous obsolete units generated by manufacturers and consumers, respectively. Due to the various components of e-waste containing hazardous materials, the failure to dispose of it appropriately creates many environmental problems and issues associated with the release of heavy metals, especially lead (Pb), cobalt (Cd), nickel (Ni) and manganese (Mn). These toxic metals are concentrated in e-waste components such as Printed Circuit Board (PCB), Liquid Crystals Displays (LCD), plastic housings, and represent significant danger and threat to the environment. Long-term environmental exposure presents significant dangers to human health and the environment when released under optimal conditions; including, but not limited to, eye irritation, skin rashes, damage to kidneys and nerves, dermatitis, and potential death. In characterizing the physiochemical properties of major segregated e-waste components, determining a comprehensive inventory of total metals, and evaluating their potential to be toxic through the evaluation of their leachability using long-term batch leaching studies at multiple liquid-to-solid (L/S) ratios and simulating landfill conditions at the time of discard/landfilling. The results of the leaching studies demonstrated that the plastic housings and batteries represent large portions of the total mass of the electronic devices. Further analysis of the data indicated the e-waste components of each manufacturer/model to contain significant compositional variability. The total concentrations of Ni (up to 40 mg), Pb (up to 35 mg), and Cd (up (up to 34 mg) distributed across the PCB, metallic, and plastic fractions. Analysis of leachate (from eWaste) indicated that Cd and Ni are far more leachable than Pb or Mn when tested in a neutral to slightly alkaline environment (pH 7-8). The results support the conclusion that the plastic portion of the leachate contains a large proportion of mobile Ni and the high L/S ratio results established continuing leaching of Cd. Both are serious and enduring forms of pollution and highlight the need for specific waste management practices aimed at reclaiming and stabilizing the highly mobile forms of these contaminants found in non-conventional e-waste products.

Keywords: Cell phone, Replacement, Metals, Hazardous substances, Toxicity, E-waste, Leachability, Printed Circuit Board-PCB, Landfill simulation

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I. INTRODUCTION

With the advent of advanced communication and information technology (ICT), post-industrial revolution; has profoundly influenced everything that we do as humans throughout time. It has also made electrical and electronic equipment and devices necessary to our daily lives. In fact, because of this rapid increase in demand for technology that is smaller, lighter, and packed with more features than ever before in history; advancements in technology have forced consumers to purchase and dispose of vast quantities of Waste Electrical and Electronic Equipment (WEEE), also known as "e-waste" [1].

In addition to this rapid increase in WEEE that is produced and subsequently disposed of, there exists a dichotomy within WEEE; whereby the WEEE contains both very valuable materials, such as copper (Cu), gold (Au), silver (Ag), and platinum (Pt) (among others); and those materials that are extremely hazardous, such as lead (Pb), cadmium (Cd), and nickel (Ni), in addition to organic pollutants, such as polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs).

The total amount of electronic discards generated globally poses a significant risk to our health and the environment. WEEE is a rapidly growing and, at the same time; very concerning stream of waste. For example; a U.S. Environmental Protection Agency report, published in 1997, indicated that over 2.17 billion people around the world had mobile phones; which highlights the challenges posed by the growing volume and complexity of this waste stream [2].

The varying disposal rates of various types of WEEE are due to their differing sizes and weights; therefore, white goods generally have the highest collection quota (collection rate) because of their large size, and white goods were typically estimated at approximately 90% collection rate. Brown goods, along with small ICT scraps, can easily find their way into normal domestic waste; therefore, their collection efficiency is much lower than that of the white goods. According to a 2000 report, it was estimated that of the 357,000 tons of ICT scraps generated in 1998, only 26% were collected. In addition, the nature of cell phones (being relatively small) allows them to be easily taken for granted or overlooked during the recycling process and to enter into the solid municipal waste stream, especially landfills. The improper disposal can also exacerbate the risks of environmental contamination and harm to human health because of the toxic materials housed in cell phones [3].

A cell phone is typically made of many components: it is made up of a circuit board (PCB), liquid crystal display (LCD), keypad, antennas, microphones, plastic faceplates, and batteries; however, cell phones made in recent years typically weigh less than 100 grams since they have more than 30 electronic materials and other components that make up a cell phone model. This means that a cell phone's composition will differ due to advances in information technology. Although the composition has changed over the years with the introduction of additional electronic components, the most common toxic electronic materials and metal components in cell phones remain the same.

The circuit board is considered the most toxic component of a cell phone because it has the highest concentration of heavy metals compared to any other component of a cell phone, but there are also other components that have toxic fractions. Specifically, cell phones can contain metals such as cadmium, lead, manganese, and nickel as well as organic chemicals such as brominated flame retardants (BFRs), polycyclic aromatic hydrocarbons (PAHs), and polyvinyl chloride (PVC). When cell phones are disposed of inappropriately, they can introduce substantial amounts of their toxic constituents into the environment. As a result, the most common methods for managing electronic waste (e-waste) are landfills and incineration; thus, both methods pose serious environmental and human health problems. For example, electronic waste disposed of in a landfill can corrode and physically degrade, causing the hazardous materials and metals to leach into the subsurface environmental, contaminating groundwater and nearby water bodies.

This pathway has been demonstrated through multiple studies focusing on key heavy metals. Lead, a common constituent in PCBs and solder, has been shown to leach from landfills into drinking water supplies. Likewise, mercury, historically found in various electronic components, can leach into surrounding soils. Once mobilized, these contaminants pose serious biological hazards to all biota, including human populations, ranging from immediate effects such as skin and stomach irritation to chronic conditions like dermatitis, damage to the kidney and lungs, nerve tissue impairment, and potentially death [4].

Therefore, the evaluation of the physical and chemical solubility and mobility of metals, is paramount in the work of the waste management profession and the evaluation of long-term risk to the environment and to the health of the population from landfill sites. The testing methods used to conduct leaching tests provide for the simulation of the environmental conditions under which metals will be leached from a landfill and to evaluate the most extreme/maximum contaminant concentrations of those hazardous metals when the metals are leached and then solubilized and made mobile [5]. Heavy metals in landfilled waste are extremely susceptible to changes in the physical and chemical conditions surrounding them; particularly changes in pH. Leaching studies have indicated that, in the acid phase of the decomposition of MSW, the leachability of lead and many other hazardous waste metals will be drastically increased by the acidic conditions [6] Presently, as the landfill continues to mature and transition to a methanogenic state (where the landfill's waste product is no longer in an acid phase) and when the landfill reaches a pH of greater than 7.0, the solubility and mobility of metals, including lead, are generally reduced. Therefore, understanding the release of metals when they are in an initial condition (i.e. Lower than 7.0 pH) is important for understanding the events that lead to contamination via contact with water that happens Phase I, Long before the bulk waste mass reaches its Chemical Stability point. [5-6]

Due to the rate at which obsolete cell phones are entering the waste stream and the fact that some contain significant amounts of toxic metals, this necessitates a thorough investigation of the potential environmental impacts of these products.Empirical data will be provided for the hazard load and mobility characteristics of these products under conditions that simulate disposal scenarios.

- To perform a detailed gravimetric and elemental characterization of obsolete cell phone components to establish the distribution and total content of toxic heavy metals such as Pb, Cd, Mn, and Ni.
- To determine the long-term leachability of heavy metals from segregated components and entire phones by evaluating the impact of Liquid-to-Solid (L/S) ratio and contact time under simulated conditions associated with typical domestic waste landfills.

II. MATERIALS AND METHODOLOGY

2.1 Sample Procurement and Disassembly

Obsolete, end-of-life cell phone units encompassing various makes and respective models were collected primarily sourced from mobile phone repair shops, friends, and relatives. All collected samples were coded, recorded, and manually dismantled within the laboratory environment. Tools utilized for partial disassembly included mobile screwdriver sets, a hammer, a cutter, pliers, and stainless steel screw-drivers.

2.2 Gravimetric Analysis and Component Segregation

Five (5) main functional categories were recognized for all of the disassembled components: PCB (printed circuit board); LCD; plastic case; metal parts; and battery. Each of these grouped components and the overall assembled electronic device were weighed using a scale that has been calibrated. The scale was used to allow for a quantitative evaluation of how much each grouped component contributed to the overall weight of the assembled electronic device and provide an opportunity to perform a comparison of the weights of different brands and models. The grouped components will be stored in airtight, heavy gauge plastic bags until they are needed for future experimentation.

2.3 Determination of Total Metal Concentration

E-waste is an example of how complicated devices can present problems for chemical analysis. The challenges associated with determining the concentration of hazardous metals such as lead (Pb), cadmium (Cd), manganese (Mn), and nickel (Ni) in fractions segregated by the type of device are due to the physical complexity and possible heterogeneous nature of those devices. A method that has been developed to assist in the determination of hazardous metal concentrations in e-waste fractions is the Acid Digestion process.

1. Acid Digestion Process: The fractions collected in Section 2 were digested with Aqua Regia ($HNO_3 + 3HCl$) to solubilise and dissolve metals. Aqua Regia is a very strong oxidizing agent that will dissolve most metallic components within a sample. By using Aqua Regia, it is possible to determine the quantity of available metals in a sample of e-waste.

2. Instrumental Analysis: After digestion, the metal concentrations in the resulting solutions were quantified by means of FAAS methods.

2.4 Long-Term Leaching Test Design

The objective of the leachate analysis was to determine the amount of solubility of the metals over time and changing amounts of leachate. These changes are representative of the effects of potential future long-term exposures to leachates from landfills.
Simulated Landfill Conditions and Leachate Medium The leachate medium used in this study was deionized water (DIW). Deionized water will have a pH which is normally very close to that of neutral pH. In this respect, the presence of unpolluted water (like rain) flowing into the municipal landfill is similar to the influence of DIW. In fact, by using DIW as the leachate medium, it is possible to assess the release of metals from the waste after the initial saturation of municipal solid waste into a landfill environment before the bulk decomposition of solid waste develops an extremely acidic or chemically complex leachate environment.

Kinetic Testing Parameters and Liquid-to-Solid (L/S) Ratios: The long-term leachability tests were performed using batch tests in the ambient temperature range of 28-33 oC using an Orbital Shaker Incubator running at 52 rpm to determine cumulative leaching at multiple L/S ratios (1:2, 1:8, 1:10, and 1:100) and operation times of 6, 18, and 24 hours (as shown in Table 1). The L/S ratio was assessed to determine the potential leachability of a material due to different conditions such as hydrologic saturation and hydraulic application methods. In general, lower L/S ratios (e.g. L/S = 1:2, L/S = 1:8) indicate an environment with a concentrated amount of the leachate being used during the test. These ratios are representative of an initial state where the contaminants are largely confined within the pores of the material being tested. While higher L/S ratios (e.g. L/S = 1:10, L/S = 1:100) with extended

duration (up to 24 hours) are indicative of conditions that would represent a sustained release, they also provide an opportunity for a maximum possible release of contaminants over time through continuous dilution of the leachate with water, or multiple reapplication of the leachate during the duration of the test. In this way it is possible to observe the differences in the kinetics of contaminant leaching associated with the two types of release mechanisms (rapid surface-bounded leaching and slower, diffusion-controlled releases).

TABLE I:
LOADING AND OPERATIONAL DETAILS OF THE LONG-TERM LEACHING STUDIES

Particulars	**A (L/S 1:2)**	**B (L/S 1:8)**	**C (L/S 1:10)**	**D (L/S 1:100)**
Cell phone fraction (g)				
Battery	17.5	17.5	17.5	17.5
Liquid Crystal Display	5.2	5.2	5.2	5.2
Metallic Parts	11.0	11.0	11.0	11.0
Plastic Housing	14.0	14.0	14.0	14.0
Printed Circuit Board	11.1	11.1	11.1	11.1
Whole Set	35.8	35.8	35.8	35.8
Operation time (h)	6	18	24	24

Leachate Separation and Physicochemical Analysis: Following the shaking period, the solid residue was separated from the leachate solution. The solution was subsequently analyzed for its pH, Electrical Conductivity (EC), and the concentration of leached heavy metals (Cd, Mn, Ni, Pb) using FAAS.

III. RESULTS AND DISCUSSION

3.1 Characterization of Obsolete Cell Phones

The gravimetric contribution of the parts that made up the different cell phones was examined as part of the characterization phase to allow for the calculation of the contribution of each of the separated components. This provided the basis for assessing the viability of recycling and assessing risks. The comparison was done on cell phones of the same make and model and those of different makes and models. The weight contributions of cell phones made by the same manufacturer and model were generally consistent with one another. The plastic component contributed the greatest weight, which was approximately 25 to 26g of the total weight of each cell phone. Each of the Printed Circuit Board (PCB), Metal Fraction, and Battery contributed between 17 to 20g. The Light Display (LCD) contributed between 6 to 7g of the total weight; both Rubber and LCD contributed less to each of the total weights of all 4 components.

When examining cell phones of different manufacturers and models, there was much more variability in weight contributions. All cell phones contained plastic, which contributed 17 to 29g of the total weight of each cell phone. However, there was a large amount of variation in the weight of the 3 core functional components. The Batteries contributed weights that ranged from 16 to 46g. The PCB weights varied from 13g to 29g. The weights of the Metal Fraction components ranged from 2g to 17g. This large amount of variability in composition of cell phones from different manufacturers has significant implications for the recovery and processing of materials from these products and customarily occurs with cell phones or other electronic devices that are manufactured by a variety of different manufacturers.

Standardized bulk handling systems designed for general e-waste may fail to efficiently recover valuable resources or mitigate hazards when the embedded material content (and thus, the appropriate treatment technology) fluctuates widely across incoming feedstock. This suggests a need for advanced sorting technologies or model-specific treatment protocols to optimize recycling yields and safety [7-8].

TABLE II:
SUMMARY OF GRAVIMETRIC ANALYSIS: COMPONENT WEIGHT CONTRIBUTION

Cell Phone Component	**Weight Range (Same Make/Model, g)**	**Weight Range (Different Make/Model, g)**
Plastic Housing	25.0 – 26.0	17.0 – 29.0
Printed Circuit Board	19.0 – 20.0	13.0 – 29.0
Battery	17.0 – 18.0	16.0 – 46.0
Metallic Fraction	19.0 – 20.0	2.0 – 17.0
Liquid Crystal Display	6.0 – 7.0	3.0 – 6.0
Rubber	1.3 – 1.5	0.5 – 4.9

3.2 Total Toxic Metal Analysis

The complete identification of heavy metals in materials allows for complete assessment of the overall hazards associated with using the materials in their respective fractions, as described in this study. The Acid Digestion method using FAAS determined the amounts of Cadmium (Cd), Manganese (Mn), Nickel (Ni), and Lead (Pb) found in the various fractions of used cell phones. Manganese (Mn) was detected in every fraction, with detected concentrations ranging anywhere from 2–25 mg/cell phone. The fractions containing the highest concentration of Mn generally contained a greater proportion of the metallic fraction. Nickel (Ni) was also found in greater amounts, with detected levels ranging from 20-40 mg/Cd and predominantly found within the Metallic and PCB fractions. Lead (Pb) was detected in similar amounts, ranging from 15-35 mg/Pb and was generally highest in the PCB and Battery fractions. Cadmium (Cd) was detected in a range from 29-34 mg, with the highest concentration located within the Liquid Crystal Display (LCD) and Plastic Housing fractions. The concentrations of each of the heavy metals found in the fractions varied from one type of component to another and from cell phone to cell phone, even among models that were similar. The heavy metal concentrations that were found were particularly significant for Cd. The concentrations for Pb found in the PCB and Battery fractions are well-known and have been a concern to regulatory authorities. The large amounts of Cd (29-34 mg) detected in the LCD and Plastic Housing fractions represent a significant, but often underappreciated, environmental risk. These non-metallic fractions are frequently managed differently than PCBs and often end up in less stringent recycling or disposal streams (e.g., plastics sent for reclamation or incineration). If the plastic housing or LCD is landfilled, the high Cd content poses a significant risk of contamination. If incinerated without adequate pollution controls, Cd—which is highly volatile—could lead to atmospheric emissions. Thus, specialized management of the plastic and display components must be prioritized to safely isolate the Cd inventory [9-11].

3.3 Physicochemical Characteristics of Leachate

Leaching analyses were conducted while also monitoring several physicochemical parameters of the leachate to understand the metal's leaching behavior under the defined leaching conditions to develop an understanding of how these factors relate to the leachate's composition as well as how these parameters influence the leaching characteristics of the materials tested via the leaching analyses. Leaching Conditions - pH effects: The pH of the leaching solution is critical to understanding the potential for movement of heavy metals because the heavy metals present in the leachate have a high dependency on pH. The pH values for all leachates produced from all fractions of the cell phones, at every L/S ratio (6-24 hrs) tested were all in the range of 7.0-8.0. That indicates the leachates have remained within the neutral/mild alkaline ranges throughout the entire long term study and therefore the leachates and the leaching environment reflect the same environment that heavy metals experience during the time that precipitation takes place and interacts with the original mass of waste disposed of. Heavy metals move into solution from the formation of complex metal ions through the exchange of H+ ions with the metal ions, therefore it can be assumed that these forms of leaching kinetics have occurred in a non-acidic, less aggressive chemical environment.

Electrical Conductivity (EC): Electrical conductivity (EC) is a proxy measurement for the total amount of dissolved ions present in the leachate. The results indicated that the EC decreased gradually as the L/S ratio increased over time. This trend is indicative of two key kinetic processes. First, there is likely an initial rapid flush of highly soluble surface-bound salts or readily dissolved ions during the early phase (low L/S, short time). Second, as the ratio of liquid to solid increases, the concentration of these dissolved ions drops due to dilution. The overall decrease over time, despite long contact periods (up to 24 hours), suggests that the inventory of easily mobile, water-soluble ionic species is limited. Subsequent long-term release would likely require chemical degradation of the bulk component matrix, which does not occur readily under neutral pH conditions.

3.4 Toxic Metal Mobilization Assessment

The study of toxic metal leachability is fundamental for assessing the long-term environmental impact of e-waste disposal. Leachate solutions were analyzed for the concentrations of Cd, Mn, Ni, and Pb across the varying L/S ratios and time intervals.

Comparative Leachability of Heavy Metals: The overall findings demonstrated that the leaching potential for Cadmium (Cd) and Nickel (Ni) was markedly higher compared to Manganese (Mn) and Lead (Pb). This high variability in solubility confirms that, even within a single disposal environment, different metals behave according to their unique chemical characteristics.

Mobility of Lead (Pb) and Manganese (Mn): All tests showed that, even though lead had a total inventory of 15 to 35 mg/cell phone, lead only leached as trace from all tests. This is due to the mild alkaline pH of the leachate solution (7 to 8). These pH levels are above the solubility of lead compounds (especially those formed with water and atmospheric carbon dioxide, such as lead carbonates). The non-acidic leaching environment prevented significant physical mobilization of lead, thereby stabilizing the overall lead inventory in the cell phone. Thus, the risk of lead in the environment is primarily dependent on the generation of acidic conditions in the landfill which can occur during the acidogenic phase of municipal solid waste breakdown. Manganese leached from cell phones and had a similar trend to cadmium; however, manganese was present in low amounts in comparison to the other metals [5].

Nickel (Ni) and Cadmium (Cd) Mobility: Nickel has more leachable potential than Lead. Moreover, when performing leaching tests based upon varying liquid-to-solid (L/S) ratios it was determined that an increasing L/S ratio provides greater resistance to leaching. The most substantial outcome of the research was that the maximum quantity of nickel leached occurred within the plasticky fraction. The high degree of mobility of nickel from plastic, which is a nonmetallic substance, indicates that nickel is not physically adhered to any metallic alloys. Nickel likely exists as either soluble salts, stabilizers or pigments that can readily disassociate into solution through direct contact with water. Consequently; when mechanical separation of metallic fractions occur, the plastic containers are still a major contributor to Ni contamination in the environment.

Cadmium (Cd) has the highest potential for leaching among all metals tested. At each increase in the ratio of volume of solution to dry weight (L/S), there was an increase in the amount of Cd leaching from the sample, with the highest amount of Cd being leached from the sample at the highest dilution (L/S 1:100). Cadmium was most easily leached from the Whole Set fraction of the samples. The fact that a significant amount of Cd continued to leach from this sample even at the highest L/S ratios indicates that Cd is present in forms that are very mobile and that the leaching will not be limited to surface wash-off of the sample. Furthermore, the continual increase in the leaching of Cd with the addition of more water to the sample indicates that this metal may cumulatively contribute to a leaching event that will last for an extended period of time and at higher hydraulic flows, resulting in a persistently high risk of contamination to the groundwater that is sustained under typical landfill conditions [12].

The pronounced and sustained mobility of Cd, coupled with its known high concentration in the plastic and LCD components, establishes Cadmium as the most critical and immediate contaminant released from obsolete cell phones under non-acidic landfill simulations [13].

TABLE III:
HEAVY METAL CONCENTRATION IN LEACHATE UNDER VARYING L/S RATIOS

Metal	Component	(L/S 1:2) mg/L	(L/S 1:8) mg/L	(L/S 1:10) mg/L	(L/S 1:100) mg/L
Pb	PCB	0.03	0.05	0.07	0.09
Cd	Plastic	0.25	0.31	0.38	0.45
Ni	Plastic	0.22	0.29	0.33	0.41
Mn	Metal	0.05	0.07	0.09	0.12

3.5 Correlation and Statistical Analysis

Pearson correlation analysis showed a strong positive correlation ($r = 0.89$) between total Cd content and leachability, suggesting Cd's high environmental mobility. ANOVA confirmed statistically significant differences ($p < 0.05$) between metals across L/S ratios.

TABLE IV:
CORRELATION MATRIX BETWEEN TOTAL METAL CONCENTRATION AND LEACHABILITY

Metal	Correlation coefficient (r)	p- value	Significance
Cd	0.89	< 0.01	Strong positive correlation
Ni	0.82	< 0.05	Positive correlation
Pb	0.41	> 0.05	Weak correlation
Mn	0.58	> 0.05	Moderate correlation

IV. CONCLUSION

Old Cell Phones represent. A complex, developing segment of the global waste stream. Old Cell Phones are complicated due to many different kinds. Old Cell Phones are an Environmentally Sensitive Waste. Why are Old Cell Phones sensitive? Because they contain a lot of hazardous substances. Old Cell Phones contain Large Amounts of Hazardous Heavy Metals. Hazardous Heavy Metals include Nickel, Lead, Manganese, and Cadmium! Gravimetric Analysis of Cell Phones has shown that the Composition of Cell Phones is varied among Models.

All cell phone models have Plastic, Battery, and Circuit Boards (PCBs); however, Different Models have Different Composition of Materials Used to Create the Cell Phones; therefore, Because of Indications from Gravimetric studies, and Subsequent Total Metal Analysis, PCB/Battery compositions represented a Very Large Inventory of Lead (Pb) and Cadmium (Cd) due to the Presence of Parts Positioned Close to Each Other within the PCB/Battery assembly(s) and the Associated Amount of Material that Contained Pb/Cd. Long-term Leaching Studies Conducted using Neutral to mildly alkali pH 7-8 Conditions Showed that there is a Different Mobility of Metals Within a Landfill Once the Landfilling Process is Complete. For example, the leaching behavior of Pb is significantly inhibited in the Alkaline Environment. Pb exhibited little if any leaching because the Alkaline Environment inhibited Pb movement.

Nickel and Cadmium had a high solubility and Leaching Potential, with Nickel showing the greatest concentration of release from the plastic fraction. This indicates that metal Hazardous Materials should not only be identified as metallic components. While the release of Cadmium increased with the increase in the Liquid to Solid ratio, this study also concluded that Cadmium is a mobile and persistent threat to the environment and that there is a cumulative effect of release from landfills. The data shows that conventional landfill disposal methods do not adequately manage the obsolescence of cell phones. Specifically, the presence of Mobile fractions of Cadmium and Nickel is not contained through conventional landfill methods. Furthermore, the exportation of E-Waste to developing nations where uncontrolled recycling methods such as burning and acid dissolution are employed causes extreme localized contamination and adverse Health effects for workers and their communities.

The management of WEEE should shift away from using Traditional disposal methods and move towards using specialty Reprocessing technologies for the recovery of Valuable Materials while minimizing detrimental environmental effects. Strategies for Management should focus on aggressive segregation and stabilization of High-Risk Components, particularly plastics and LCDs, in order to mitigate the immediate and Long-Term Risks associated with the mobilisation of Cadmium and Nickel independent of pH conditions present in leachate.

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