Promoting Responsible Recovery and Handling of Mercury from Contaminated Artisanal Gold Mining Tailings in Colombia.

Technical protocol for the responsible management of mercury-contaminated tailings in Colombia.

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Introduction

This technical protocol and regulatory review for the management of tailings from artisanal gold mining in Colombia, is executed under the development of the project entitled: "Promoting the recovery and responsible management of mercury in contaminated tailings from artisanal gold mining in Colombia" (hereinafter the "Project"), which is executed by Pure Earth and funded by the U.S. Department of State.

The overall objective of the Project is to reduce the amount of mercury present in tailings from the use of this element in Artisanal and Small-scale Gold Mining (ASGM) in the country, such type of mining is regulated in Colombia by Decree 1666 of 2016 under the denomination of subsistence and small-scale mining. The specific objectives of the project are:

- Identify promising mercury recovery techniques and increase understanding of criteria for choosing a technique for use in the Colombian ASGM context.
- Develop a model for the responsible and profitable recovery of mercury and gold tailings, based on experiences in experimental processing plants.
- Develop technical protocols to safely handle, store and dispose of the mercury recovered or seized from ASGM activities, including contaminated tailings and the captured mercury from amalgam burning.

This document is developed in the framework of the third specific objective of the Project, which will include information on the integrated management of tailings and mercury recovered in the implementation of the technical schemes developed in objectives one and two of the Project. Additionally, there are some opportunities for improvement in technical and administrative capacity identified from working groups carried out in the framework of the project, which are aimed at the integrated management of tailings from small-scale and subsistence mining activities, as well as mercury recovered in these processes or that may be seized.

The support and direct support of the National Center for Cleaner Production and Environmental Technologies (CNPMLTA), who have been partners in the development of this document and the Project, is noteworthy. In addition, during the execution of the Project there has been collaboration with the Ministry of Environment and Sustainable Development (MinAmbiente), the Ministry of Mines and Energy (MinEnergia), but there has also been interaction with other government agencies such as National Parks, National Police, National Army, Attorney General's Office, Corantioquia, Government of Antioquia, among others, as well as approaches with groups of artisanal miners and cooperatives in the municipalities of Yalí, Cisneros and San Roque, among other actors linked to the activities.

Finally, it should be noted that this Project and all documents derived from it, are aimed at strengthening compliance with the Minamata Convention approved by the Congress of the
Republic through Law 1892 of May 11, 2018 in terms of providing information that serves as input for the fulfillment of the country’s responsibilities under Article 7 of the Minamata Convention in the scope of Artisanal and Small-scale Mining (ASM), Article 11 on mercury waste and the Single National Mercury Plan.
1 Scope

This document is focused on presenting the most relevant technical parameters under the current Colombian context, in the identification of improvement opportunities oriented to an adequate integral management of tailings from subsistence and small-scale mining activities, which in most cases contain mercury concentrations that can generate a risk to human health and the environment, according to the reference limits established by international agencies (EPA US 2020), taking into account that at the date of preparation of this document no reference values have been defined under national legislation.

From the technical point of view, the aspects contained herein are mainly focused on the evaluation and analysis of total mercury, including its elemental state (Hg°) and its other chemical forms such as inorganic and organic, such as methyl mercury.

Likewise, illegal active mining activities will not be taken into account, where the use of mercury is no longer allowed, only those tailings that have been abandoned by mining operations prior to June 2018 and that in their composition persist with mercury concentrations will be taken into account.

The aspects contained in this protocol may be taken as alternatives to complement the management of contaminated sites and environmental liabilities that have been generated by the mismanagement of mercury-contaminated tailings.
2 Background

The Colombian government, through MinAmbiente and MinEnergia, has worked continuously to strengthen the management of the different mining activities and their environmental impact, including both the regulatory framework and projects to promote mercury-free technologies. However, one of the problems that still needs attention and continued efforts to improve management are the mercury-contaminated tailings generated mostly by gold mining. In particular, subsistence and small-scale mining used mercury as a technique to obtain gold, but criteria have never been defined for storing, classifying, handling and properly disposing of mercury-contaminated tailings.

Since 2010, the first negotiations of the Minamata Convention were developed under the representation of the Ministry of Foreign Affairs and MinAmbiente. Subsequently, in July 2013, Law 1658 was issued, which establishes the regulation of the use, importation, production, commercialization, handling, transport, storage, final disposal and release to the environment of mercury in industrial activities, whatever they may be, in order to protect and safeguard human health and preserve natural resources and the environment. This law also prohibits the use of mercury in mining activities as of July 2018 and the use of mercury in any other industrial sector as of 2023.

In October 2013, Colombia together with 128 countries signed the Minamata Convention, committing the country to develop actions aimed at reducing and eliminating the use of mercury. In line with the convention, Law 1658 gave rise to the Single National Mercury Plan, which was presented in December 2014, subsequently updated and signed on August 6, 2018 and establishes guidelines on technology transfers, use of clean technologies, training and awareness on the use of mercury and products containing mercury, minimizing its impact and protecting human health and the environment.

In May 2017, together with MinAmbiente, CNPMLTA and the United Nations Industrial Development Organization (UNIDO) developed the project entitled "Early Preparation for the Minamata Convention on Mercury", which had among its key components the identification of institutional gaps and barriers, a review of existing regulations related to mercury and the identification of policy reforms necessary to prepare for the implementation of the Minamata Convention, in addition to establishing the national profile of mercury, based on the initial inventory.

Finally, with Law 1892 of May 11, 2018, the Congress of the Republic approves the Minamata Convention on Mercury, which was declared constitutional by the Constitutional Court in June 2019 and was deposited in August of the same year before the United Nations Organization.

In parallel, the MinEnergia adopted the National Mining Policy through Resolution No. 40391 of April 20, 2016¹, which states that "[...] The fundamental objective is that the mining activity

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¹ Resolution 40391 of 2016 (April 20) Whereby the National Mining Policy is adopted.
in all its scales, is developed in an orderly, inclusive, competitive and responsible manner...". which includes the management of the environmental impacts that these activities may generate.

Among the highlights of this policy is the generation of tools and strategies to support miners so that with the help of the State they can formalize their activity and improve their living conditions, as well as the need for coordination between the different levels of the State to eliminate the use of mercury in mining activities. Within the framework of the Single National Mercury Plan in 2016, MinEnergia formulated its strategic plan on mercury.

Under this policy, in early 2019 a series of guides entitled “Methodological guides for the productive improvement of gold beneficiation without the use of mercury”, were published, studies conducted for gold mining areas in Antioquia, Cauca, Nariño, Huila and Caldas. These guides not only describe purely technological elements, but also consider economic and financial analyses, in order to establish the convenience of successfully undertaking a mining project and making an efficient allocation of resources. Likewise, the guides provide the methodological foundations, minimally necessary, so that the miner can carry out a planning exercise and financial evaluation of the future operation of his beneficiation plant, using a metallurgical route proposed for the development of these guides and economic models.

On the other hand, two legal instruments that contemplate important aspects in tailings management are Decree 1073 of 2015 of the administrative sector of mines and energy, Law 685 of 2001 (Mining Code) and Decree 1076 of 2015 of the environment and sustainable development sector respectively.

Although the advances in technical and regulatory aspects in the control of mining activities in reference to gold extraction and the non-use of mercury are significant, it is still required to increase efforts in the comprehensive management of tailings, since they continue to present a current problem due to potential for stockpiled tailings to present a risk to human or ecological health, as well as evidence that they are still using mercury illegally, i.e., mercury-contaminated tailings are being generated adding to those that had already been generated before the ban in 2018. Therefore, the negative impact on the environment and people's health is still occurring.

The reasons for this situation can be both diverse and complex, but include the social context of small and subsistence miners, schooling and culture; because the health effects of mercury are long-term, many miners consider these to be non-existent. The same happens with the lack of availability of alternatives in mining areas, complexity and costs of mercury-free technologies compared to the use of mercury, disputes over mining titles with large-

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2 Decree 1073 of 2015 (May 26) Whereby the Sole Regulatory Decree of the Administrative Sector of Mines and Energy is issued.

3 Law 685 of 2001 (August 15) Whereby the Mining Code is issued and other provisions are issued.

4 Decree 1076 of 2015 (May 26) Whereby the Sole Regulatory Decree of the Environment and Sustainable Development Sector is issued.
scale mining, difficulty in accessing environmental permits, lack of space for dialogue and negotiation tables with all interested parties, lack of clarity in management procedures by the national government and municipal administrations, the lack of clarity in management procedures by the national government, These are not part of the scope of this project, but it is clear that all efforts add up to achieve an integrated management of tailings, considering the term management as the set of operations or actions that are developed to achieve a specific objective, in this case to control the existing impact of mercury in the tailings.
3 Definitions

Considering the scope of this document, it is important to be clear on some of the definitions that relate to the management of tailings from small-scale gold mining activities. Many of these definitions are already contained within the current legal legislation, however, there are some terms that are taken from international references.

Mining Wastes

Mining wastes correspond to the material resulting from leaching and ore concentration processes containing very little valuable metal, which can be reprocessed or disposed of. (Minminas, Resolución 40599 . Glosario Minero 2015)

Mercury compounds

Means any substance consisting of mercury atoms and one or more atoms of different chemical elements that can be separated into different components only by chemical reactions: mercury (I) chloride or calomel, mercury (II) oxide, mercury (II) sulfate, mercury (II) nitrate, cinnabar ore and mercury sulfide. (Minamata Convention) (ONU 2019).

Mercury Waste

Means substances or objects: (a) consisting of mercury or mercury compounds; (b) containing mercury or mercury compounds; or (c) contaminated with mercury or mercury compounds, in an amount exceeding relevant thresholds defined by the Conference of the Parties, in collaboration with the relevant bodies of the Basel Convention in a harmonized manner, the disposal of which is undertaken, proposed to be undertaken or required to be undertaken under the provisions of national legislation or this Convention (Minamata Convention) (ONU 2019).

Risk management

It is the social process of planning, implementation, monitoring and evaluation of policies and permanent actions for the knowledge of risk and promotion of greater awareness of it, prevent or avoid its generation, reduce it or control it when it already exists and to prepare for and manage disaster situations, as well as for subsequent recovery, understood as: rehabilitation and reconstruction. These actions have the explicit purpose of contributing to the safety, well-being and quality of life of people and to sustainable development (Decreto 1076 de 2015)

Tailings pond

1. Depression used to confine the tailings resulting from the beneficiation process.
2. Area whose lower limit corresponds to a retaining wall or dam, towards which the effluents from the beneficiation flow, whose first function is to allow sufficient time for the sands and heavy metals to settle or for the cyanide to be destroyed before the "clear" water is discharged or recirculated to the mill (Minminas, Resolución 40599 . Glosario Minero 2015).
Tailings

Considering that to date there is no definition of the term "Tailings" within the current legal legislation, for this document the same definition of Tailings is adopted. *Tailings correspond to the material resulting from leaching and mineral concentration processes that contains very little valuable metal, which can be treated again or disposed of.* (Minminas, Resolution 40599. Mining Glossary 2015). (Minminas, Resolución 40599. Glosario Minero 2015)

Tailings Pool "Relavera"

Considering that to date there is no definition of the term "Relavera" within the current legal legislation, for this document the same definition of "Tailings Pond" is adopted.
1. *Depression used to confine the tailings resulting from the beneficiation process.*
2. *Area whose lower limit corresponds to a retaining wall or dam, towards which the effluents from the beneficiation process flow, whose first function is to allow enough time for the sands and heavy metals to settle or for the cyanide to be destroyed before the "clear" water is discharged or recirculated to the mill.* (Minminas, Resolución 40599. Glosario Minero 2015).

Mining waste

1. Residues resulting from the extraction and exploitation of minerals.
2. Cuttings, tailings, tailings, wastes and slag resulting from mining and metallurgical activities. (Minminas, Resolución 40599. Glosario Minero 2015)

Hazardous waste

It is that residue or waste that, due to its corrosive, reactive, explosive, toxic, flammable, infectious or radioactive characteristics, may cause risks, damages or undesired effects, direct and indirect, to human health and the environment. Likewise, packaging, containers and packaging that were in contact with them will be considered hazardous waste. (Decreto 1076 de 2015)

Risk

Probability or possibility that the handling, release to the environment and exposure to a material or waste will cause adverse effects on human health and/or the environment (Decreto 1076 de 2015)

Mercury contaminated site

Contaminated sites, according to Article 12 of the Minamata Convention, are considered to be those areas that are contaminated with mercury or mercury compounds and can generate harm to human health and the environment. (ONU 2019).
4 Importance of tailings management

The management of waste generated in mining operations, especially tailings, despite being included in the environmental obligations assumed by mining operators, generally presents a significant financial burden, even more so in the case of subsistence and small-scale mining.

Although this type of mining should assume the correct management of tailings, they often do not do so because they do not have access to a documented or practiced and economically viable management alternative, for example, miners who develop the activity of barequeo do not have the resources to build tailings dams or treat tailings. And although mercury is already banned, it is still used illegally, resulting in a growing number of mercury-contaminated tailings in need of attention and management.

According to the European Commission, the final management of tailings could have the following alternatives, as long as they comply with the conditions of non-presence of contaminants (European Commission 2009):

- Disposal of tailings in suspension in ponds or pools.
- Backfilling tailings or waste rock in subway mines or open pits or using them for tailings dam construction.
- Stacking dry tailings in the open air.
- Use of tailings and waste rock as a land use product, as aggregate, for restoration or backfill.

The management of tailings under mining title lands should be the responsibility of the title holder, however, the big problem lies in those tailings that are abandoned on land outside of a mining title and therefore have no one responsible for their management. The alternative of reprocessing tailings to obtain an economic return, such as obtaining residual gold, eliminating the mercury previously present, should be considered in accordance with the provisions of the mining and environmental authorities.

In this order of ideas, under the concepts of environmental aspect, environmental impact and risk, it is possible to identify the conditions that usually present abandoned tailings with mercury content (CEPAL 2003):

Table 1. Risk conditions of mine tailings in Colombia.

<table>
<thead>
<tr>
<th>Environmental Aspects</th>
<th>Environmental Impact</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abandonment of tailings with the presence of mercury and other substances of</td>
<td>Environmental contamination by the release of mercury and other substances of health interest present in the tailings through</td>
<td>• The probability of contamination of the environment by mercury emissions and releases in the different environmental components is extremely high, even more it can be said that it is a reality that is lived in the country.</td>
</tr>
</tbody>
</table>
sanitary interest without proper environmental protection measures, often deposited in sacks or direct soil, exposed to the elements, near water sources and vulnerable populations.

- leaching into the soil and water sources, but also mercury emissions into the air by evaporation.
- Spread of mercury in the biotic environment entering the trophic chain that ends up affecting health by ingestion of contaminated food, especially large fish.
- Generation of contaminated sites that can cover larger areas due to the migration of mercury and other pollutants.
- High probability of affecting human health due to exposure to vapors, bioaccumulation, biomagnification, contact or ingestion of food contaminated by the presence of mercury in the food chain.
- The probability of generating impacted sites is extremely high, even more it could be said that it is already a reality in the country.
- The probability that a person will be sanctioned for abandonment of tailings and environmental contamination is moderate, because there are no frequent complaints or operations for this fact yet, however, in case of being presented their legal situation would be seriously affected.
- Economic, disciplinary and judicial sanctions for those who carry out this bad practice of abandonment or improper disposal of contaminated tailings.

| Source: Own elaboration. By way of convention, this table uses qualitative risk descriptions of low, moderate, high and extremely high depending on the probability of occurrence and severity of the impact. |
| The International Commission on Large Dams (ICOLD) has produced a bulletin entitled "Tailings Dams: Risk of Hazardous Occurrences, Lessons Learned from Practical Experience". The Bulletin has compiled 221 cases of known tailings dam accidents and incidents. It indicates that in the decade from 1979 to 1989 there were 13 major tailings dam failures. Between 1989 and 1999, 21 events have been reported. From an assessment made, the Bulletin mentions the following causes that led to the failures (CEPAL 2003):

- Inadequate management of tailings disposal.
- Failure to detect foundation conditions.
- Lack of control of the hydrological regime.
- Uncontrolled drainage.

In addition to the physical and control failures identified, in Colombia there is also the risk of contamination due to the presence of chemical substances of sanitary interest, such as mercury, lead and cyanide, since the combination of these effects can result in the generation of contaminated sites that are difficult to intervene.

Although the scope of this protocol is focused on the management of mercury-contaminated tailings, the relationship with the potential for the generation of contaminated sites due to these tailings is direct, so the options presented here also contribute to the management of a site impacted by mercury.
5 International reference context

The normative experiences and international technical guides that have been generated in favor of tailings management are of great help to propose solutions in the Colombian context from the technical and legal point of view. The most relevant approaches that have been developed in other countries are presented below:


- Recognizes that the sustainable management of mineral resources and metals contributes significantly to the achievement of the Sustainable Development Goals.
- Emphasizes the need to share knowledge and experiences regarding regulatory approaches, practices, technologies and implementation strategies for the sustainable management of mineral resources and metals, including throughout the life-of-mine and post-mining phase.
- Encourages governments, companies, non-governmental organizations, academia and international institutions, within their different areas of competence, to promote:
  a) Knowledge of how extractive industries can contribute to the sustainable development of countries and the well-being of their populations, as well as the potential negative impacts on human health and the environment, when these activities are not properly managed;
  b) Best practices in due diligence along the supply chain to address broader environmental and human rights, labor issues and conflict-related risks in mining, including the continued enhancement of transparency and anti-corruption, supported by the implementation and monitoring of environmental standards and accountability by the Extractive Industries Transparency Initiative;
  c) Capacity-building mechanisms for the sustainable management of mineral resources and metals, in particular the management of severe risks, as well as for addressing mine closure needs and the rehabilitation of contaminated sites, including abandoned mines;

(Naciones Unidas 2019)
Guidance Document (Minamata Convention)

This is the most important reference in the international context and one of the few that refers specifically to the management of mercury-contaminated tailings. The United Nations Guidance Document entitled "Development of a national action plan to reduce and, where feasible, eliminate the use of mercury in artisanal and small-scale gold mining" (ONU, Medio Ambiente 2017), emphasizes that untreated mercury-containing tailings represent a diffuse but constant source of mercury release to the environment. These mercury-contaminated tailings should never be discharged directly into a water body or in locations prone to flooding.

Disposal of mercury-contaminated tailings should be in accordance with appropriate regulations including liner, depth, distance from water bodies, size, deposition structures, capping, vegetation reestablishment, etc. To date, under Article 11 of the Minamata Convention there are no specific parameters for determining the concentration of mercury wastes. However, the Conference of the Parties, which will be held in November 2021, included the setting of thresholds for mercury wastes in its agenda.

The Berlin II Guidelines on Mining and Sustainable Development 2002

Mining and Sustainable Development 2002

In 2002, the United Nations Environment Programme (UNEP) published a document entitled "Berlin II Guidelines for Mining and Sustainable Development," which stated that, "If sustainable development is defined as the integration of social, economic and environmental considerations, then a mining project that is developed, operated and closed in an environmentally and socially acceptable manner could be considered as contributing to sustainable development." In its Fundamental Principles for the Mining Sector, it states that governments, mining companies and mineral industries should recognize environmental management as a matter of high priority, establish environmental responsibility, and ensure direct stakeholder involvement. (BOTIN 2009)

India

Tailings are regulated under the Minerals Conservation and Development Rules of 1957, as amended in 1958, 1988 and 1994. Under these regulations, the operator is obliged, among other things, to rehabilitate the affected land, prevent pollution and restore the flora. The same policy stipulates that in the event of closure, the closure must be carried out in an orderly and systematic manner and that company employees and members of the community affected by the closure must participate in the respective rehabilitation. In general, the climatic conditions on this continent are favorable for reforesting land affected by mining operations, which has facilitated this aspect of mine closure. However, it does not detail specific requirements regarding the type of tailings or their possible contaminant content (Muñoz, Planes de Cierre Mineros – Curso Resumido 2008).
South Africa

The Mineral and Petroleum Resources Development Act (MPRDA) of 2002 includes as a basic requirement the obligation of companies to present a cost study of future closure, as well as to make the corresponding provision of funds. The law also establishes that companies that have demonstrated good environmental compliance may transfer their responsibilities to the State or to another company, together with the respective funds. The main outstanding issues relate to the reuse of the sites of former closed operations and the restrictions that should be formulated in this respect (e.g., when they involve the agricultural use of potentially contaminated land).

(Muñoz 2008) (Sutton, MW & Weiersbye, I 2008)

A notable aspect of South African legislation is the high degree of personal responsibility assumed for environmental failures. For example, under the provisions of the Department of Environmental Affairs and Tourism (DEAT): "The following persons are responsible for remedying total or partial failures to comply with environmental provisions or for bearing the respective costs:

- Any person responsible for environmental pollution or degradation or who has directly or indirectly contributed to it.
- The owner of the affected land at the time the damage occurred, or his successor.
- The person in control of the land or who had the right to use it when the damage occurred.
- Any person who, through negligence, failed to prevent the activity or process causing the damage.

This regulation, like that of India, also does not go into detail on specific requirements regarding the type of tailings or their possible contaminant content (Muñoz, Planes de Cierre Mineros – Curso Resumido 2008).

Australia

The primary responsibility for tailings and tailings storage facility (TSF) regulation in Australia rests with each state and territory government. While regulatory requirements vary between jurisdictions, common principles apply, including the following:

- Responsibility for tailings disposal and management regulation (including rehabilitation and closure) rests with the mining department or environmental protection agency.
- Responsibility for pollution control and regulation of TSF water discharge rests with the Environmental Protection Agency.
- The objective of regulation is to ensure that tailings management methods and TSFs are safe and stable and non-polluting during operations, and that TSFs remain safe,
stable and non-polluting after closure (this requires ongoing consideration of closure design, construction and aftercare throughout the TSF Life Cycle).

Regulators today expect all TSF design submissions to demonstrate beyond a reasonable doubt that sustainable outcomes will be achieved during operations and post-closure through the application of practicing risk-based design that:

- Fully assesses the risks associated with tailings storage at a particular site.
- Compare the suitability of all available tailings storage methods, particularly those involving tailings dewatering and/or eliminating the requirement to dam excess water within the TSF.
- Demonstrate that the selected tailings storage method will manage all risks within acceptable levels and as low as reasonably achievable. (ICOLD (International Commission on Large Dams) 2013)

Where tailings management actions are likely to have a significant impact on a national issue of environmental significance, they are subject to a rigorous assessment and approval process under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). Matters covered by the EPBC Act include national natural heritage, threatened species, and wetlands of international importance (Australian Government 2016).

Although the document does not refer to mercury contaminated tailings they contain from a legal, administrative and technical point of view quite sound parameters that will be included in the development analysis of this document.

European Commission

Although not a normative document, the technical reference document Best Practices in Tailings and Rock Waste Management (Comisión Europea 2009) compiles a number of interesting technical approaches to tailings pollution prevention.

For the European Commission, the management of tailings generated in mining operations is of great concern as it generally presents an unwanted financial burden on operators. Generally, the mine and mineral processing plant are designed to extract as much marketable product(s) as possible, and the waste and overall environmental management is then designed as a consequence of the process steps applied. There are many options for managing tailings and waste rock. The most common methods are:

- Disposal of tailings in suspension in ponds.
- Backfilling tailings or waste rock in subway mines or open pits or using them for tailings dam construction.
- Dumping more or less dry tailings or waste rock in heaps or hillsides.
- Using tailings and waste rock as a product for land use, as aggregate, or for restoration.
- Dry stacking of thickened tailings.
Dispose tailings to surface water (e.g., sea, lake, river) or groundwater.

Tailings and waste rock management facilities vary greatly in size, from tailings ponds to 1,000-hectare tailings ponds, and from small piles of tailings or waste rock spread over a hundred hectares to tailings nearly 200 meters high. The selection of the disposal system usually depends on the joint evaluation of three fundamental factors:

- Costs
- Environmental performance
- Probability of failure

On the other hand, when an operation comes to an end, the site must be prepared for further use. Typically, at least for the last few decades, site closure and cleanup plans will have been part of the site permit, from the planning stage onwards, and should therefore be subject to periodic updates with every change in the operation and in negotiations with permitting and other stakeholders. In some cases, the goal will be to leave as small a footprint as possible, while in other cases a complete landscape change may be sought. The concept of "design for closure" implies that site closure is factored into the feasibility study of a new mine site and then continually monitored and updated throughout the life cycle of the mine. In all cases, adverse environmental impacts must be kept to a minimum.

In relation to mine tailings, the document sets out best practices for the disposal of cyanide residues used in the different operations but does not mention any specific parameters for the management of mercury in tailings.

United States of America - Environmental Protection Agency (EPA) - USA

The U.S. Environmental Protection Agency has a very special focus on the management of mining waste generated at operations. Initially, although there is the Solid Waste Disposal Act of 1980 (Public Law 96-482), which regulates the issue of hazardous waste in the United States, this law makes an exception according to a classification called "Special Waste", where within its categories are all those wastes that are generated from mining activities among other types of waste.

Mining wastes include wastes generated during the extraction, beneficiation and processing of minerals. Most mining and beneficiation waste from hard rock mining (the mining of metallic minerals and phosphate rocks) and 20 specific mineral processing wastes have been excluded from federal hazardous waste regulations under Subtitle C of RCRA. However, within these categories, none are mentioned in reference to mercury-containing wastes or gold processing tailings, as if any such as copper, lead, and zinc were excepted. (EPA 2009).

On the other hand, the EPA has published a technical document for the Abandoned Mine Site Characterization and Cleanup Manual (EPA US 2000), which compiles all the activities necessary to manage potentially contaminated sites with tailings. Interesting parts of the
document include the regulatory "Toolbox", which compiles all the rules available to project managers in developing strategies for abandoned mine cleanup, through a complex web of sometimes overlapping jurisdictions, laws and regulations covering various environmental media and land ownership locally and nationally.

It also includes a chapter on remediation and cleanup options to be considered when designing and implementing remediation at inactive mine sites with contaminated tailings. This chapter consists of four general sections. The first section discusses technologies with demonstrated effectiveness at mine sites. The second section focuses on emerging or innovative technologies. The third section discusses institutional controls. Finally, the last section identifies sources of information on available technologies and means of accessing this information.

This technical document becomes a fundamental part of the analysis of this protocol.

Peru

Peru stands out as one of the Latin American countries where more specific tailings regulation can be found and referenced. For example:

- Specific requirements for active mining operations (DS N°016/1993/EM, “Reglamento para la protección ambiental en la actividad minero-metallurgica - DS N°40 of 2014”, “Reglamento de protección y gestión ambiental para las actividades de explotación, beneficio, labor general, transporte y almacenamiento minero”,
- Control of permissible limits of contaminants of mining effluents, including tailings (DS N°010-2010-MINAM, “Maximum Permissible Limits for the discharge of liquid effluents from Mining - Metallurgical Activities”).
- Environmental remediation for mining activities (DS N°078-2009-EM. Implements environmental remediation measures in charge of the mining holder who has carried out activities and/or executed projects related to mining activities foreseen in the General Mining Law (DS-Pe-78)

(Ministerio de Minería Chile 2018)

Brazil

In Brazil, Article 225, paragraph 2 of the Brazilian Fundamental Charter (constitution) presents the obligation to recover the impact caused by mining activities, where it is established that the mining company must inform the Ministry of Mines and Energy, by means of a report, the relevant information regarding the environmental issues of the mine.
On the other hand, there is an "Economic Development Plan" which must include information on mineral substances, output volume, reserves, production flow and a Degraded Area Recovery Plan Report, which must include the closure plan and must be approved by the Environmental Protection Agency, required for the granting of the Preliminary License.

Brazil does not have specific regulations regarding mine tailings for the mine closure plan. Consequently, the Environmental Impact Assessment, which includes the requirements of a rehabilitation plan for degraded land, is used to manage the closure plan.

There is no obligation under Brazilian law for the mining company to provide a financial instrument to serve as a guarantee to restore possible environmental damage after the closure stage. However, a catalog of measures is available to ensure physical stability. It highlights the need to implement drainage systems, to prevent flooding, in addition to measures to prevent wind or water erosion and general landslide. (Ministerio de Minería Chile 2018)

Chile

Chile is one of the countries in the region that presents greater mining activity, being this one of its most important economic inputs, therefore, its impact is considerable on the environment and with it its legal regulation issue, this is evidenced in what is related to mining liabilities, contact waters, inadequate environmental management and generation of waste including mining waste (Ministerio de Minería Chile 2018).

The main legal rules or regulations in relation to mining and particularly to mining waste are:

- Mining Code established in Law 18248 of 2011 approved by the Ministry of Mining which is constituted as the legal axis of the mining activity in Chile and is the highest hierarchy mining norm in this country.
- Law 19300 of 1994, where mining liabilities are regulated by the Ministry of Environment, it is entrusted with the task of proposing standards, plans and programs and monitoring in environmental aspects such as waste management, protected areas, contaminated soils, risk assessment of chemicals, recovery and conservation of water resources, genetic, flora, fauna, habitats, landscapes, ecosystems, among other environmental aspects.
- Under the protection of Law 19300 of 1994, it is proposed the approval of a methodology for the Identification and Preliminary Evaluation of Abandoned Soils with Presence of Contaminants and a risk assessment of already contaminated sites in different strategic points of mining exploitation.
- Law 20551 of 2012, regulates the closure of mining facilities by actions of the Ministry of Mining. It establishes the procedures and responsibilities for the approval and monitoring of closure plans for mining activities.
- Environmental Qualification Resolution (REA), which corresponds to one of the requirements of the closure plan.
• Law 2055 of 2011 corresponding to the requirements of the closure plan is the set of measures and activities proposed by the company to obtain physical and chemical stability at the site of the mining site, safeguarding the life, health, safety of people and the environment.

The regulations are of a more administrative nature and do not specify waste management methods or closure measures. However, according to the National Geology and Mining Service, the regulations seek to make mining companies responsible for the externalities of their process, prevent the creation of abandoned mine sites and ensure that the state has an economic guarantee that it will not have to respond for these mining liabilities.

In Chile, manuals are established for the stabilization and protection of tailings deposits, which is the main destination of tailings. Among the factors considered important are geology, seismicity, topography, drainage network, hydrogeology and climate; the characteristics of the sludge, effluents and the environmental limitations that may arise are also evaluated.

In relation to tailings dam construction, Chile establishes four main methods which are (I) conventional "breakwater" dams, (II) "upstream" construction, (III) "downstream" construction and (IV) "centered" construction, all under the approval of the National Geology and Mining Service (Sernageomin). On the other hand, tailings tanks need the approval of the General Water Directorate, when they exceed five thousand cubic meters and to terminate the operation of tailings tanks Sernageomin must approve a Closure Plan, which includes both environmental and safety measures. (Ministerio de Minería Chile 2018).

Chile's experience is mainly based on copper mining, but does not cover anything concerning the management of mercury-contaminated tailings, although the options proposed under heavy metal contamination can be taken as a foundation for this protocol.

**Mexico**

In Mexico, NOM-141 establishes the procedure for characterizing tailings and the specifications for site preparation, design, construction, operation and post-operation, while for mine closure, the Mexican standard establishes the closure notification for the control of hazardous waste or the obligation to adhere to the closure program for the operation of the mine.

In terms of tailings storage in Mexico, tailings can be stored directly at the site where they are generated, according to the site characterization information, applying the environmental protection criteria specified in the law. When a tailings dam is required to be located in protected natural areas, the permit will be subject to the environmental impact assessment, as well as the provisions of the Protected Natural Area Decree and the respective Management Program.

Mexico has specific regulations that provide standards, design parameters and contractive methods.
The upstream construction method, known to be one of the most dangerous and most susceptible to landslides, is not strictly prohibited in Mexico. The corresponding authority in Mexico may authorize this type of construction method under certain special conditions, in certain territories and depending on the geographical, seismological and climatological characteristics of the site.

Some of the regulatory standards on tailings issues in Mexico are described below (Ministerio de Minería Chile 2018):

- **DOF 09-01-2015 General Law of Ecological Equilibrium and Environmental Protection**: in Article 108, it establishes that the NOM will be issued to allow the proper location and form of the deposits of waste rock, tailings and slag from mines and mineral beneficiation establishment.

- **NOM-141-SEMARNAT-2003 Norma Oficial Mexicana (NOM-141-SEMARNAT-2003 Official Mexican Standard)**: this standard presents the specifications for characterizing tailings, sites and criteria for mitigating environmental impacts. It also relates the stages of the project, construction, operation and post-operation of tailings deposits and their monitoring.

- **DOF 07-06-2013 Federal Environmental Liability Law**: Presents the regulation of environmental liability for damages caused to the environment, its repair and compensation when required through judicial processes, alternative dispute resolution mechanisms, administrative procedures and those corresponding to the commission of crimes against the environment and environmental management.

- **DOF 22-05-2006 General Law for the prevention and integral management of waste**, refers to the protection of the environment by waste management. Article 17 states that waste from the treatment of minerals such as tailings is a federal competence and that it may be disposed of at the site where it was generated.

- **NOM-052-SEMARNAT-1993 Mexican Official Standard, which determines the characteristics of hazardous waste (list and limits)**. This standard establishes that tailings from the processing of antimony, copper oxides, copper pyrite, lead and zinc are classified as hazardous.

**Reflection of the international context**

Regarding chemical stability, the countries reviewed present indications that mainly have to do with isolating contaminated tailings deposits from the environment, because removing tailings with high concentration of contaminants from sites can prevent the generation of acid drainage, prevent the generation of dust and in general provide recommendations or instructions to restore the natural characteristics of the site, as far as possible, establishing financial guarantees to ensure compliance with the obligations after the closure of the project.

In most of these cases, the corresponding environmental legislation presents indications for the recovery, rehabilitation or remediation of the sites, with the aim of restoring the impacts,
as far as possible, to achieve the original characteristics, prior to the mining project. In many of the countries reviewed, environmental legislation is comprehensive, addressing the problems associated with failures in the chemical stability of the project, through management systems for contaminated sites, or directly supporting the prosecution of cases.

From the review it can be established that, although some countries have some regulatory instrument related to tailings contaminated with heavy metals or acid drainage, such as Chile, Peru and Mexico, no country has advanced specific management of tailings contaminated with mercury.
6 Technical protocol for the management of mercury-contaminated tailings

The main objective of this technical protocol is to present good practices in the development of a management process for mercury-contaminated tailings in Colombia, which may serve as reference material for officials of government entities involved in the issue such as the Ministry of Environment and Sustainable Development, Ministry of Mines and Energy, regional environmental authorities, regional mining secretaries, as well as professionals and any other persons involved in small-scale mining activities.

Although since July 16, 2018 the use of mercury in mining activities in Colombia is prohibited, the problem of tailings contaminated with this element is usually presented under the following scenarios:

- Presence of large number of abandoned tailings that were generated by mining activities under mining title or by artisanal subsistence mining before 2018 and that were never properly managed.
- Tailings that continue to be generated by illegal mining in different parts of the country with the process of amalgamation and subsequent cyanidation, this type of tailings generally do not arouse the interest of miners or investors and are the most susceptible to be abandoned without proper control.

Considering the above, it is important to establish a protocol for the integrated management of tailings, which mitigates the current risk and minimizes the impact of existing tailings in the country. This implies the reduction of mercury present in the tailings, the establishment of adequate technical and administrative parameters, safe intervention procedures that result in slowing down the generation of contaminated sites or interrupting the contamination of sites currently impacted.

It is feasible to find tailings with different mineralogical, physical and chemical characteristics, which must be properly managed under the same management strategy proposed in the following scheme.
6.1 Current status of mercury-contaminated tailings in Colombia

Tailings in Colombia can be found in different forms in the environment since they vary according to the type of mining process that generates them, the topography of the terrain and the environmental conditions to which they have been exposed, as well as the age or time of their production. It is also important to consider that each tailing may be generating a risk to the exposed population depending on their proximity to residential sites or water sources, which should be an important factor at the time of an environmental analysis. The
following are the most common forms in which mercury-contaminated mine tailings can be found in the country.

6.1.1 Tailings accumulated in piles

These tailings usually come from alluvial mining activities (sediments on the banks of rivers) where their extraction occurred mainly by the use of dredges, backhoes and other heavy equipment, which is screened in flowing streams. Current mercury concentrations in such tailings can be influenced by factors such as exposure to high ambient temperatures, weathering and its easy migration to environmental matrices by both evaporation and leaching.

![Figure 2. Tailings in the banks of the Quito river - Choco. Source: TSIP program – Pure Earth 2019.](image)

Most of these tailings come from illegal mineral extraction in departments such as Chocó on the banks of the Quito and Negua rivers, among others.

6.1.2 Tailings piled in sacks

The existence of these tailings is mainly due to the waste generated by the different processing plants, also known as "Entables", where mercury was incorporated into the gold extraction process in order to generate gold amalgam. The mercury concentrations present in this type of tailings can be representative, some tests within the framework of the project suggest values between 80 ppm and 550 ppm of total mercury.
In many occasions these tailings are stored with certain precautions and special conditions, such as storage under roof or the use of tarpaulins, since they could still have the presence of values (such as associated gold) and tailings with low moisture content is desirable, i.e., they are stored for a second processing for value extraction. Most of these tailings come from informal mining or illegal extraction of minerals and are distributed in different departments of the country being Antioquia, Choco, Cauca, Valle del Cauca and Nariño the most representative ones.

### 6.1.3 Tailings deposited in tailings ponds

As with tailings piled in bags, most of these tailings come from the mills (entables), although they are also found in areas where illegal alluvial mining activities have been carried out. However, unlike those deposited in sacks, tailings ponds allow for a larger storage volume and a higher percentage of humidity. This type of infrastructure is often monitored by environmental authorities to verify mercury limits in final discharges and the owner beneficiation plants are subject to retributive rate payments. (CORANTIOQUIA 2016)
Many of these tailing dams, especially those coming from illegal mining, are not well designed, so not only a high physical risk of a catastrophic failure but also the filtration of these tailings and the possibility of generating a contaminated site are quite high. On the other hand, the mercury concentrations present are quite high, in reference to international reference standards, both in the solid material (tailings) and in the aqueous phase that can reach existing water sources and its transport to other sites for final disposal or possible reprocessing becomes a challenge. Most of these tailings are found in the departments of Antioquia, Chocó, Cauca, Valle del Cauca and Nariño, among others.

### 6.1.4 Tailings scattered in the environment

One of the biggest current problems is the presence of this type of tailings, where the negative impact they have had on the environment is very large, since they were tailings that did not have any type of containment and on the contrary were spread over large extensions of land generating large impacted sites with high concentrations of mercury in the environment.
Under this concept, it is no longer possible to speak of tailings management per se, but rather of the management of a potentially contaminated site, where the parameters for evaluation and intervention depend on the configuration defined according to the criteria of the environmental authorities and the type of population exposed, among others.

6.2 Characterization of tailings

The tailings characterization process is an important step since with this process it is possible to define their potential degree of contamination by mercury or other components, define the final disposal processes and the selection of the best option in mercury-free technology for recovery of residual gold if possible. It should be taken into account that many of the abandoned tailings often do not correspond to a single type of exploitation and a mixture of different tailings can be found, which makes it necessary to characterize them.

6.2.1 Tailings Sampling

To carry out a correct characterization of the tailings, it is important to develop a very good sampling strategy in order to be representative, since, depending on the location and condition of the tailings, the way to do the sampling may vary. Some considerations to keep in mind are:

- Simple, Composite or Multiple point sampling. The goal is to assure that the sampling accurately reflects the levels and diversity of mercury in 100% of the tailings, as well as the presence and levels of cyanides.
- Simple sample: Material collected in a single sampling point. That is, the samples collected at a particular time and place. Generally, a single sampling location will not accurately reflect the mercury content of tailings in all but the smallest tailing piles, such as less than 1 cubic meter.

- Composite sample: It is made up of a set of simple samples (sub samples), suitably mixed, and taken to the laboratory for their corresponding analysis, the result being an average analytical value of the property or compound analyzed. The number of subsamples will depend on the variability, extent and accessibility of the tailings.

- Multiple point samples are a series of separate samples at a tailings site which are then analyzed separately, either using field instruments or at an off-site laboratory. The number of discreet samples, like with composite samples, will depend on the variability, extent and accessibility of the tailings. Cost is also a consideration, especially if an off-site laboratory is used, as analysis of multiple samples is more expensive than analysis of a single (or several) composite samples.

- For tailings that are in bags, ensure that samples are taken from the center of the bags, and enough bags are sampled to be sure that the total volume is accurately reflected.

- For tailing piles, the sampling strategy must take into account the entire area of the pile and the variation in pile depth. A modified grid sampling strategy is often used, with samples at multiple depths where the piles are deepest. Samples should notably be taken at depth, rather than on just the surface or shallow depths of a pile, as mercury may be greater at depth due to infiltration and less evaporation. For deeper piles, it may be necessary to have a mechanical means of drilling rather than just manual excavation.

- For tailings ponds that are fairly uniform in depth it is important to design a grid-type sampling strategy, as well as to have mechanical means of drilling in order to obtain samples from the bottom of the material.

- When the tailings are dispersed in a site, it is recommended to apply methodologies for sampling contaminated sites, among which are “Investigation of potentially contaminated sites - Code of practice - BSI 10175” (BSI 2013) and UK government ‘Sampling Strategies for Contaminated Sites’ – CLR4 (Environment 1994).
Pure Earth has managed to standardize the method of sampling of tailings, management, conservation and transport of the sample in the document “Protocol for the collection, storage, conservation and transport of environmental samples” which is available at https://www.pureearth.org/colombia

6.2.2 Chemical characterization of tailings

The chemical characterization of a tailings can have different approaches and a number of parameters can be incorporated, so it is necessary to identify the presence of substances of health and environmental interest that may be present in the tailings and prioritize those that provide relevant information to the target process. For this reason, this section presents the most relevant parameters to be taken into account in tailings management, which should not be considered as a restrictive or exclusive list, i.e., the inclusion of any other parameter not described in this section can be completely valid from the perspective of those who wish to advance a tailings processing project.

Total Mercury Determination

The determination of mercury concentration in a tailing corresponds to one of the most important and fundamental environmental factors in tailings management decision making. Mercury is a toxic element, and therefore its presence in the tailings can have a major negative impact on human health and the environment if appropriate precautions are not taken for its management and final disposal.

The mercury present in tailings can be present in the three oxidation states, metallic mercury [Hg(0)], mercurous mercury [Hg(I)] and mercuric mercury [Hg(II)] forming inorganic salts, such as chlorides, nitrates, sulfates, and other organometallic compounds (Cortés Castillo 2017). However, the most advisable is to make the determination of total mercury at first and then migrate to the other species, if necessary, in its characterization.
Mercury levels in a tailings pile or pond are likely to vary, sometimes significantly. This is because mercury may have been used to remove gold for some of the tailings materials, but not for other materials, such as rock or sediments excavated outside the primary gold-bearing veins (but still deposited with the other tailings.) Also, mercury may settle or infiltrate in tailings materials differently, and evaporate from shallow tailings areas in high temperature areas. It is important to find and note the variation in mercury levels through the sampling strategy (usually through multiple point samples or multiple composite samples) so that any remediation or risk reduction efforts are focused on the tailings with mercury levels of concern, as opposed to non-contaminated materials.

It is recommended to initially perform the determination of total mercury in tailings using "screening" type analysis devices, which correspond to rapid and direct readings mostly used in the field. Among the recommended devices are X-Ray Fluorescence (XRF) guns and mercury vapor analyzers such as Lumex, Jerome or Hermes. Having this information in advance it is possible to establish a more effective sampling strategy where such samples do require mercury determination analysis by laboratory.

Among the mercury determination analysis methods recommended and available in the country under IDEAM accredited laboratories are (IDEAM 2021):

- US EPA 7471 B, Atomic Absorption Spectrophotometry, SM 3112 B
- US EPA 7473, Rev 0, February 2007
- US EPA 3051A, Rev 1, February 2007

Elemental mercury [Hg (0)], which is its highest form is liquid, has a high degree of evaporation at room temperature, which can generate distortion in data from the moment the sample is taken or readings in the field until its analysis in the laboratory, which is recommended to follow the instructions of the laboratories in the conservation protocols of the samples.

It is important to note that to date there is no allowable limit value for mercury (Hg) in tailings or mining waste, which determines whether it can be considered a potential risk to health or the environment and be classified as "Mercury Waste" under the current definitions of the Minamata Convention.

To date, Colombia does not have any reference values for mercury concentrations in soil within its current legal legislation, for this reason and in order to have an international reference framework, we can take as a initial reference value the elemental mercury concentration given by the Environmental Protection Agency of the United States (EPA) where it relates the following values (EPA 2020):
Likewise, it is important to note that Decree 1076 of 2015 stipulates a maximum mercury concentration value of 0.2 mg/L through the Toxicity Characteristic Leaching Procedure (TCLP), which is applied to a waste in order to be classified as hazardous waste. TCLP is a method designed by the Environmental Protection Agency of the United States (EPA) meant to simulate potential leaching from wastes in landfills.

Occupational mercury exposure values are also a fundamental factor in the analysis when implementing an integrated management strategy for contaminated tailings. According to the current national regulation, i.e., Resolution 2400 of 1979, the maximum permissible values of chemicals in the workplace are referenced according to those published annually by the American Conference of Governmental Industrial Hygienists (ACGIH) of the United States. These values are often very restrictive and it is advisable to review other sources of information such as the National Institute for Occupational Safety and Health (NIOSH) and the U.S. Occupational Safety and Health Administration (OSHA). The following table shows the occupational limit values for each agency:

<table>
<thead>
<tr>
<th>Agency</th>
<th>TWA*</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACGIH</td>
<td>0.025</td>
<td><a href="https://www.acgih.org/forms/store/ProductFormPublic/2020-tlvs-and-beis">https://www.acgih.org/forms/store/ProductFormPublic/2020-tlvs-and-beis</a></td>
</tr>
<tr>
<td>NIOSH</td>
<td>0.05</td>
<td><a href="https://www.cdc.gov/niosh/npg/npgd0383.html">https://www.cdc.gov/niosh/npg/npgd0383.html</a></td>
</tr>
<tr>
<td>OSHA</td>
<td>0.1</td>
<td><a href="https://www.osha.gov/laws-regs/standardinterpretations/1996-09-03-0">https://www.osha.gov/laws-regs/standardinterpretations/1996-09-03-0</a></td>
</tr>
</tbody>
</table>

* Time-weighted permissible limit value under the conditions of 8 hours of exposure, 40 hours per week and 50 weeks per year.

**Cyanide (CN)**

There is a high probability that the existing tailings contain traces of cyanide in their content, because many of them were subjected to the cyanidation process, after the addition of mercury in the gold extraction process. Effort should be used to determine if cyanide was used relative to a specific tailings pile or area, and if so where the use occurred and where tailings from cyanide-processed material were deposited. Interviews with people who worked in the area can be a good source of such information, if they are available and willing to discuss past practices.

There are several methods that can be implemented for the determination of cyanide in the form of Total Cyanide, the laboratories accredited by IDEAM in Colombia use techniques such as: Distillation - Volumetric, SM 4500 CN- B, C, D, Leaching SM 4500 CN A.2 B,
photometric equivalent, ion selective electrode and colorimetric determination (IDEAM 2021).

Cyanide in combination with mercury can react and form Mercury Cyanide, which is a toxic compound and represents one of the biggest problems at the environmental level (Veiga 2018), for such reason it is important to establish the presence of these two compounds to establish the treatment or elimination methods in tailings management. Likewise, the Minamata Convention in its Annex C, the action plans of the parties (countries) that are subject to the provisions of paragraph 3 of Article 7, which refers to the significant presence of artisanal and small-scale gold mining in the country, must include actions aimed at eliminating cyanide leaching from sediments, raw ore, or rocks to which mercury has been added, without first eliminating the mercury (ONU 2019).

Another way to determine the amount of cyanide present is to apply instrumental methodologies that combine distillation and potentiometry. One of these is total to free cyanide decomposition, which is performed using the ion selective electrode method integrated to a cyanide analyzer. It is based on the distillation of the cyanide solution by air cooling; the hydrocyanic acid (HCN) produced during the reaction is condensed and absorbed by bubbling in a sodium hydroxide solution (NaOH 0.1 N) and immediately detected and read using the ion selective electrode for cyanide. The analysis allows the determination of total cyanide in any type of solutions, with a detection range from 5 ppb to 260 ppm. It can also be applied for the analysis of wastewater, water from metallurgical processes and mining activity. In the determination of cyanide in a solution, the following stages are taken into account: the first consists of a titration of free cyanide, then the measurement of total cyanide (cyanurometer equipment or distillation equipment) and finally the interpretation of the result (Servicio Geológico Colombiano 2018).

Other heavy metals

In a tailing it is possible to find another series of compounds and substances that may be of importance within the chemical characterization, which are of interest and may represent risk to the health of people and the environment. The analytical methods recommended under IDEAM accredited laboratories are (IDEAM 2021):

<table>
<thead>
<tr>
<th>Metal</th>
<th>Description</th>
<th>Analytical Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead (Pb)</td>
<td>The methods used for the determination of lead are called precipitation volumetry because the lead present in the sample is first separated as a precipitate (lead sulfate, PbSO4), and then put into solution (with ammonium acetate solution) to be titrated with ethyl endiaminetetra acetic acid or EDTA. Called EDTA (III) method: and xylenol orange as indicator. By dry route it can also be determined by atomic absorption spectrometry.</td>
<td>Atomic Absorption Spectrometry EDTA (III) method</td>
</tr>
</tbody>
</table>
Arsenic (As) | The concentration of As in the tailings is a function of the size of the grain, the concentration increases as the grain is smaller, reaching its maximum value in the smallest grain size | Microwave digestion with royal water

Zinc (Zn) | The most general classical method for the determination of zinc is, like that of lead, precipitation volumetry. It is based on the titration of Zn by EDTA, in a slightly acidic solution. | EDTA (III) method, Atomic absorption spectrometry

Source: Taken from [http://www.ideam.gov.co/web/contaminacion-y-calidad-ambienta](http://www.ideam.gov.co/web/contaminacion-y-calidad-ambienta)

The use of portable devices, such as an XRF, for determining concentrations in the field is also highly recommended, as these field instruments allow for many samples at minimal cost and with sufficient sensitivity and accuracy to assess whether other metals present environmental or health risks.

It should be noted that the list included here is neither limiting nor exclusive and that depending on the scope of tailings management, the analysis of other substances or compounds is totally feasible.

**Gold (Au) determination**

Within tailings management, the extraction of the residual gold present in the tailings can be considered as an alternative, however, in order to consider this as an option, the process conditions stipulated by the environmental authorities must be complied with. The main purpose of this chemical characterization corresponds to the determination of the gold content. This concept is defined as the mass of gold in a sample, divided by the total mass of this sample; this can be represented in percentage (%, grams of gold per 100 grams of material) or in parts per million (ppm), which corresponds to grams of gold per ton of material (g/t) or milligrams of gold per kilogram of material (mg/kg).

The verification of the gold content is normally done by the Fire Assay technique, which is the most accurate method because it reveals all the gold that may be present in the sample. This method consists of fusing the sample with the help of reagents (lead oxide) and fluxes to obtain two liquid phases: one is the slag, consisting mainly of complex silicates, and the other is the metallic phase, consisting of lead, which collects the metals of interest, generally gold and silver. The metals must then be subjected to chemical analysis or gravimetric determination, depending on the final conditions of the sample. The sample must be previously prepared by pulverization and fusion occurs in a crucible by subjecting the prepared sample to direct heat (between 900 °C and 1000 °C) (Ingemmet 2019).

Gold determination by colorimetry is an alternative instrumental analysis that can also be used. This method is applicable in field work. To determine micro-quantities of gold in cyanide solutions, precipitation with zinc is performed in order to eliminate interferences. This precipitation is carried out with cyanide solutions containing a cyanide concentration greater than or equal to 1 g/L, and which are at pH values greater than 11 units. The precipitate formed is dissolved and color is developed using the stannous chloride method.
This reagent allows quantification of gold in solutions using the Cassius purple method test (Servicio Geológico Colombiano 2018).

6.2.3 Tailings mineralogical characterization.

Complementary to the chemical characterization for environmental purposes, a characterization of the mineralogical composition of a tailings is of vital importance in decision making for its management, especially if tailings reprocessing is considered as a viable alternative. Some alternatives for mineralogical characterization are presented below.

Petrographic testing

Although petrography specializes in analyzing the mineral composition, structure and descriptive section of rocks, it can be used as a complementary test in the characterization of tailings in the determination of minerals such as gold in composition, grain size and content. In order for this test to be valid in the characterization of tailings, the following considerations must be taken into account:

- It presents more data reliability in tailings coming from the same mining operation, i.e., from the same sector.
- Its application should be carried out with the preparation of thin section films. For its application, a previous work of sample preparation must be carried out, where samples are marked, referenced, cut and roughed up to a thickness of 30 um for the preparation of thin sections; to finish with a polishing process, the use of diamond pastes of different granulometries between 9, 3 and 1 um is recommended.

X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) Testing

As in traditional mining, each ore has totally different compositions, tailings have different characteristics depending on their origin. Depending on these characteristics, different extraction methods are proposed. These methods try to take advantage of the physical and physicochemical properties of the materials (Ojeda Escamilla et al., 2010). For this reason, it is essential to have a full understanding of the material to be worked, in order to predict its behavior, and to correctly select the separation techniques, as well as possible necessary pretreatments. Mineral characterization is focused on the identification of minerals of economic interest, gangue minerals, minerals detrimental to recovery etc.

The mineralogical characterization of tailings is usually performed by two types of analysis, one corresponds to an X-Ray Fluorescence (XRF) that is performed with an X-Ray spectrometer. This technique uses highly energetic X-rays to excite atoms, this stimulation is unique for atoms of different elements, using this property the concentrations of the different elements are determined (Meléndez & Camacho, 2009).
The second analysis corresponds to an X-Ray Diffraction (XRD) that is performed with an X-ray diffractometer. The diffraction method consists of incident a beam of X-rays on a single crystal, the diffraction of this beam is different for each mineral, because their crystalline structures are different, so by measuring the diffraction angle and intensity a qualitative data of the mineral is obtained (UVa 2020). This technique is fundamental, because it is the only one that allows to obtain a qualitative measure of the most abundant mineralogical species of a sample, although its limitation is that it cannot detect minerals in compositions lower than 5%. (Ojeda Escamilla et al., 2010). The results obtained are percentages of a certain mineral in the sample. With the results of the analysis, it is possible to form an idea about the composition of the materials with which they are working and many of the behaviors that they present in certain situations can be explained. In addition to these analyses, it is necessary to carry out other types of tests such as particle size distribution, release tests, determination of relative hardness, etc. That combined give a better description of the characteristics of the material (tailings in this case) and allow to select a correct approach to the treatment of tailings.

6.3 Recovery or removal of mercury present in tailings

Considering that tailings with the presence of mercury presents a risk to the health of people and the environment, it is important to develop actions to recover the mercury from the tailings in its entirety or at least below the reference limits established as safe (not defined to date by the Colombian government or by the Minamata Convention).

Under the objectives of the Project “Promoting the recovery and responsible management of mercury in contaminated tailings from artisanal gold mining in Colombia”, of which this technical protocol is a part, actions have been taken to identify the most efficient mercury recovery technique from tailings from a cost-benefit point of view, among which are:

- Workshop of national and international experts
- Development of a technical report on the compilation of promising technologies for mercury recovery from tailings.
- Laboratory tests and pilot tests of the "Copper Plate" technique, identified as the most cost-effective in the evaluation process.

From the activities mentioned and executed, a technical document was published that compiles the most promising technologies for the recovery of mercury present in tailings from artisanal gold mining. It should be noted that within the literature review, many of the technologies consulted are focused on gold recovery without the use of mercury or soil remediation issues, but very few were identified exclusively for tailings. The full paper is available at [https://www.pureearth.org/colombia/](https://www.pureearth.org/colombia/)

A compilation and summary of the techniques identified is presented below:
<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper plates</td>
<td>This technique involves the use of copper (Cu) plates coated with silver (Ag), which is identified as an easy and economical way to remove mercury from tailings. Among its operating conditions are the age of the tailings (due to the salt content), the processing capacity and the flow rate of the tailings in front of the copper plates. It allows the processing of large volumes of tailings.</td>
</tr>
<tr>
<td>Foam Flotation</td>
<td>This technique is characterized by allowing the most appropriate combination of reagents to recover mercury, gold and silver from small mine tailings. The materials and methods used in this technique involve a previous characterization of the samples, the solid-liquid concentration of the pulp, a granulometric input phase, a pH regulation by means of caustic soda (NaOH), an activator by means of lead acetate and a collector.</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>This technology is based on an electrokinetic system, which applies a low magnitude direct electrical potential between two or more sacrificial electrodes placed on opposite sides of a contaminated soil or sediment mass. The electrical potential generates a strong EH-pH gradient between the two electrodes, promoting anodic dissolution, metal migration and precipitation strength, at near-neutral pH values at the interface of the anodic and cathodic domains. Thiosulfate leaching and electro recovery are required for this technique.</td>
</tr>
<tr>
<td>Activated carbon and electrowinning</td>
<td>This technique is characterized by the combination of several independently tested alternatives that are in the adaptation and testing stage. This technology was designed primarily for obtaining residual gold in tailings from small-scale artisanal mining. However, with the necessary tests it has been concluded that the adaptation to mercury recovery is fully feasible and effective.</td>
</tr>
<tr>
<td>Nanotechnology</td>
<td>The key system of this technique consists in the leaching of mercury with cyanide aided by a nanocatalyst. At the moment is an experimental results. Catalysis with nanotechnology consists of the supply of activated oxygen, that is, air is passed through the nanocatalysts, thus activating it to be injected into the cyanidation tanks where the leaching takes place, this process takes approximately 4 hours. This process operates by potholes and is designed to recirculate as much water as possible, but when this option is no longer viable the wastewater is treated by bioremediation. Finally, recovery is done by using activated carbon in a desorption process.</td>
</tr>
<tr>
<td>Distillation</td>
<td>The vacuum distillation technique used by INNOVA is mainly applied for the extraction of mercury from fluorescent luminaires, however, thanks to its simplicity in the process, this technique can be coupled to</td>
</tr>
</tbody>
</table>
materials such as mine tailings. Treatment of large volumes of tailings may be very expensive and require extensive equipment.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart burners</td>
<td>This is a separation technique between the contaminant and the soil. The technology heats the soil through conductivity, which generates heat in the soil that allows contaminants such as hydrocarbons and metals to evaporate. The heated air flows back through the external steel tube and will be released at the end. The second step is to recover the contaminated elements. This is done by absorbing the elements through the holes in the tube next to the heated tube. Smart burners can treat mercury contamination and are water resistant. The process can be effective but requires large amounts of energy and effective measures to capture and recover evaporated mercury.</td>
</tr>
<tr>
<td>Gravimetric Processes</td>
<td>This technique begins with the collection and transport of contaminated sludge from the affected sites to the processing plant, where a main sludge stockpile is available, followed by a sludge cleaning and desliming phase to carry out a process of regrinding and gravimetric concentration of Hg. In general, gravimetric separation cannot achieve very low levels of elemental mercury in treated tailings, owing to the presence of micro-droplets that are often present and not amenable to separation gravimetrically from soils.</td>
</tr>
</tbody>
</table>

Source: Pure Earth 2019. Mercury recovery expert workshop

Each one of the above technologies has limits with respect to:

- The starting concentration of mercury for which the technology is effective. In general, lower concentrations of mercury are harder to remove.
- The concentration of mercury that the technology can achieve in treated tailings.
- The form of mercury that the technology can be effectively used for. In general, elemental mercury is the target for removal.
- Cost, energy use and infrastructure requirements (such as buildings, water, wastewater treatment and electricity.)
- Expertise, monitoring and testing required to assure effective operation.

All of these factors need to be taken into consideration when selecting and designing mercury removal measures. Unfortunately, there is no one technology that is good for all types of tailings, and often the mercury levels in treated tailings (done at an economically possible cost) may not reach levels that would be considered as safe for disposal or future use as non-hazardous material.

Any intervention process carried out on tailings for mercury recovery or removal will generate mercury waste and mercury-containing waste, which also needs to be properly managed in order to avoid accidental release of mercury back into the environment. The measures presented below are based in principle on the Guidance for the Management and Storage
of Mercury (CNPMLTA-ONU Medio Ambiente 2019) and adapted to the context of waste from tailings treatment.

### 6.3.1 Packaging of Mercury Waste

For metallic mercury waste in liquid form, the following recommendations should be taken into account to ensure tightness against evaporation, non-reactivity between mercury and the container material, and mechanical capacity to withstand weight during handling, storage or transport.

According to a study made by the Technological Laboratory of Uruguay – LATU (Oestreich, y otros 2010) mercury storage containers are designed for volumes of 3l, 1 mt, 2 mt and 10 mt. These containers have special designs that resemble the definition of a closed metal drum in the Colombian Technical Standard NTC 4702-6, however, LATU refers to these containers as flasks.

The reliability of the container will be subject to compliance with the following criteria:

- The depth of the mercury should be within 0.7 m of the top of the filler neck. (The maximum height that a vacuum pump can raise the mercury is 0.76 m).
- Using a drain valve for mercury removal from the vessel should be avoided.
- The welds are probably the weakest point of the containers, so they require more attention during design, manufacture and quality control. Newer containers are made without welds, these are the most recommended.
- The use of a national pipe thread plug (NPT) with Teflon® tape provides excellent sealing at low cost.
- The use of two ports at the top of the container provides the fastest filling method. One port is connected to a vacuum pump, while the other is the mercury inlet.
- Carbon steel (ASTM A36 minimum) is the recommended steel option.

Recommendations for 3 L container design are:

- Seamless container (seamless, similar to gas cylinders).
- Top interior volume 2.9 L
- Estimated empty mass, 9 kg

Containers provide the highest cost per volume of mercury during storage. However, it is a good option for small mercury generators and can be easily transported by ship, land or air. Container packing is generally done in boxes with pallets, typically 49 flasks per pallet (pallet size 1.25 m x 1.25 m). The cost reported by the study is approximately US $ 20.00 / flask.

The 1 mt, 2 mt and 10 mt containers should be constructed of carbon steel (ASTM A36 minimum). A protective coating (epoxy type paint) must be applied against external corrosion. The containers cost more than twice the cost of the 3 L flask. The advantage is a reduced cost per volume of mercury stored compared to 3 L flasks, plus they are easy to transport and handle with a forklift.
6.3.2 Packaging of mercury-containing wastes

Depending on the type of technology used to recover mercury, a range of mercury-containing wastes can be generated, which can vary from their physical state to their size, shape and material type. For example, solids, liquids, foams, plastics, metals or synthetic materials can be generated, all impregnated with mercury in their content or on their surface.

Regardless of the type of waste, these must be classified as hazardous waste according to the provisions of Decree 1076 of 2015 and therefore must be managed as stipulated therein. However, some important general considerations should be taken into account when selecting the appropriate packaging for each type of waste.

For this, it is recommended to follow the parameters and technical requirements established in Colombian Technical Standard 4702 (1-9). "Packaging and containers for transport of dangerous goods". (Ministerio de Transporte - ICONTEC 1999)

It is important to remember that mercury as a chemical substance has a high degree of volatility; therefore, the idea is to look for packaging that avoids mercury evaporation into the environment. For this reason, it is recommended that the waste has as much packaging as possible, including covering the surfaces with "Paper Film" or "Transparent Paper".

6.3.3 Labeling of mercury waste and waste containing mercury

Each container (for metallic mercury waste) and packaging (for materials impregnated with mercury) must be labeled according to the legal provisions in force, in our case it corresponds to the Globally Harmonized System, which was adopted in the country under Decree 1496 of 2018, which describes that the suggested label for mercury must contain at least the warning phrases indicating danger, the technical name, risk phrases (H Phrases) and Prudential Advice (P Phrases).

This information should be indicated on the material safety data sheet of the material to be transported, ¡Error! No se encuentra el origen de la referencia. shows the construction of a label for metallic mercury based on a commercial Safety Data Sheet5.

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It is important to mention that other labels may be necessary to record important information, such as the amount of mercury, the liquid or solid phase, the date of receipt, among others.

6.3.4 Storage of mercury waste and mercury-containing waste.

According to decree 1076 of 2015, section 2. activities intended for the storage of mercury or waste with mercury, must process before the corresponding environmental authority an environmental license or equivalent permit.

The technical considerations for the storage of mercury waste or waste with mercury set forth herein are adapted from the U.S. Department of Energy's Guide for Transport, Packaging, Storage and Management of Mercury Elements. (Oak 2009).
Physical Facilities Considerations

The physical facilities are proposed to contain four main physical areas as follows: Receiving and Shipping, Handling, Storage, and Office Administration.

- **Receiving and Shipping Area**: This should be the operational interface area to and from the facility. This area admits the reception of the material after inspection and subsequent transfer to the Handling or Storage areas. It also allows for the inspection, packaging, marking, manifestation and safe exit of the material if necessary. As a good engineering practice, it should be an enclosed area, adjacent to the handling and storage areas, with sufficient space and physical conditions for the entry and exit of the material.

- **Handling area**: It should be an enclosed, separate and dedicated location for contaminated work. Emergency transfer of the contents of a leaking container, bulging operations and/or limited container storage, as well as normal sampling for laboratory sample preparation, should be performed in this area. It must have a drainage and ventilation system.

- **Storage area**: Comprises most of the facility. It should be an enclosed area with ample space for storage and transit of materials and people. The walls, ceiling and a base under the containers should minimize emissions. The area should have sufficient ventilation and adequate lighting. The area and location of the containers should allow a good location of the materials with ease of access and permanent inspection. The average temperature of the room should be below 15°C in order to ensure evaporation of the mercury.

- **Administration area**: Area dedicated to administration, operations, record keeping, training and all other administrative functions. It should preferably be physically separated from the other three areas of the facility.

Air monitoring

In order to ensure that mercury vapors are not being generated in the storage of mercury waste and mercury-containing waste, it is necessary to design a permanent monitoring system within the facility to ensure not only the health of the workers, but also the content of the stored material.

The mercury vapor analyzers that are recommended to be used for monitoring mercury vapors in the storage facility should be capable of measuring mercury vapor concentrations in the breathing air in excess of the allowable specified in Occupational mercury exposure values are also a fundamental factor in the analysis when implementing an integrated management strategy for contaminated tailings. According to the current
national regulation, i.e., Resolution 2400 of 1979, the maximum permissible values of chemicals in the workplace are referenced according to those published annually by the American Conference of Governmental Industrial Hygienists (ACGIH) of the United States. These values are often very restrictive and it is advisable to review other sources of information such as the National Institute for Occupational Safety and Health (NIOSH) and the U.S. Occupational Safety and Health Administration (OSHA). The following table shows the occupational limit values for each agency:

Table 3. These mercury vapor analyzers should be removed from service when the calibration expiration date is reached or when a situation occurs that could affect the analyzer calibration. Analyzers to be calibrated should be labeled, tagged or otherwise conspicuously labeled.

Supplementary recommendations

Some supplemental recommendations at mercury and mercury-containing waste storage facilities are:

As a best management practice, do not eat, drink, smoke or chew in the material storage area. Upon leaving the mercury storage area, personnel are expected to wash their hands with soap and water. Clothing should be changed if it has become contaminated.

Material Safety Data Sheets (MSDS) for elemental mercury and other chemicals stored and/or used in the facility shall be readily available on site.

Unless personnel are wearing appropriate respiratory protection, the concentration of mercury vapor in breathing air should be below the ACGIH recommended guideline values (Occupational mercury exposure values are also a fundamental factor in the analysis when implementing an integrated management strategy for contaminated tailings. According to the current national regulation, i.e., Resolution 2400 of 1979, the maximum permissible values of chemicals in the workplace are referenced according to those published annually by the American Conference of Governmental Industrial Hygienists (ACGIH) of the United States. These values are often very restrictive and it is advisable to review other sources of information such as the National Institute for Occupational Safety and Health (NIOSH) and the U.S. Occupational Safety and Health Administration (OSHA). The following table shows the occupational limit values for each agency:

Table 3).

6.3.5 Final disposal of mercury waste or waste with mercury

The final disposal of mercury waste or waste with mercury of small volume will be subject to the provisions provided by the MinAmbiente specifically for this type of waste or otherwise the same considerations contained in Decree 1076 of 2015 on hazardous waste management must be applied.
6.4 Tailings intervention methods and alternatives

As in any industrial activity, waste generation is a common part of a productive transformation process that seeks to obtain a final product. Mining is no exception, and with a generation rate of tons of processed material per gram of precious mineral obtained, it is necessary to identify the best way to manage them in order to avoid the generation of environmental impacts on soils.

The alternatives to intervene a tailing could be classified in two ways, one as volume reduction for final disposal and the other as utilization of the residual gold. The selection of the alternative is subject to different factors such as, for example, the mercury content in the tailings or other substances of sanitary interest, the quantity generated and the availability of managers near the area that make a recovery project feasible.

6.4.1 Final Disposal

According to the (Ministerio de Ambiente, Vivienda y Desarrollo Territorial 2005) final disposal “is the process of isolating and confining hazardous waste or residues, especially those that cannot be used, in specially selected, designed and duly authorized places, to avoid contamination and damage or risks to human health and the environment”. This definition is generally understood as the disposal that takes place in a safety cell and is one of the most used alternatives in the country for hazardous waste.

The parameters to be taken into account for final disposal of mining waste in general, are contained in the Terms of Reference 13 for Environmental Impact Assessments (EIA) of the mining sector (Ministerio de Ambiente 2016) (ANLA 2016), these correspond to:

- Taking into account the different alternatives for the final disposal of existing tailings, such as the formation of tailings deposits (free dumping, dumping by attached phases, standing retention dam, superimposed ascending phases, among others) and backfilling, an analysis of the selected alternative for the final disposal of tailings must be developed, justifying its choice and the environmental advantages it has over the other existing alternatives.
- Geochemical characterization of the projected tailings disposal site(s), as well as of the rocks that make up the different lithological levels that will be exploited, in order to establish the potential for acid drainage and metal leaching over time, as well as neutralization.
- The classification of the materials must be included, involving static tests (acid-base balance, metal leaching, mineralogical analysis) and kinetic tests (field and laboratory) for different states of weathering and climatic periods.
- In accordance with the results obtained, works or actions should be proposed for the adequate management of the areas of final disposal of leftovers over time.
- Detailed description of the management and restitution of water bodies, in case of temporary and definitive diversions and their compatibility with the project schedule.
- Detailed description of management to prevent contamination of aquifers before, during and after final disposal.
• List of the volumes of material to be disposed of at each identified site, indicating its origin according to the mining plan and definition of the route to be followed by the vehicles that will transport the material.
• Georeferenced location and topographic maps with planimetry and altimetry.
• Detailed description of the construction and land adaptation works, prior to the disposal of leftovers.
• Global stability analysis considering the tank - foundation soil assembly (in longitudinal and cross sections), analysis of safety factors and risk of displacement under external loads.
• Design parameters and plans at a scale of 1:5,000 or more detailed, including, among others, the necessary infrastructure works for the adequacy of the area (drains and sub-drains, confinement and containment structures and slopes, among others).
• Plan and profiles of the development and progress of the leftover’s disposal site, showing the different stages of its execution and the final design contemplated.
• Proposal for the final adaptation of the waste disposal site and revegetation program (landscape design).
• Identification of the final uses of each of the proposed waste disposal sites.

Although there is no maximum mercury content given in Colombia regulations regarding acceptable levels of mercury in tailings, it must be recognized that once in tailings, the complete removal of mercury is not possible in any realistic cost scenario for larger tailing piles or contaminated areas. Some residual mercury must therefore be accommodated in final disposal plans. As stated above, USEPA gives a value of 11 mg/kg as a residential soil standard and 46 mg/kg for industrial soil, which may serve as a guide.

One of the most widely used alternatives is the tailings storage facility (TSF). This has the purpose of being the final disposal considering that tailings dams accumulate and store tailings during the entire useful life of the mining project.

Some of the documents that contain detailed information on the final disposal of mining tailings corresponds to, one published by the European Commission entitled "Management of Tailings and Rock Waste in Mining Activities" (European Commission 2009) and the other is “Guidelines on Tailings Dams”, written by ANCOLD of Australia and last updated in July, 2019 (see www.ancold.org.au).

Some options are presented below.

**Tailings dams**

Tailings dams are infrastructure works to store or dam tailings, built from an initial wall made of borrow material, tailings and/or thick tailings material previously separated in physical treatment processes and with a high percentage of humidity. These dams can be constructed using three methods: upstream, downstream, central axis or mixed (Figure 7)
Tailings dams depend on the morphology of the terrain and are generally located near the processing plant.

Tailings impoundments

Tailings impoundments are structures that house tailings with low moisture content compared to conventional tailings placed in dams, which means that the containment structures do not require such elaborate infrastructure and the associated risks are lower, with an embankment to prevent overflow or movement of the stored tailings. These structures generally have perimeter channels and subway drainage systems to prevent water saturation of the tailings. The water captured in these systems is generally conveyed to sedimentation and treatment systems for subsequent water recirculation or discharge processes (ATG 2020).

6.4.2 Emerging tailings treatment technologies

Alternative technologies are being developed for the treatment of tailings for final disposal, including tailings thickening and/or filtering, backfilling of mines with tailings paste and enhancements of existing structures. It should be noted that the application of any of these technologies will have to be contrasted with the characterization of the tailings to be used and the possible presence of contaminants in it. The main technical characteristics of these emerging technologies are summarized below (Beltran Rodriguez, Larrahondo y Cobos 2018).
Tailings thickening and/or filtering.

Engineer Eli I. Robinsky, developed in 1975, for a mine in Canada, a tailings disposal system that does not require dam, weir or other structure for containment. The system takes advantage of the increased viscosity of the tailings slurry if its solids concentration is intentionally increased. The proposal includes a curve to relate the tailings slope at rest to the solids content of the slurry. It was concluded that tailings can be arranged in the form of a "cone" discharged from a central discharge point, and the slope of the cone corresponds to its respective solid’s concentration.

Although the concept of thickening was developed in 1975, it was not until the mid-1990s that the technology was formally implemented. Although this type of deposit does not require the construction of a dam to limit the committed area, the construction of a relatively low embankment, away from the outer edge of the deposit, is recommended in order to contain the water released by the tailings, which can eventually be captured, pumped and recirculated.

On the other hand, filtered tailings are similar to thickened tailings, except that the material contains even less water due to a process similar to that used to filter concentrate slurries, specifically with filter presses, vacuum or pressurized air blast. The disposal of filtered tailings is sometimes referred to as "dry stacking".

The filtered tailings are first thickened prior to the filtering process so that the appropriate water content is obtained for final disposal, which is normally by compacted backfilling. However, site rainfall and evaporation, dewatering time and area, and operational flexibility can limit the application of tailings filtration.

In Latin America, the first attempts to implement and dispose of filtered tailings took place in low-yield operations in regions such as the Atacama Desert in Chile, where water retention is of great importance. In Colombia, the first project to implement them was Santa Rosa in Antioquia.

Mine backfilling

A "tailings paste" is a dense, viscous mixture of tailings and water, which, unlike suspensions, does not segregate at rest. The major advantage of tailings pastes is that they can be efficiently transported in pipelines without the segregation or sedimentation problems that normally occur in tailings slurries. In addition, once deposited, the tailings are allowed to dry and then stockpiled, thus minimizing the footprint of the disposal site. Paste technology originated in the metal mining industry more than 30 years ago.

The practice of applying a thickener or cementitious additive to the manufacture of paste and thickened tailings is relatively new, but paste tailings operations are rapidly becoming more popular. Furthermore, the use of thickening or cementing agents to produce paste for mine backfill has attractive potential as an alternative to conventional disposal. In particular,
the technology to dispose tailings as cemented backfill in subway workings is currently under full development.

Mine backfilling is therefore a process by which mine waste, combined with small amounts of cement and/or waste rock, is hydraulically disposed of within drifts ("stopes") in order to stabilize the rock mass, allow complete extraction of the adjacent ore and reduce the waste disposal footprint on the surface. To facilitate the transport of the paste into the drifts, backfilling typically involves using large volumes of water to keep the paste at a fluid consistency. Additionally, the backfilling process normally requires the construction of structural barricades ("bulkheads") to block the access tunnel at the base of the gallery. Mine backfilling also must take into account the potential for contaminating ground water. However, mine backfilling can have the decided advantage of removing mine tailings, including any low levels of mercury they contain, from the surface environment and places where people are exposed, using existing holes and excavations. Such backfilling can greatly reduce or eliminate future maintenance requirements as opposed to tailings dams and impoundments, as well as prevent risks to surface water.

**Piggy-backing of Existing Structures ("piggy-backing")**

Piggy-backing is a technique aimed at increasing the tailings holding capacity of existing or even decommissioned tailings containment and management structures, where possible without increasing their footprint. This disposal strategy is usually justified by the large footprint of existing structures and the increasing difficulty in obtaining licenses for the construction of new disposal areas.

Of the common tailings dam construction techniques, upstream, downstream and centerline, enhancements typically implement the upstream method. This method consists of gradually raising the dam by constructing low berms above and behind the existing level dam. Unlike the upstream method, the downstream method consists of emptying and reshaping the sand-sized fraction of the tailings, usually cycloned, on the downstream slope of the wall, while the fine tailings ("slimes") are deposited upstream. Of necessity, the downstream method gradually increases the footprint of the structure. Finally, the centerline method seeks to deposit the sand fraction to the downstream side and the fines to the upstream side, such that the new crest follows the same axis as the original starter dam.

Any enhancement requires drainage works to maintain the water table below the dam, thus facilitating its consolidation and improving the stability of its slopes, particularly considering the possible uncertainty in the behavior of the existing dam to be enhanced. Drainage works are typically constructed using clean sand, uniform gravel, perforated pipe and geotextile.

### 6.4.3 Utilization

The circular economy deals with, among many factors, seeing waste as by-products that after a second transformation process can have an added value and a second opportunity to be reincorporated into the market.
In the case of mining tailings, the utilization can be presented in different innovative alternatives, however, any of them are only viable if it can be guaranteed that there is not presence of mercury or other contaminants that can generate risk to human health and the environment, as well as the non-leaching of such substances. Some alternatives are presented below in the form of examples and research phase projects.

**Tailings in furniture**

Combination of the use of dry tailings, without contaminants and fiber-reinforced concrete, pilot tests have been developed in social infrastructure works, such as chairs, drinking fountains, billboards and mats, which are already installed in the three educational institutions of Jericó, a municipality in southwestern Antioquia, thanks to the Innovation and Development Department of the mining company Anglo Gold Ashanti (Minera Quebradona 2020).

*Figure 8. Furniture built with tailings at Jericho.*

**Tailings in tertiary roads**

The combination of tailings with asphalt components has been considered as an option to improve soil conditions, improve access to poorly passable sites, and reduce the cement required to pave roads. As a pilot test, paving one kilometer of road with the soil-cement technique costs approximately $160 million, provided that local soil is used in the mix. The use of mine tailings could achieve a 2% reduction in the amount of cement, which translates into a 15% cost savings. If the quality of the soil is poor and soil has to be brought in from another area, the cost per kilometer increases by up to 240 million, so using mine tailings could achieve a reduction of up to 30% (AngloGold Ashanti 2021).
Tailings in bricks and tiles

Motivated by the problem in Peru, which is estimated to have around 450 abandoned polymetallic mines, with the permanent risk of environmental contamination, generating a negative visual impact and the continuous contamination produced by climatological effects of the surrounding physical environment. A research project at the Universidad Nacional Mayor de San Marcos in Peru reviewed an alternative for the valorization of tailings in the form of construction aggregate for the manufacture of bricks and tiles (Romero y Flores 2010).

The experimental part of this study was carried out through the experimental design of construction aggregates with the performance of tests to obtain the aggregates themselves and to obtain bricks and tiles from these aggregates, all of which were carried out at the laboratory level.

The results show that, with respect to the quality of the construction aggregate, through various toxicology tests and applying the 3111-EPA, 3113-EPA and 3114-EPA methodology, it was established that the final product, which is the construction aggregate obtained from the polymetallic mining tailings, is not contaminating. This is based on the physicochemical stability achieved through the technique of microencapsulation of heavy metals in the matrix of the aggregate obtained, after the process of treating the polymetallic tailings with di- and tricalcium silicate of Portland cements type I, type II, type V.

However, if this is not the case and the tailings still contain mercury or other substances of health concern, it is still under discussion whether strategies such as encapsulation are effective or safe, and in the case that it is demonstrated that they are, there is still a long way to go in the legal field for the corresponding technical regulations to be established.

6.5 Considerations for handling mercury-containing material

The direct handling of materials or tailings containing mercury is a critical point for the safety of the people who carry out this work, for this reason, every time it is necessary to handle these tailings, the requirements described here must be complied with.
It should be taken into account that the handling of tailings can occur in any part of the process, i.e., directly where the tailings are located or in the collection centers for reprocessing.

6.5.1 Personal protective equipment

All persons directly involved in the handling of mercury-containing tailings or mercury-containing waste should consider the following parameters for personal protective equipment in their activities.

**Respiratory protection**

- Use of a half-mask respirator with activated carbon filters for metallic vapors, which usually corresponds to those filters with an "orange" stripe, as shown in Figure 10.
- Complement of protection with a filter film for particulate matter N95.
- The replacement times depend on the exposure time of the filters, for which it is recommended to carry out saturation tests with the filter suppliers’ laboratories to estimate the exact filter replacement.

![Figure 10. Activated carbon cartridge for metal vapors.](https://www.3mchile.cl/)

**Face protection**

- Goggles protect the eyes and surrounding eye area from unwanted chemicals and particles. This is important to avoid exposure to mercury vapor. It is recommended that protective eyewear be ANSI Z-87 certified.

**Gloves**

- Safety gloves protect hands from contact with mercury, it is important to reduce exposure to this toxic element. The suggested material is NBR (nitrile rubber) because it offers good resistance to mercury and is readily available in the Colombian market.
Clothing

- Mercury handling often occurs in processing centers where other chemicals are present, chemical protective clothing is required to avoid contamination of the technician's clothing with mercury or other chemicals.
- Desired technical specifications: Coverall, breathable, anti-wrinkle, acid-proof, anti-shrinkage, waterproof and disposable.

Footwear

- Safety boots protect feet from chemical spills; in addition to mercury, other chemicals may be present in mining processing centers where mercury is often present such as cyanide, peroxide, hypochlorite, among others.

6.5.2 Occupational Health Aspects

Some of the general recommendations to be taken into account for people working with tailings in mining areas or handling waste containing mercury are as follows:

- Lifting loads for men should not exceed a load greater than 23 kg in frequent activities during the 8-hour workday.
- Lifting loads for men should not exceed a load greater than 12.5 kg in frequent activities during the 8-hour workday.
- It is recommended to have a rest period (active break) of 10 minutes every 1.5 hours of continuous work, as well as to establish defined snack and lunch hours.
- Hydration of people working with this type of material must be regular, no more than 1 hour, where a minimum of one glass of water is recommended.
- All tools available for use must be in good condition, otherwise they should be changed and taken out of operation if necessary.

6.6 Tailings transport considerations.

As part of the management activities for tailings with mercury content, it is highly probable that it will be necessary to move them from one place of origin to another for final disposal or intervention. In order to carry out this mobilization in a safe manner, without risk of environmental contamination, the most relevant aspects that should be considered for the development of this activity are exposed. These aspects can also be taken into account for the transport of other types of materials containing mercury, such as mercury waste or waste containing mercury. Given that mercury presents hazardous characteristics, all these aspects are framed under the current legislation for the transport of hazardous goods, which is contained in Decree 1079 of 2015.
6.6.1 Packaging

It is important to consider packaging for tailings that require mobilization from their place of existence, taking into account considerations such as the following:

- When the transport vehicle does not have a sealed container that avoids possible spills of fluids or leachates generated.
- When the tailings have a large amount of moisture in their physical composition.

Among the recommended packaging are:

**Canvas bags**

Many tailings can be found packed in canvas bags, which can facilitate their handling. However, it is advisable to carry out an inspection of these canvas bags and change them if they are found to be broken or in poor condition.

*Figure 11. Tailings packaging duffel bags.*

*Source: [https://www.multisac.es/productos/sacos-rafi-laminados/](https://www.multisac.es/productos/sacos-rafi-laminados/)*

**Plastic bins**

This type of packaging is recommended for tailings that have a high percentage of humidity, since they can be easily handled and transported, avoiding spills and preventing the release of mercury vapors with the use of container lids.

*Figure 12. Plastic tailings packaging bins.*

*Source: [https://www.canecas.com.co/index.php?id=2928]*

Packaging for mercury-containing waste varies according to the conditions in which it is found, i.e., solid, liquid and physical conditions of the material such as temperature, humidity percentage and size. What is important is that this packaging avoids possible releases of leached mercury or vapors.
6.6.2 Vehicle requirements

According to decree 1079 of 2015 the requirements to be met by the transport unit intended for the transport of tailings are:

- Identification signs and plate the United Nations (UN) number.
- Basic elements for emergency attention such as: protective clothing, flashlight, first aid kit, collection and cleaning equipment, absorbent material and other special equipment and supplies as stipulated in the Emergency Card (Colombian Technical Standard NTC 4532, Annex number 3).
- Carry at least two (2) multipurpose extinguishers according to the type and quantity of dangerous goods transported, one in the cabin and the others near the cargo, in an easily accessible place where they are readily available in case of emergency.
- Have an audible device or whistle that is activated when the vehicle is moving in reverse.
- In no case may a vehicle loaded with tailings circulate with more than one trailer and/or semi-trailer.

The vehicles that may be required for tailings transport are rigid vehicles and bulk transport vehicles, the technical specifications according to the type of vehicle are described below:

**Rigid vehicle**

According to the vehicle classification system in Colombia (resolution 4100 of 2004 of the Ministry of Transportation) these correspond to motor vehicles that can be trucks or vans with axle designation from 2 to 4 and a load capacity ranging from 6 to 36 tons.

In order to transport tailings in this type of vehicle it is necessary to pack the tailings in canvas bags or plastic buckets and secure them inside the vehicle, since the tailings cannot be deposited directly in the loading section of the truck. This type of vehicle could also be used to transport mercury waste and waste containing mercury, which should be properly packaged according to the conditions of the material.

![Rigid vehicle for tailings transport](https://www.manualdecomercioexterior.com/2018/03/que-tipos-de-vehiculos-de-carga-son-los.html)
**Dump truck**

Bulk transport vehicle used for earth moving and for hauling materials in general. It is equipped with a tilting open body that unloads by tipping and transports loads of up to 20Tm. This type of vehicle is recommended for the transport of tailings with low moisture content and does not require prior packaging and in addition to complying with the size and weight limits established in resolution 4100 of 2004, it is recommended to:

- Have tanks for leachate storage.
- A cover for the dump truck to protect rainwater and prevent the release of vapors into the environment during transport.

![Figure 14. Dump truck type vehicle for tailings transport. Source: https://sp.depositphotos.com/vector-images/volqueta.html](https://sp.depositphotos.com/vector-images/volqueta.html)

### 6.6.3 Transport documentation

Includes all safety documents that must be kept on hand at the time of transport. As stipulated by Colombian regulations, these documents are:

- Tailings emergency card,
- Tailings safety data sheet.
- Emergency plan
- Cargo manifest
- Transport plan (origin and destination)
- And all those documentary requirements contained in decree 1079 of 2015, or any regulation that complements or replaces it, provides for transportation.

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6 [https://sites.google.com/a/correo.udistrital.edu.co/manualviviendas/4-equipo/volqueta](https://sites.google.com/a/correo.udistrital.edu.co/manualviviendas/4-equipo/volqueta)
6.6.4 Vehicle labeling

It is important to clarify that the vehicle labeling depends on the information contained in the Safety Data Sheet of the material to be transported, so it is necessary to have the respective document of the transported material and also comply with the provisions of Decree 1079 of 2015.

The vehicle placard consists on the one hand the specifications established in NTC 3971 that relates to the transport of hazardous products, Class 8 - Corrosive substances and NTC 3969 for class 6 - Toxic substances and on the other hand the UN number for emergency response.

The corresponding placards for tailings containing mercury are Class 8 Corrosive Substance and Class 6.1 Toxic. The plates should be made of reflective material, black and white, with a minimum size of 25 cm by 25 cm and the pictograms are for Class 8: Two test tubes dropping a drop on a metal plate and a hand, the word corrosive and the number 8 corresponding to the hazard class should also appear. Class 6: Skull and crossbones, the word toxic and the number 6 must also appear in the lower corner. These placards must be installed on all visible faces of the transport unit.

![Class 8 (6.1) label for vehicle](source)

The second placard that the transport unit must comply with is the UN box, which must be made of reflective material with the number 2809 corresponding to mercury, with orange background, numbers and black borders. This label must be installed on all fronts of the vehicle.
6.6.5 Driver training

According to Decree 1079 of 2015, the mandatory basic training course for drivers of vehicles transporting dangerous goods is the preparation that drivers must receive to operate vehicles intended for the transport of dangerous goods, in order to acquire knowledge necessary for the safe handling of the materials to be transported, which, in the scope of this study correspond to the risks associated with mercury waste, waste with mercury and mercury-containing tailings.

7 References


Ministerio de Ambiente, y Desarrollo Sostenible. Resolución 2206 - “Por el cual se adoptan los términos de referencia de Estudio de Impacto Ambiental EIA”. Bogotá, 2016.


