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

Technical Report on Mercury Recovery from Tailings

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1. Introduction

Identifying technologies that recover mercury from tailings generated by artisanal and small-scale gold mining (ASGM) is part of the project "Promoting Responsible Recovery and Handling of Mercury from Contaminated Artisanal Gold Mining Tailings in Colombia," implemented by Pure Earth and financed by the U.S. Department of State (DOS). The project's strategic partners include the Centro Nacional de Producción más Limpia (CNPML) and the private company Innovación Ambiental - INNOVA S.AS E.S.P.

The general objective of the project is to reduce the amount of available mercury by use in the artisanal and small-scale gold mining (ASGM) sector in Colombia. Specific objectives include:

- 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 within the framework of the first specific project objective. It presents the results of the project's review of available information for the identification and description of promising technologies that recover mercury from tailings generated by ASGM in Colombia.

Much of this document's content derives from a technical workshop carried out in Medellin on May 7-9, 2019. Attended by national and international experts, this event consolidated information concerning the potential technologies available that recover mercury from tailings generated by ASGM, as well as comments and discussions contributed by members of government institutions.

The project "Promoting Responsible Recovery and Handling of Mercury in Contaminated Artisanal Gold Mining Tailings in Colombia" began in October 2018 and continues until September 2021. This document represents a first approach to Hg recovery technologies in contaminated tailings and may be complemented and / or modified based on progress during the project's lifetime.

2. Background

In Colombia, management of mercury contamination began between 1995 and 2000 under leadership agreements between the Ministry of Environment and various independent corporations to promote cleaner production in the country. These addressed the handling of mercury in various levels of productive processes (Hoof & Herrera, 2017). Between 1999 and 2005, the project Río Suratá in Santander,

conducted in cooperation with Germany and the BGR (Bundesanstalt Für Geowissenschaften und Rohstoffe), began to develop mercury-free gold mining techniques (Hruschka, 2003).

Furthermore, in 2010, 2014 and 2018, the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) published the National Study of Water (ENA), which presents the monitoring data on mercury in the country's main surface sources (IDEAM, 2010) (IDEAM, 2015) (IDEAM, 2019). This research supported Colombia's commitment to the Minamata Convention from 2010-2013 (Garcia., et al, 2017) and the 2013 Law 1658 (Congreso de Colombia, 2013), which focused primarily on the eradication of mercury in mining. In 2014, the Ministry of Environment and Sustainable Development (MADS), in conjunction with the Ministries of Mining, Health, Labor, Agriculture, Transportation, Commerce, Industry and Tourism, created the National Mercury Plan, which is intended to regulate, relocate and dispose of the element throughout the country (Ministerio de ambiente y Desarrollo Sostenible, 2014).

Between 2018-2019, Colombia passed Law 1892 (Congreso de Colombia, 2018), which included the approval of the Minamata Agreement and the initial implementation of the National Mercury Plan as well as the Plan of Environmental Sectoral Action on Mercury (SINA), both of which were milestones in Colombia's commitment to combatting the problem of mercury use. The issue of mercury eradication is also part of the National Development Plan and is included within the broad goals to transform the country.

While these antecedents demonstrate the practical steps taken to address mercury use and disposal, for this project it will be necessary to describe the reality of mercury use in the Colombian ASGM sector.

The history of mining in Colombia, including the industry's large growth in the 1970s due to the oil crisis, involved an expansion in gold mining in regions such as Remedios and Segovia (Antioquía), Marmato (Caldas), Buenos Aires (Cauca), Santa Rosa del Sur (Bolívar) and Istmina and Tadó (Chocó), among other municipalities (PNUMA, 2012).

Although the development of the Colombian mining sector has generated economic benefits, there are also negative impacts to the environment, which affect the health of the population in proximity to the mining sites, disturb the social order and even generate potential national security risks for Colombia. The proliferation of illegal gold exploitation and the emergence of other mineral holdings such as coltan, which are used for electronics manufacturing, hinder the government's control of mining activities, expand participation in mining activities of illegal groups, violate the rights of ancestral mining communities, and pollute natural resources (Ministerio de Ambiente y Desarrollo Sostenible, 2012)

In general, mining activities tend to negatively impact fertile lands, natural and forest reserves, and water sources because the techniques used in artisanal mining are primarily rudimentary.

Artisanal gold production in Colombia is distributed in 261 municipalities and in 19 departments in the country *(Ministerio de Ambiente y Desarrollo Sostenible, 2014),* the

majority of which use rudimentary techniques to amalgamate gold with mercury. This process is carried out in processing plants called “Entables”, using equipment such as shaking tables, small ball mills and other technologies that add mercury to ore and generate a residue called a “tailing” *(Veiga, 2011).*

These tailings are the final residues left behind by the mining process, are composed of the characteristic material of the mineral containment deposit, and are frequently contaminated with traces of mercury, cyanide and other heavy metals such as lead. In Colombia, residual mercury pollution by gold extraction is one of the most significant problems because of the difficulty of handling this metal, due to its physicochemical properties, especially its volatility and ability to form metallic compounds that become difficult to stabilize *(Beltrán-Rodríguez, L.N., Larrahondo, J.M. and Cobos, D, 2018).*

The above cases lead to the mismanagement and mishandling of tailings, since they are stored in rudimentary canvas bags or arranged in artificial “pools” that do not meet any technical specifications, increasing the risk of environmental pollution.

3. The Chemistry of Mercury

Because mercury concentrations in tailings is highly variable and mercury has a high degree of physicochemical changes in the environment, it is important to know its properties clearly, in order to understand how the different technologies presented here function.

The most important sources of mercury are volcanic emissions, the generation of coal-based energy, the use of mercury-containing industrial products (lamps, thermometers, blood pressure monitors, electronic switches, etc.) (Morel, Kraepiel and Amyot, 2002), and ASGM, which has the highest impact and relevance in Colombia.

Mercury is a global contaminant because its mobility as an inorganic form in the environment facilitates its presence in air currents and its solubility in water according to the temperature at which it is found. A chief environmental concern is that mercury can extend several kilometers from the point of origin, affecting communities far removed from the site of release. Mercury and its interactions with microorganisms, plants, and animals generate a closed cycle that can be observed in Figure 1, which causes long-lasting and increased chemical risk.

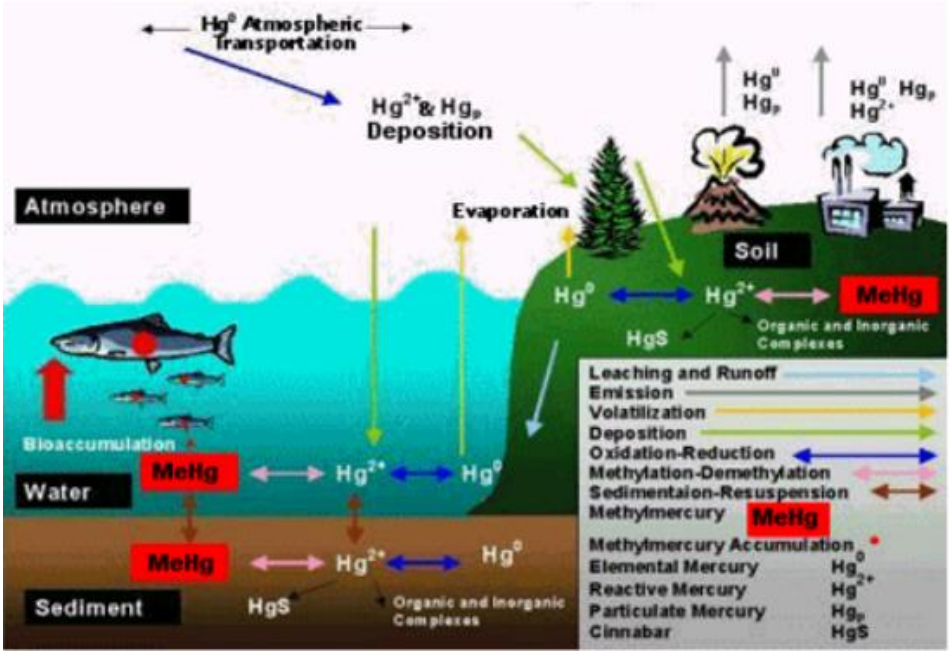

Figure 1 Mercury Cycle

Taken from: http://www.bdigital.unal.edu.co/1125/1/angelicamariajimenezgomez.2005.pdf

Studies such as those conducted by the University of Windsor Montpellier (Amélineau et al., 2019, Hudelson et al., 2019) have shown that the effect of mercury contamination has reached places as far as the Arctic Circle, where species of the region, such as the foraging auk (Alle alle) (Amélineau et al., 2019), the alpine trout (Salvelinus alpinus) (Hudelson et al., 2019) and the pilot whale (Globicephala melas) (Bolea-Fernández et al., 2019) have been seriously affected, despite the significant distance from the source of emission. The presence of mercury in such remote places is explained by the fact that its mobility in the atmosphere increases at high altitudes, where the oxidant environment promotes the formation of divalent species, which are deposited on the surface in the form of soluble halides.

The adverse effects of mercury also harm humans. Studies in India and China (Chen et al., 2019, Subhavana, Qureshi and Roy, 2019), two of the countries with the highest mercury contamination, have shown that this element can directly enter into contact with people using water contaminated by agricultural activities, such as rice crops and fishing. In water, the mercury present (Hg0) may be oxidized photolytically or chemically to Hg (II) in the form of oxides, chlorides or cyanides, which results from improper cyanidation practices during mining activities (Velásquez-López et al., 2011).

Mercury in its oxidation state +2 can undergo a methylation process to produce methylmercury (MeHg +) due to the intervention of sulfate-reducing bacteria, a phenomenon that has been studied for several years (Gilmour, Henry and Ralph, 1992, Boening, 2000, Ullrich, Tanton and Abdrashitova, 2001, Morel, Kraepiel and Amyot,

2002). Studies suggest that an environment rich in methyl groups and thiol groups, found in the proteins and enzymes of these bacteria, forms highly neurotoxic, methylated products.

In addition to the introduction of mercury into ecosystems by rivers and natural channels into vegetation, it also enters the trophic chain through smaller organisms, such as fish, where it bio-accumulates and bio-magnifies, as it is scaled up in the food chain (Morel, Kraepiel and Amyot, 2002) until reaching humans. Cases have been reported of fish with Hg concentrations as high as 0.83 ± 0.43 µg Hg / g in the Brazilian Amazon (Castilhos et al., 2015) and 0.77 µg Hg / g on the coast of South Africa (Bosch et al., 2016). In Colombia, several critical cases have been documented in the department of Bolívar with concentrations of 1.20 ± 0.06 µg Hg/g (Marrugo-Negrete, Benitez and Olivero-Verbel, 2008), which is more than twice the maximum concentration suggested by the World Health Organization (0.5 µg Hg/g).

Considering the biological threats posed by mercury and the complex dynamics it presents in the biosphere, it is important to make decisions that reduce and eliminate mercury from industrial and mining activities, replacing it with more efficient and cleaner technologies.

4. Methodology for Identifying Technologies

In order to identify technologies available for mercury recovery from tailings generated by gold mining, the project team conducted an extensive bibliographic review of existing mercury recovery techniques in the pilot or finalized stage.

To obtain this information, the project team conducted a keyword search using open search engines such as Google, Google Scholar, and ResearchGate as well as multidisciplinary and specialized databases such as ScienceDirect, Scopus, Springer Link, Academic Search Complite, CSR and ACS. Keywords used included: gold, mercury, gold mining, mercury recovery, tailings, gold recovery techniques in tailings, among others. In addition, companies that extract gold without the use of mercury directly participated, providing detailed technical information. Interviews were also conducted with key stakeholders and actors. This enabled the project team to identify relative ongoing projects and offered important information for the project's objectives.

To avoid loss of information during the research process, the team employed a two-stage search strategy. Firstly, general information was collected on techniques related to mercury recovery (Hg^0) from tailings, as well as remediation strategies that decontaminate or immobilize metallic or oxidized mercury (without recovering gold), as these strategies can complement Hg^0 recovery techniques. In total, 17 technologies were included in this first stage:

- Gravimetric concentration of mercury
- Cal and Humus Concentrations

- Retort Thermal Treatment
- Amalgamation with Copper Plates
- Sulfide treatment for tailings
- Electrokinetic Remediation
- Yoduro Solution System
- Ion Exchange
- Membrane Process I
- Membrane Process II
- Nano-leaching
- Mechanical Grinding and Recovery with Lixiviation
- Thermal Treatment
- Neutralization
- Mercury Recovery of Mixed Waste - Rotating Retort
- Retention during Liquid Phase Assisted by Polymers
- Mercury Capture by Deep, Eutectic Solvents

During the second stage, the team refined the selection process by restricting the search to technologies that ideally meet the following criteria:

i) are in pilot scale or higher;
ii) have the objective of recovering mercury in its elemental state.

The following 8 technologies were selected that conform to these criteria:

- ✓ Copper Plates
- ✓ Foam Flotation
- ✓ Electrolysis
- ✓ Activated Carbon and Electrodeposition
- ✓ Nanotechnology
- ✓ Distillation
- ✓ Smart burners
- ✓ Gravimetric Concentration Methods

These technologies are described in detail in section 5 of this document.

To objectively compare the technologies selected in the second stage, the team created a technical spreadsheet to compare technologies in terms of complexity, limitations, field implementation, performance, operation, maintenance, and impact of operation on the environment. Companies implementing these technologies participated directly in the creation of the spreadsheet, enabling a practical evaluation of recovery strategies. This spreadsheet can be found as an annex to this document.

4.1 Tailings mineralogy in Colombia

The mineralogical composition of tailings is consider one of the parameters of great importance that can affect the effectiveness of the mercury recovery technology that is selected. However, establishing the mineralogy of tailings directly is not very easy, because there are no methodologies or processes established for this purpose so far. For this reason, available secondary information that describes the mineralogy of different areas of the country will be assumed as the same of tailings, without forgetting that these tailings are already they went through a process of extracting gold with mercury (for free gold) and possibly a cyanidation process (for associated gold).

The mineralogical composition of deposits determines the behaviour of ores in the benefit processes. For this reason it is of great importance to know from its origin the geological processes involved in their formation, as well as the final conditions of the mineral deposit (Servicio Geológico Colombiano, Ministerio de Minas y Energía, 2018)

Thus, the Colombian Ministry of Mines and Energy, in association with research centers and the national university, developed a study in 2018 with several areas of the country where the following methodology was met:

- Rock analysis: the sample was selected and a fraction was extracted, which was polished, from 60 to 40 microns (thin sections polished) to perform microscopic analysis (petrographic and metallography).
- General mineralogical analysis: the sample was selected, sprayed at a d80 of 1.4 mm to polish the particulate material.
- Specific mineralogical analysis for gold: the sample of the general mineralogical analysis was sprayed at a d80 of 300 microns and concentrated to subtract the gold and make it visible to the petrographic analysis. The material was concentrated and mounted on glass to make roughing at 40-50 microns. Subsequently, this concentrate was polished and shined to undergo a petrographic and metallographic analysis.

A summary of the results obtained from the type of minerology and the amount of gold available for each of the areas studied can be seen in tables 1 and 2.

Table 1. Mineralogical distribution of the land of the mining front in different municipalities of Colombia.

		type of mineralogy (%)			
Municipaly	**Department**	**Pyrite**	**Arsenopyrite**	**Ganga**	**Others**
Andes (S1)	Antioquia	16.1	48.62	25.56	9.72
Andes (S2)	Antioquia	52.20	6	27.79	14.01
Iquira	Huila	19.22	3.06	76.97	0.75
La llanada	Nariño	9	16	54	21
Andes – Soto Mayor	Nariño	0.7	7.4	69.3	22.6
Marmato	Caldas	22.24	0.04	71.29	6.43
Riosucio	Caldas	49.33	2	48.32	0.35
Quinchia	Risaralda	8.6	0.2	81	10.2
Suarez	Cauca	18	17	25	40
Buenos Aires	Cauca	13	0	75	12

Fuente: Servicio Geológico Colombiano, Ministerio de Minas y Energía, Guía metodológica para la eliminación del uso del Mercurio en la actividad minera (Buenos Aires y el tambo - Cauca, Andes - Antioquia, Íquira - Huila, La Llanada y Andes Sotomayor – Nariño, Rio Sucio, Quinchía y Caramanta – Caldas). Bogotá, Colombia 2018.

Table 2. Percentage of the different gold available in different municipalities of Colombia.

		Gold available (%)		
Municipaly	**Department**	**Free**	**Associated**	**Included**
Andes (S1)	Antioquia	75.46	24.34	0.2
Andes (S2)	Antioquia	64.53	30.6	4.87
Iquira	Huila	17	43	40
La llanada	Nariño	9	27	64
Andes – Soto Mayor	Nariño	40	30	30
Marmato	Caldas	2	29	69
Riosucio	Caldas	82	16	2
Quinchia	Risaralda	2	16	82
Suarez	Cauca	87.3	9.9	2.8
Buenos Aires	Cauca	39.6	0.6	59.8

Fuente: Servicio Geológico Colombiano, Ministerio de Minas y Energía, Guía metodológica para la eliminación del uso del Mercurio en la actividad minera (Buenos Aires y el tambo - Cauca, Andes - Antioquia, Íquira - Huila, La Llanada y Andes Sotomayor – Nariño, Rio Sucio, Quinchía y Caramanta – Caldas). Bogotá, Colombia 2018.

As can be seen in the two previous tables, the variability of the mineralogy and the amount of gold available according to its form varies greatly between different areas of the country, including between the same department. We must remember that the data

obtained were achieved thanks to the measurement of sulfide released in each of the samples.

4.2 Current status of tailings in Colombia and some case studies.

In Colombia, artisanal gold mining employs approximate 200,000 people, who produce about 30 tons of gold per year. These miners take the gold-bearing ore to processing centers that operate in urban areas and amalgamate the material without using concentration, filtration or previous condensation before burning the gold (Ministerio de Ambiente y Desarrollo Sostenible (MADS) & United Nations Environment Programme (UNEP), 2012). According to studies carried out in several Colombian departments, 50% of the mercury added to the gold mills is lost, with 46% lost in tailings and 4% during the burning of the amalgam (Cordy et al., 2011). These studies demonstrate the high degree of mercury contamination found in mining tailings.

In developing this project, three case studies were selected that are of high priority for the government due to their effects on protected ecosystems or high concentrations of mercury. Furthermore, due to their location and geochemical characteristics, these studies are broadly representative of conditions found throughout Colombia.

Below, the general characteristics of the three prioritized cases are briefly described (REF: Ministry of Mines, MADS and PNN documents).

a. Case Study 1: Benefit Plants in the Department of Antioquia

The department of Antioquia is characterized its large quantity of mining municipalities, where gold is extracted using mercury in “entables” or independent ore processing centers. The municipalities that have these characteristics include Segovia, Remedios, Cisneros, San Roque, Providencia, Butirica, among others.

There is no precise data on the total amount of tailings existing in Antioquia; however, Colombia has emerged as the third largest producer of mercury emissions, between 50 and 100 tonnes per year (Telmer & Veiga, 2019). Among the advanced characterizations conducted in these sites, mercury levels vary between 5 ppm and 400 ppm. Pure Earth’s Toxic Sites Identification Program (TSIP) has identified almost 20 sites with these characteristics.
Access to these sites usually is not difficult. However, one of the biggest challenges associated with these sites is the threat posed to public order by illegal groups.

b. Case Study 2: Municipality of Rio Quito – Choco

The municipality of Rio Quito – Choco has an area of 69,914 ha, 60,966 ha of which correspond to Afro-descended communities and 9,034 ha to indigenous reserves. It

contains 7,559 inhabitants, 94.9% are from the Afro-descended communities and 5.1% from indigenous communities (Castro, 2018).

Rio Quito – Choco is located in the middle section of the Atrato River basin in the region of equatorial calms (doldrums). According to the Holdridge system, which classifies terrestrial areas according to global bioclimatic behavior, the municipality is part of the very humid tropical forest life zone (bmh-T), characterized by having a higher temperature than 24 ° C and precipitation of 8,000 to 10,000 mm per year (Instituto de Investigación SINA, 2015).

Unfortunately, there is not much data available that describe the concentration of mercury or other contaminant in abandoned tailings of this area, some few evidence shows the presence of mercury at more than 0.1 ppm in sediments in the mouth of Rio Quito (WWF & Universidad de Cartagena, 2016). However, studies have shown that mean values of total Hg in human hair in Quibdó was 1.26 µg / g (range: 0.02-116.40 µg / g) and 0.67 µg / g (range: 0.07-6.47 µg / g) in Paimadó, which exeed the WHO maximum safe level is 5 µg / g (Correa, 2016). Furthermore, mercury concentrations in fish of the Atrato River exceeded the WHO limit, with higher levels in *Pseudopimelodus schultzi, Ageneiosus pardalis, Sternopygus aequilabiatus, Rhamdia quelen and Hoplias malabaricus*, while the lowest levels occurred in *Cyphocharax magdalenae* and *Hemiancistrus wilsoni*.

Although there is no difficulty in accessing the affected sites, the issue of civil security in the area should be strongly considered.

c. Case Study 3: Farallones National Park - Valle del Cauca

Farallones National park is the largest protected area in the Valle del Cauca where more than 540 species of birds are conserved and more than 30 rivers are born that supply the southwest of Colombia. It has four ecosystems, which are: Tropical Humid Forest (between 200 and 1,200 meters of altitude), Humid Subandino Forest (between 1,200 and 2,000 meters above sea level), Humid High Andean Forest (between 2,000 and 3,500 meters of altitude) and Páramo (with altitudes superior to 3,500 meters) (Parques Nacionales Naturales de Colombia, 2013). Within the natural parks the development of industrial activities that affect the environment and much less mining is not allowed. For this reason, the available data corresponds to data provided directly by the nature park authorities, which have promoted risk analysis studies with private companies, data that are often confidential.

Since 2014, mining extraction centers have been identified in the sector of Alto del Buey and Minas del Socorro that extend within the national protected area for an estimated 677 hectares. Currently, 421 tunnels have been identified, which were constructed in non-technical conditions and used for gold extraction. In addition, various camps and access roads have been built using inadequate techniques and technologies, which are insecure and do not prevent or mitigate environmental damage. Of the mining

exploitation sites, about 85% are located in a primitive zone, 10% in an intangible zone and 5% in a natural recovery zone (Contraloría General de Santiago de Cali, 2018).

In many of these sectors, the environmental effects are mainly due to local pollution (poor waste management), regional influence (improper use of toxic substances, such as cyanide and mercury), and alteration of water channels and surface bodies. Relevant data can be found in *Table 3* and *4.*

Table 3 Variation of mercury concentrations in sediments in the Socorro / Alto del Buey mines in 2016, 2017 and 2018 (mg Hg / kg). Analysis performed by the CVC environmental laboratory

No.	Sector/Camp	April 2016	March 2017	September 2017	May 2018	July 2018
1	Anchicayá	102.06	16.43	1.21	109.08	29.45
2	Ferney	2.11	2.11	0.61	6.33	<1.78
3	Teófilo	1.48	0.78	1.49	15.52	2.54
4	Trasvase	2.08	0.55	0.46	5.19	12.44
5	Simón Bolívar	2.13	4.56	4.29	15.74	6.72
6	Zacarías	2.89	0.99	3.42	10.23	<1.78
7	Quebrada Juntas	2.57	0.35	<0.2	<1.78	<1.78
8	Paqueteso	-	10.1	7.42	3.23	14.48
9	Base Militar	-	3.18	11.08	57.23	18.42
10	Gimnasio	-	12.48	11.84	6.91	90.99
11	Rio Cali Santa Rita	-	-	-	-	<1.78

The available data show the presence of mercury in 10 of the 11 areas evaluated, a variation of the concentrations found over the years is also seen due to the fact that, being mining activities, they permanently change their site, achieving a representative extension of the problem.

Table 4 Estimation of the volume of tailings present in the mines in Socorro

No.	Camp	Coordinates		Altitude (m)	Volume (m^3)
1	Campamento Base (checkpoint)	0.3°24'0.76"	76°41'00.2"	3.184	114.7
2	Campamento "Feo"	03°24'46.4"	76°40'58.4"	3.358	20.4
3	Cancha (basecamp)	0.3°24'08.2"	76°41'00.0"	3.251	3.9
4	Base (near sanitary unit)	0.3°24'06.6"	76°41'24.9"	3.263	5.4
5	Derrumbe "Zacarías"	03°24'21.6"	76°41'18.4"	3.484	2254.5
6	Socavones o bocaminas "Eider Martínez"	03°25'02.2"	76°41'16.0"	3.140	910.1
7	Socavones o bocaminas "Feo"	03°24'39.4"	76°41'34.1"	3.398	2835.8
8	Campamento y bocaminas Paqueteso	03°24'51.3"	76°41'46.3"	3.100	3235.3
9	Campamento Trasvase	03°24'44.0"	76°41'55.0"	3.030	1063.3

The study also makes an estimate of almost 10,500 m^3 of contaminated tailings, which is considered a fairly representative amount considering that it corresponds to a protected area and its level of risk is different. Also, the complexity of accessibility to the sites for being considered a mountainous terrain and stone roads is other point to consider.

5. Mercury Recovery Technologies

The technologies described below correspond to those that were selected for presentation during the Medellín Technical Workshop on May 7-9, 2019, by the corresponding responsible party. Selection took into account field tests conducted at the laboratory or industrial level. Testing signified that results exist on the technology's process, either with specific mercury data or data on recovery from this metal, with which the feasibility of obtaining Hg from mining tailings can be approximated. These technologies include:

- ✓ Copper Plates
- ✓ Foam Flotation
- ✓ Electrolysis (Prototype)
- ✓ Activated Carbon and Electrodeposition
- ✓ Nanotechnology
- ✓ Distillation
- ✓ Smart burners
- ✓ Gravimetric Concentration Methods

Note: Information contained in this section, including, but not limited to information concerning mercury recovery technologies, was provided by participants of the 2019 Medellin Mercury Recovery Workshop and does not necessarily reflect the opinions, endorsement or property of Pure Earth, project partners or the US Department of State.

Under no circumstances shall Pure Earth or the Department of State, or either organization's staff, board members, consultants, affiliates, suppliers or partners be liable for any direct, indirect, incidental or exemplary damages arising out of the use of technologies, methodologies or other information contained herein.

5.1 Copper Plates.

Description: This technique uses copper (Cu) plates coated with silver (Ag), which has been identified as an easy and economical way to remove mercury from tailings so the tailings can be used in the cyanidation process to extract residual gold. As a result, this technology does not work effectively alone and instead should be combined with other processes in order to increase efficiency.

According to the information given by the expert, this technology has been piloted in countries such as Venezuela, Costa Rica and Brazil with excellent results, obtaining almost 95% of the mercury present in tailings.

The technique works because the silver layer on the surface of the copper captures drops of mercury (and some traces of gold). Cu-Ag silver plates are commercially available in Brazil, where they are modified using a cover of tin (Sn) and then silver (Ag). This provides a good protection for the copper surface, which can oxidize if exposed.

Figure 2 Silver-Covered Copper Plates in a Cascade Arrangement

Taken from: *Avances. Las buenas prácticas de Recuperación de Oro y Mercurio*. Professor Marcello Veiga, University of British Columbia. Workshop: Promoting the Recovery and Responsible Management of Mercury in Contaminated Tailings from Artisanal Gold Mining in Colombia. May 2019. Medellín Colombia

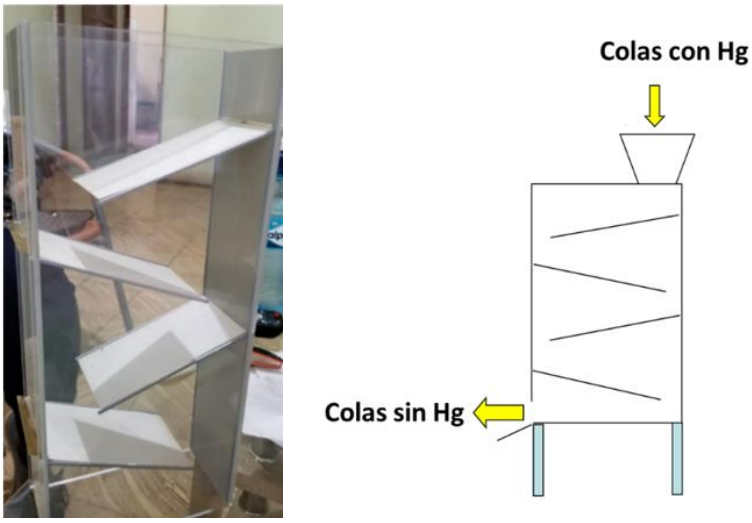

Figure 3 Silver-Covered Copper Plates in a ZigZag Arrangement

Taken from: *Avances. Las buenas prácticas de Recuperación de Oro y Mercurio*. Professor Marcello Veiga, University of British Columbia. Workshop: Promoting the Recovery and Responsible Management of Mercury in Contaminated Tailings from Artisanal Gold Mining in Colombia. May 2019. Medellin Colombia

Operating conditions: According to the experimental work carried out by the work team that developed this technology, the copper plates are 30 x 40 cm and should be arranged in a cascade or in two zigzag-shaped sets inside a plastic or wooden container. The amount of tailings to be treated depends on the size of the plates and whether or not it is possible to recirculate the process at least three (3) times. For this reason, a pretreatment phase is necessary, which involves dissolving the tailings in a solution, so it can be adapted into an existing process.

Field application (efficiency): According to field tests developed with copper plates, for every 63 g/ton Hg of mining tailings that enter the plates, 3 g/ton Hg exits the plates, representing a 95% efficiency rate.

Implications for Implementation: Silver-covered copper plates have the advantage that they can be manufactured locally and that they are easily implemented in ASGM sites. The process also requires a 12 V battery as well as silver nitrate solution to be implemented.

One of the principle obstacles to implementation is the capture of oxidized drops of mercury. These drops form a thin layer of mercury oxide, which must be removed by heavy shaking before the process since it cannot be trapped by the silver. If heavy shaking does not remove the oxidized layer, adding reagents such as hydrogen peroxide may also be effective in removing the HgO layer.

The plates are easy to manufacture. They should have a rough, clean surface, which is achieved by applying nitric acid, and then must be immersed in a silver nitrate solution. In other words, the metallic plate must be dissolved in nitric acid, in order to connect the battery's negative and positive sides in the silver nitrate solution so that they can be recovered.

Considerations and discussion: This technique has several advantages, including onsite application and feasible management by miners due to the ease of implementation and low-cost compared to other techniques. However, it is important to note that, if the cyanidation process is applied to obtain residual gold after the initial recovery process, the technique can generate an environmental impact due to traces of mercury present in the tailings.

5.2 Foam Flotation

Description: This technique presents the most appropriate combination of reagents to recover not only mercury, but also gold and silver, from small mining tailings through the foam flotation process and evaluates their effectiveness in solution. The materials and methods involve a characterization of the samples, the concentration of solid-liquid pulp, an input granulometric phase, a pH regulation by caustic soda (NaOH), an activator by means of lead acetate, and a collector. This process can be observed in Figure 4.

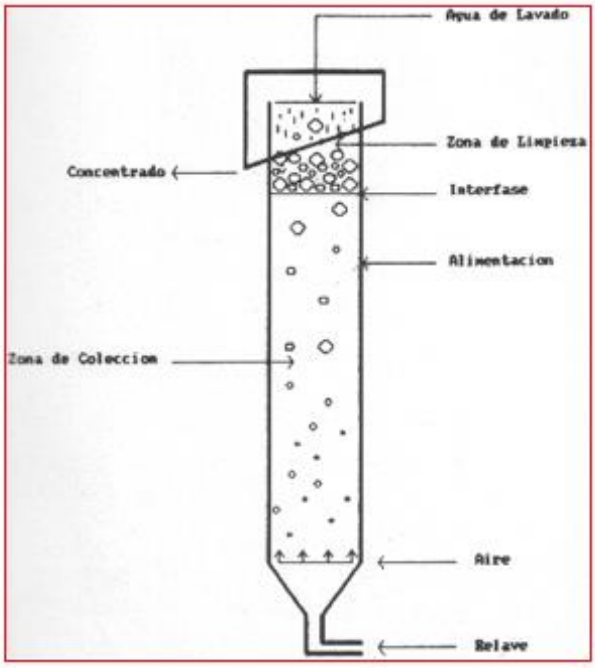

Figure 4 Flotation Equipment by Column

Taken from: Mineralogical advances in the recovery of mercury in mining tailings. Engineer Moisés Oswaldo Bustamante. Workshop: Promoting the Recovery and Responsible Management of Mercury in Contaminated Tailings from Artisanal Gold Mining in Colombia. May 2019. Medellín Colombia

Operating Conditions: The required operating conditions are: granulometry according to each benefit facility sampling (<75 µm); solid-liquid dilution of pulp: 1:3; six foaming flotation tests for each benefit facility; size of the sample: 3 Kg; pH regulator: caustic soda (NaOH); pH of flotation: 6; activator: lead acetate (50 g / ton of mineral); collector; conditioning time: approximately 9 min; and mineralogical characterization (Mineral & Metallurgical Processing Division (MPD), Society for Mining, Metallurgy & Exploration, 2019).

Field application (efficiency): From the available data, three-quarters (3/4) of the initial mercury contained in the samples was recovered as well as considerable quantities of gold and silver. Mercury recovery values of up to 75% and over 90% for gold and silver can be recovered by this method. During the field test in the municipality of Cañasgordas, recovery of Hg varied from 16.5% to 49%, recovery of Au varied from 39.5% to 94%, and recovery of Ag varied from 79.5% to 95.5%. (Bustamante, Francisco J, & Patiño S, 2019)

Implications for implementation A flotation column must be provided according to the amount of tailings to be treated and operating conditions must be correctly measured. There is no estimate of the costs and pretreatment of the tailings must be carried out before the process begins.

Considerations and discussion: Although the technology has some efficiency, the process of pretreating the tailings is an important aspect to evaluate in the technique's implementation viability, since it can significantly increase the costs of treatment.

This technology involves the construction of a plant with a flotation column and the transport of tailings to the plant. As a result, the technique is recommended in cases with easily accessible tailings. For example, this method could be considered in the case of the beneficiation plants in the Departments of Antioquia and Chocó.

5.3 Electrolysis (Prototype)

Description: This technology is based on an electrokinetic system, which applies a low magnitude of direct electric potential between two or more sacrificial (galvanic) electrodes placed on opposite sides of a contaminated soil mass or sediment. The electrical potential generates a strong gradient of EH-pH between the two electrodes, promoting an anodic dissolution, a migration of the metals and a precipitation force, in the almost neutral pH values at the interface of the anodic and cathodic domains. After several tests carried out by the work team that developed this technology, it was determined that the system uses approximately one tenth (1/10) of the energy requirements of most conventional electrokinetic systems. For this technique, a lixiviation with thiosulfate and electro-recovery are required. The equipment used in this process can be seen in Figure 5.

This technique has been initially worked to obtain gold, however, due to the tests and results obtained in the field, although the efficiency on mercury has not been quantified, if traces have been obtained that make it easy to adapt to the recovery of mercury.

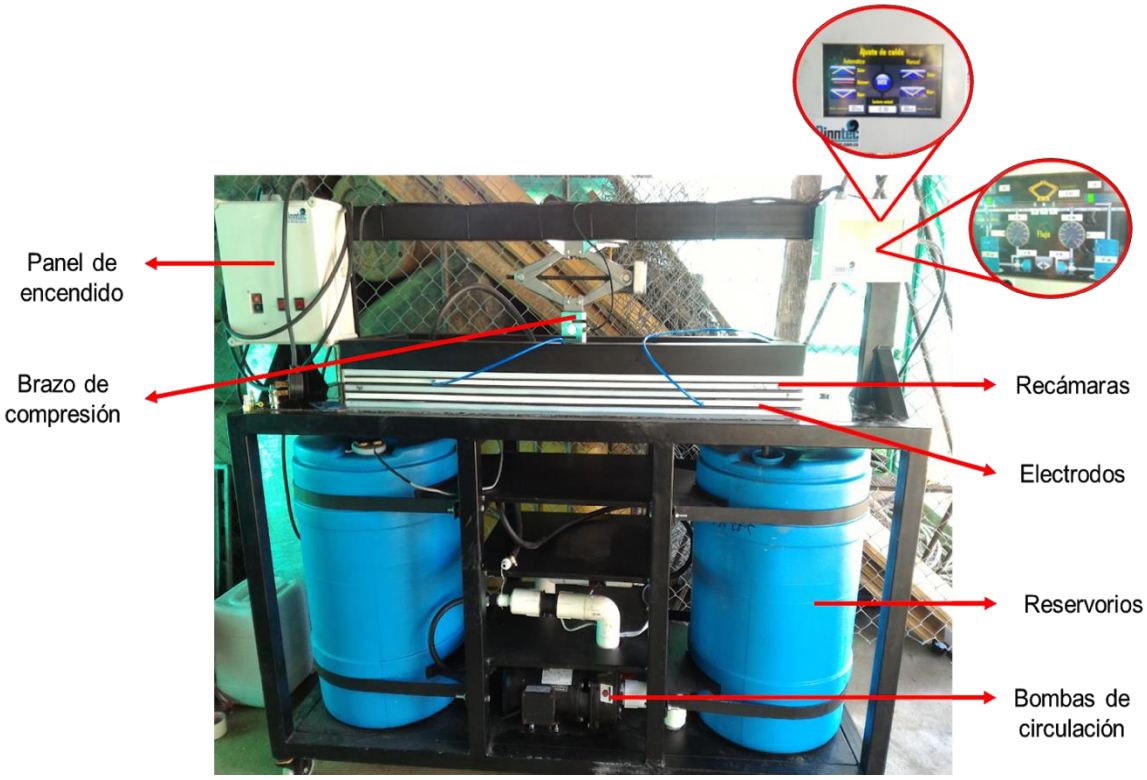

Figure 5 Electro Equipment – Gold Recovery

Taken from: Mineralogical Advances in Mercury Recovery from Mining Tailings. Engineer Moisés Oswaldo Bustamante. Workshop: Promoting the Recovery and Responsible Management of Mercury in Contaminated Tailings from Artisanal Gold Mining in Colombia. May 2019. Medellín Colombia

Operating Conditions: the three basic processes of this technology are oxidation, lixiviation and electrodeposition. The variables to be considered in the process are: pH, which can be acidic, generating the formation of Hg_2Cl_2(S), neutral, decreasing the speed of dissolution, or basic, generating the formation of HgO (S); the anode, which generates a high resistance to electrolytic oxidation: Ti – DSA; and the cathode, which permits the formation (or lack thereof) of the amalgam Al, the current density that allows control by activation for below potentials and control by mass transport for above potentials.

Field application (efficiency): This technique has only been tested at the laboratory level rather than in the field.

During the lab tests, the technology obtained gold with recovery efficiencies on the order of 80%. However, although efficiency for Hg has not been quantified, traces have been identified during the tests and, in theory, the technique should work similarly for mercury as for gold.

Implications for implementation: After several tests, its determined that in order to implement this technology for electro-recovery, the reactor must conform to the parameters shown in Table 5:

Table 5 Parameters for the implementation of the electro gold recovery reactor

Reactor Dimensions and Capacity	
Number of chambers	2
Number of tanks	2
Capacity of each tank (L)	125
Number of electrodes in each chamber	2
Electrode exposed area (m^2)	0.207 (90cm x 23cm)
Flow velocity at the reactor inlet (m/s)	0.114
Flow at the tank outlet (L/min)	90
Processing capacity per day (kg concentrated/day)	200

Considerations and discussion: The energy costs for this technology are very high due to the permanent use of electric current, which can be challenge to this technique's implementation and viability. Furthermore, this technology is in the research phase and the reports reached are specifically for gold and not for Hg.

The critical variables for the electrolysis process include: the pH, which should be as neutral as possible; the electrodes, which must have a high resistance to electrolytic oxidation; the current density; and the hydrokinetic conditions of the process.

According to the results obtained from the tests developed on this technology, it was determined that the advantages of using electrokinetic technology include: lower degree of corrosion in the electrodes; stable pH between 7 and 10; Au and Hg can be recovered; it is an environmentally friendly process; and the thiosulfate used can be recovered. The disadvantages of the process include a processing time of 2-6 hours per batch, high cost of the reagent, and high energy expenditure. Selectivity in the electrokinetic process is achieved using electrokinetic studies, the application of voltages of 220,000 volts, with 90% gold, to 320 thousand volts; and selectivity by application of potentials according to their reduction potentials.

5.4 Activated Carbon and Electrodeposition

Description: This technology includes the combination of several alternatives tested independently that are in the adaptation and testing stage. This technology is primarily designed for the recovery of residual gold (Au) in tailings from artisanal mining and not for Mercury (Hg) recovery purposes. However, its adaptation to mercury recovery is extremely viable. The model of the plant used for this process can be found in Figure 6.

Figure 6 Activated Carbon and Electrodeposition Plant

Taken from: Recovery Experience of Environmental Liabilities in the Municipality of Yali- Antioquia. Engineer Oscar Jaime Restrepo and Mining Consultant Oseas García Rivera. Workshop: Promoting the Recovery and Responsible Management of Mercury in Contaminated Tailings from Artisanal Gold Mining in Colombia. May 2019. Medellín Colombia

Operating Conditions: According to the experimental work carried out by the work team that developed this technique the following parameters should be considered in operating this combination of technologies: the total capacity of the plant is estimated at 15 - 20 tons / day; the capture with activated carbon takes approximately 2 hours; the de-absorption process of metals is a slow operation that takes around 36 hours; this is accompanied by an electrodeposition process that causes a precipitation of the compound of interest (Au - Hg) according to the voltage supplied in the solution and is given in a cyclical form with an average operating time; it includes decantation pools with a capacity of 1,500 tons and a storage capacity of 10,000 tons of tailings. The operation of this procedure includes pools of poor solutions, meaning that they have been previously treated.

Field application (efficiency): Concerning gold recovery, there is high certainty of effectiveness; however, the mercury recovered to date has been accidental, without being a principal objective of the process.

Implications for implementation: Identifying the exact potential for the deposition of mercury and the desorption time are variables that must be very well established. Likewise, the process of treating the generated solutions should be reviewed thoroughly in order to avoid generating discharges that contaminate soil and water beds.

Considerations and discussion: This technique must be modified so that it focuses on obtaining mercury. Furthermore, it is important to assess the cyanidation phase to ensure that it complies with the Minamata Convention. Another technique is the adsorption with activated carbon for the proposal, which includes dissolving Au and Hg - CNHg complexes and precipitation processes.

5.5 Nanotechnology.

Description: The central system consists in leaching mercury with cyanide using a nanocatalyst. The traditional process of leaching does not utilize any type of catalyst and takes approximately 48 hours per batch. The catalyzation with nanotechnology consists in activating the oxygen supply, which is to say that air is passed through the nanocatalysts and activated so it can be injected into the cyanide tanks, where the leaching takes place. This process takes approximately four hours. Lastly, the recovery is finalized by using activated carbon in a desorption process.

The process is bumpy and is designed to recirculate as much water as possible. However, when this option is no longer viable, the wastewater is treated by bioremediation. The company has invested in the research and modification of the roots of the Leucaena plant so that they can absorb cyanide. In the pilot, plant there are plantations to which this ferti-irrigation system is applied. The process of nano cyanuration is illustrated in Figure 7.

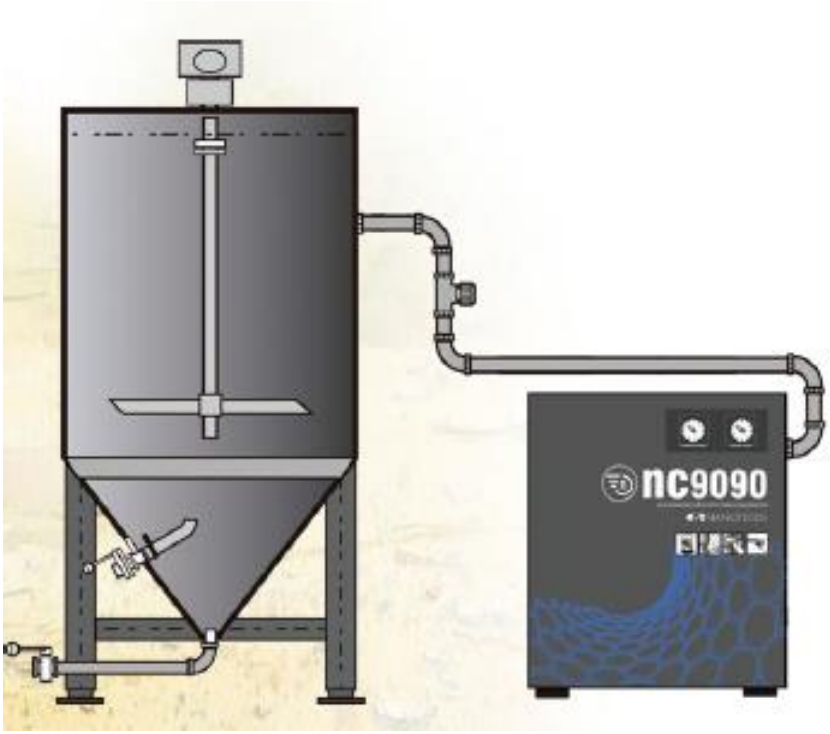

Figure 7 Nano Cyanuration Process

Taken from: Process of extraction of gold and mercury in sludge with nanotechnology and biotechnology guaranteeing the circular economy. Professor Raul Zapata H. Workshop: Promoting the recovery and responsible management of mercury in contaminated artisanal gold mining tailings in Colombia. May 2019. Medellín Colombia

Conditions of Operation; The conditions of operations require a cyanuration plant that must include a cyanurate tank, sedimentation tanks, sedimentators, filter presses, bags for cementing, water, energy for agitation in the tanks and no caloric consumption during the catalysis phase.

Field Application (efficiency): experimentally, sludge from Buriticá was processed using this technology. The sludge contained mercury concentrations between 3173 ppm and 18442 ppm. The tests recovered between 1% and 94% of the mercury.

Implications for Implementation: The implementation of this technology requires the completion of several stages. The first one includes the chemical and nano-analysis of the mineral to be used (amount of gold, percentage of mercury recovery, type of mercury, design of ecological pre-treatments, nanocatalyst design and discharge management design). The second stage is the plant design (permits for plant operation, construction and water access). The third phase includes management of assembly and construction (analyzing land ownership, construction of civil works and teams for nano cyanation). The final stages include disposal of poured liquids and, finally, plant operation (cost of supplies, labor, administrative costs).

Considerations and discussion: This technology's vulnerable point is the use and availability of nanocatalyst, which is the property of the nanotech company who would be the only provider.

An advantage of this technique is that it can be implemented in any plant or place. There is no particular area designated by the nanotech company for using the catalyst. The process is done by leaching with spheres that corrode and filter using an oxidation reaction. The mercury in an oxidized state should be cemented and separated.

The necessary operating conditions require a cyanidation plant, a cyanurator tank, settlers, filter press for cementation. The nanotechnological process is self-sustainable, because it requires less use of chemical supplies, less recovery time and is a lower-cost process. The nanocatalyst is provided by the nanotech company and the physical and chemical properties of the catalyst are not known.

As this technology requires the construction of a plant and the transfer of tailings, it is also recommended for the cases in the Departments of Antioquia and Chocó.

5.6 Distillation.

Description: The vacuum distillation used by INNOVA is primarily applied for the extraction of mercury from fluorescent lights. According to laboratory tests carried out by the work team that developed this technology it was possible to determine that the technology operates for 1 hour, between 200 and 500 ° C and recovers mercury between 80-95% efficiency (initial Hg = 15 g / ton). The simplicity of the technique enables it to be applied to materials such as mining tailings.

Figure 8 presents the design of the Innova plant for mercury recovery.

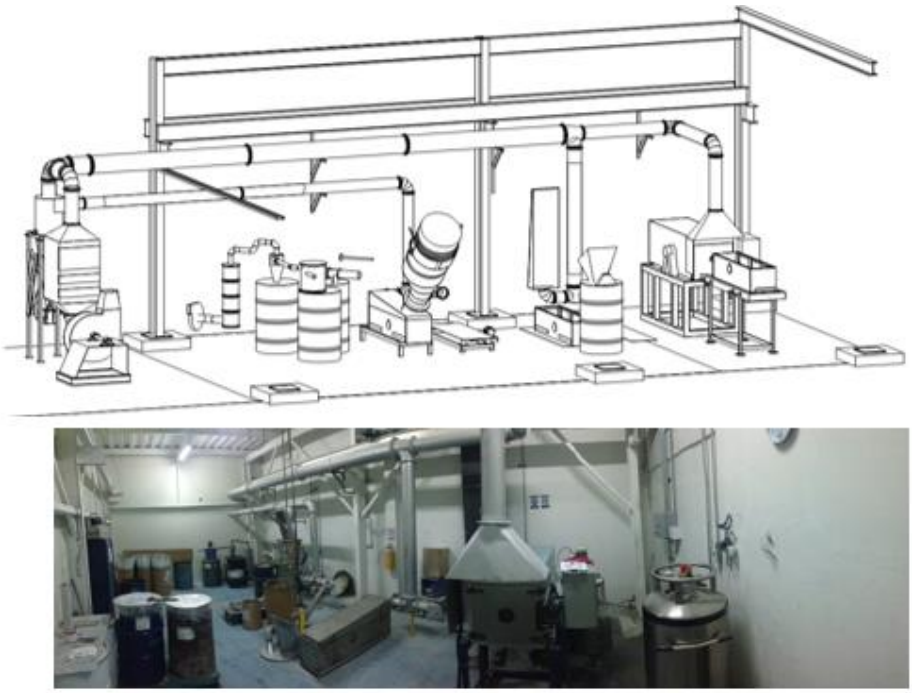

Figure 8 Design and Distillation Process of the Existing Plant

Taken from: Thermal Recovery of Mercury. Director of Research. Miguel Osejo Knudson Workshop: Promoting the recovery and responsible management of mercury in the contaminated tailings of artisanal gold mining in Colombia. May 2019. Medellín, Colombia

In general, terms, the distillation system uses a high vacuum and heating system to reach the extraction conditions of the mercury matrix, reaching recovery levels of 99%. The Innova team according to the operation it performs reports this efficiency. urrently, different vacuum systems exist on the market that can be modified to achieve different application necessities. Basic supplies for the operation of the distillation system are: electric energy sources for vacuum generation and thermal requirements, as well as systems of ventilation and vapor extraction.

Operation Conditions: In general, terms, the distillation system is a retort whose basic supplies are a heating system (oven) and a condensation system, which should include controls for safety purposes (cracking valves, post-combustion chamber, cryogenic trap) that detect possible Hg emissions to the environment and exposure of operators. According to experimental work, it is possible to describe that the distillation system operates in batches with a processing capacity of 230 kg and a treatment time of 1 hour, for approximately 1800 kg / day. Amount that must be optimized based on maximum mercury recovery, data presented by the Innova work team

Field Application (efficiency): INNOVA applies distillation under reduced pressure on the fluorescent lights. The lights are broken and mercury is released. Hg vapor is captured by an extraction system and condensed Hg is distilled and captured in a cryogenic trap The processed material has a chemical composition of SiO_2 70 %, Na_2O 15 %,

fluorescent powder and other matter ≤ 15%, with particle sizes of glass between 2-5 cm, which provides a low surface area and facilitates mercury recovery. The fluorescent lights have about 15 mg Hg / kg of which approximately 95% of the mercury is extracted.

After several tests carried out by the work team that developed this technology, some additional technical requirements are presented in Table 6

Table 6 Technical Requirements for Operating Distillation Equipment

Requirement	Value
Capacity per batch	0.8 m^3
Yields	50 tons/month (8 h/day)
Energy (T = 450 °C)	380 V (50 Hz)
Max Electric Consumption	15 kW
Vacuum Pump	1.8 mm Hg
Coolant $N_{2(l)}$	-
Approximate Area	30 m^2
Recovery Efficiency Hg	>95 %

Implications for Implementation: Although the distillation vacuum does not require an environmental permit, its operation is restricted by a national patent owned by INNOVA S.A.S E.S.P. Furthermore, implementing the technique requires facilities with access to a fixed electricity grid, should it be necessary to establish a permanent installation or adapt a mobile platform for transfer to different locations.

While this technology theoretically possesses among the highest mercury recovery efficiency rates, it has not yet been tested in Colombia and its viability will depend on results in the pilot tests.

Considerations and discussion: This technique recovers mercury selectively and requires additional processes for the extraction of residual gold. Because the treatment plant is located in the city of Cali, there are costs associated with transporting tailings. The principal variables of the distillation process include pressure and system

temperature, so using additional volatile compounds in the sample can generate contamination to the recovered mercury.

According to the results obtained from the tests developed on this technology, it was determined that the advantages of Innova's thermal distillation process are that it enables the recovery of metallic mercury, presents an efficiency rate of over 95% and it does not require personal specialization or additional chemicals. On the other hand, the disadvantages are the high-energy cost, the adequacy of facilities, special supplies such as nitrogen (optional) and the lack of simultaneous Au recovery.

As this technology requires the construction of a plant and the transfer of tailings, it is also recommended for the cases in the Departments of Antioquia and Chocó.

5.7 Smart Burners

Description: Smart burners are a separation technique between the contaminated element and the soil. The technology heats the soil through conductivity, which causes the contaminated elements to evaporate. The heated air flows again through the external steel tube and is released at the end of the process. The second step involves recovering the contaminated elements. This is done by absorbing the elements through the holes in the tube adjacent to the heated tube.

A burner can be used to heat up to three tubes. Smart burners can treat mercury pollution and are water resistant. The most recent version of the smart burners can treat contaminated soil from 1 m until 20 m deep. An example of the implementation of this technology is seen in Figure 9.

Figure 9 Onsite Design of Smart Burners

Taken from: Haemers Technologies. Exchange Trade Mission: Colombia 2019. Workshop: Promoting the recovery and responsible management of mercury in contaminated tailings of artisanal gold mining in Colombia. May 2019. Medellín, Colombia

Conditions of Operation: Mercury recovery occurs by thermal conductivity to heat the soil, which causes the pollutants to evaporate and the tubes to capture the Hg vapor. The arrangement and depth of the burners is a fundamental factor in the technology's efficiency.

The technology also requires fuels, such as diesel fuel, to heat the vapor in each burner. As a result, fuel consumption and emissions in the environment should be considered as an additional negative impact.

Field Application (efficiency): It has the capacity to recover mercury from 1-20 m deep by thermal conductivity. A significant amount of fuels and monitoring personnel must be available. The electrical cables between the burner are fundamental to field application.

One of the projects implemented using this technique involved decontamination of a property in France, where ground levels reached below the legal permissible limits and a significant amount of elemental mercury was recovered (no exact data available).

Implications for Implementation: The energy cost is very high, given that it requires a large quantity of combustibles. Since the technology was developed in Belgium, it requires importing the necessary equipment.

Furthermore, because no specific data exists on the technology's efficiency, there is considerable risk in adopting it, given the technique's high initial investment requirements.

Considerations and Discussion: The costs are substantial due to fuel expenditure and the importation of the burners.

This technology is designed for in-situ treatment of contaminated soils, so it is recommended for inaccessible areas or where it is difficult to transport the tailings. Because of this, it is recommended for soils in protected areas, such as the Farallones National Park.

However, this technology has two disadvantages: firstly, the operating temperature is high, which damages plant roots and possibly insects, such as worms. As a result, the heating rate would need to be very low, which can affect the implementation of the process. Secondly, this technology's CO2 emissions would be considerable on a large scale. This is an important consideration given that one of Colombia's national goals is to reduce emissions, in order to mitigate global warming.

5.8 Gravimetric Methods

5.8.1 Combined gravimetric process (Coambiental, 2019)

Description: Coambiental's metal recovery process by gravimetric methods begins with the relocation and transportation of sludge from the affected sites to the plant, where the main sludge collection takes place. This material passes to a stage of dilution and sludge-cleaning to initiate a process of re-grinding and gravimetric concentration of Hg.

In these phases the sludge passes through an attritioner, mill and centrifuges that subsequently bring the tailings to a mercury recovery system, which uses a separation process of chelation and smelting to facilitate adequate leaching. Figure 10 displays the processing design of Coambiental's plant.

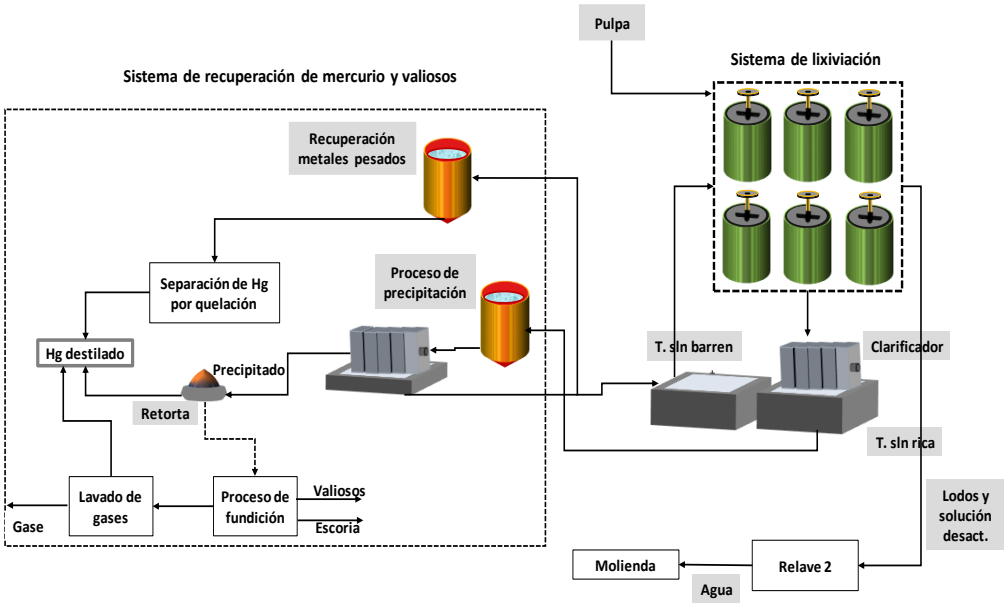

Figure 10 Mercury Recovery System by Gravimetric Methods

Taken from: Collection project, transportation, storage, treatment and final disposal of contaminated residuals with mercury and cyanide from informal mining in the municipalitiy of Buriticá, Antioquía. Engineer Carlos Graciano. Coambiental. Workshop: Promoting the recovery and responsible management of the mercury in the contaminated tailings of artisanal gold mining in Colombia. May 2019. Medellín, Colombia

Conditions of Operation: According to the work team that developed this technology To carry out this process, it is first necessary to count the sludge and/or tailings in the plant's collection site, given that all equipment is located on the premises of the plant. Furthermore, it requires equipment such as an attritioner, tramel, dehydrator, hydrocyclone, centrifuge, washing tanks, retort casting oven, clarifier, mill and leaching tanks.

Field Application (efficiency): its application in the field has been tested primarily in the Department of Antioquia experimentally by the work team that developed the combined gravimetric process, where it demonstrated mercury recovery efficiencies of 65% and 67% by exclusively gravimetric methods. However, it is important to note that there is significant variation in the initial concentration of Hg in treated tailings, since they include mixtures from multiples sites.

Implications for Implementation: It is necessary to first perform a pre-treatment in the plant, because the process is not designed to work with onsite tailings. Furthermore, a prior preparation of the tailings is required. At the administrative level, the company must have its own operation permits, provided by the corporation of Antioquia.

Considerations and Discussion: This technology is implemented by one company and has a variety of applications, giving it a broad range of operational development

potential. According to many international experts, the plant can undergo some minor operational adjustments to improve mercury and gold recovery efficiency.

5.8.2 Improved gravimetric concentration (Valle, E. 2019)

Description: This technology was developed in Honduras by the company Raptor Mining. It recovers mercury from mining tailings by means of centrifugal, gravimetric and thermal processes such as metallic mercury collection treatment. The technology was designed with the objective of recovering mercury tailings and has a recovery percentage of 97%.

Figura 1. Raptor gravimetric concentration equipment

Taken from: Mercury and Gold Recovery. Researcher: Ernie Valle. Raptor – Honduras Workshop: Promoting the recovery and responsible management of mercury in contaminated artisanal gold mining tailings in Colombia. May 2019. Medellín Colombia.

Conditions of Operation: The process consists of four operations:

1) Milling: the milling time must be considered to ensure optimum size and increase efficiency of the separation process;
2) Centrifugal separation: in this process, agitation speed is key to guarantee the separation of the mercury from the sand.
3) During the gravimetric concentration process, a spiral concentrates the mercury along with other minerals.
4) Finally, the material is recovered at high temperatures, in order to obtain elemental mercury.

Field Application (efficiency): Tests conducted in the field and with tailings with the intentional addition of mercury (for demonstration purposes) have shown a mercury recovery efficiency of 97%. However, there is no evidence of mercury recovery with tailings from mining areas in Honduras.

Implications for Implementation: Operating the system is environmentally friendly and requires basic supplies such as water and electricity. The technology can be portably mounted on a pilot scale to recovery mercury and decontaminate sites that have been closed or are designated for the purpose of responsible mining. The process is covered by a patent, so it can only be implemented through Raptor Mining.

Considerations and Discussion: As it is covered by a patent, its implementation is subject to the conditions of the company and its permanent use will cost approximately 5 million dollars. The advantage of the technique is that it currently operates in productive conditions and can effectively recover mercury and gold.

6. Conclusions

- It is evident that most of the technologies identified pertain to mercury-free gold mining or soil remediation. The technologies available specifically for mercury recovery are very limited, since many are accidental adaptations or processes from operations already being implemented.
- Because none of the technologies offers 100% mercury removal, additional stabilization processes or final tailings disposal should be considered after processing.
- A standardized tailings characterization process should be developed in order to technically evaluate and compare the selected technologies.
- It is important to establish the necessary legal instruments for large-scale implementation of the selected technologies. This effort will be incorporated in the upcoming phases of the project.
- It is important to define what is expected before a technology is applied, given that there is significant difference between remediating contaminated soil and recovering mercury and gold from tailings.
- There are different limitations of gravitational concentration per size of the particles. When working per batch, it may be initially beneficial but afterwards will require additional cleanings that lead to cost overruns. It is also not feasible to apply pretreatment of tailings.
- The technologies must be operable in any situation and terrain, so the flexibility of the available technology is an essential factor in the selection process.
- Although obtaining gold makes the process more sustainable, the success of technologies should focus on mercury recovery rather than gold recovery.
- Gold recovery should be considered as a secondary part of the mercury recovery process. Cyanidation processes are usually the most practical for this purpose. This would make the project more economically sustainable. Regulatory

arrangements for this purpose are also a component of the project's development.

- The economic evaluation of technologies will be conducted in later stages of the project, given that the information currently available is insufficient to report conclusive financial data.

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ANNEX

Technical Datasheet

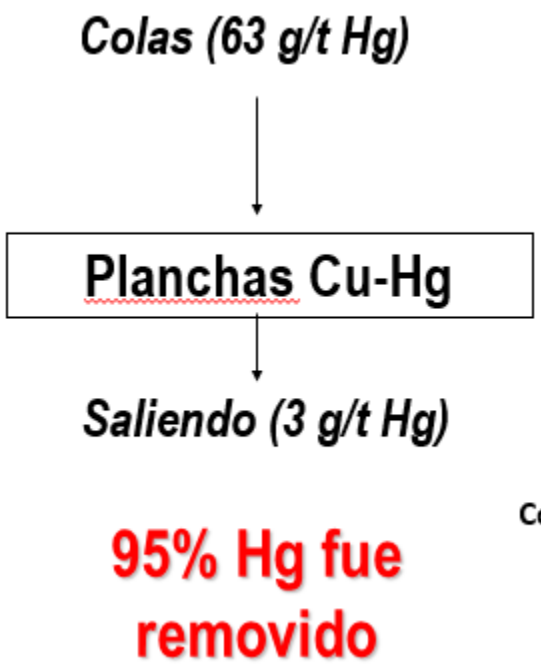
Technologies Mercury Recovery

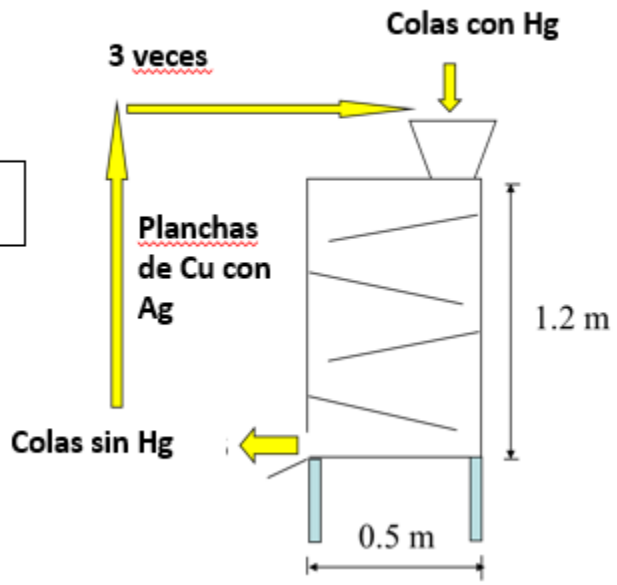
No. # 1	DATA	COPPER PLATES

General Description

It includes the use of copper (Cu) plates coated with silver (Ag), which is identified as an easy and economical way to remove the tailings mercury, so that the latter can be used in the cyanidation process to extract the residual Gold that the tailings can contain. For this reason, it is not a technology that works alone, but it is recommended that it adapt to other processes in order to increase its efficiency.
This technique has been piloted in countries such as Venezuela, Costa Rica and Brazil, with very good results, obtaining almost 95% of the mercury present and tailings.
The technology principle corresponds to the fact that the silver layer on the surface of the copper captures drops of mercury (and can also capture some traces of free gold).
Cu-Ag silver plates are commercially available in Brazil, which modify the process with a cover with Sn (tin) and then Ag (silver). This is a good protection for the copper surface that can oxidize.

Illustrative Diagrams





Pretreatment Systems Required

For operating conditions, silver-covered copper plates must be arranged in a cascade.

Advantages	Disadvantages
• Copper plates can be easily implemented in situ by artisanal miners • Its implementation is low cost compared to other techniques	• Requires subsequent cyanidation After obtaining Hg, solidification and stabilization are required, which increases costs

Design Features

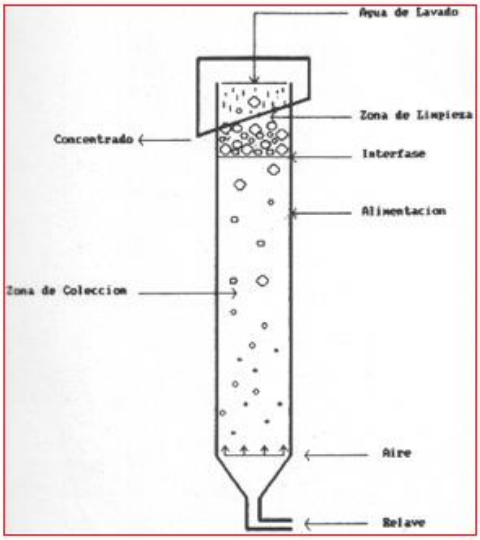
• Electric Power 12 V (Car / Moto – Battery) • Silver nitrate solution • Copper plates • Silver coating • Complementary cyanidation equipment. Special license: • Operating permits may be required, due to the cyanidation phase
Expected Returns
According to field tests, for every 63 g/ton Hg of mining tailings that enter the plates, 3 g/ton Hg exits the plates, representing a 95% efficiency rate.
Aspects of Operation and Maintenance
To operate, the silver-covered copper plates must be arranged in a cascade, which is relatively easy to assemble. It is important to confirm that the cascade has a rough and clean surface by applying acid. These plates must be submerged in a solution with silver nitrate (e.g. the metallic silver plate must be dissolved in nitric acid), in order to connect the battery's negative and positive sides in the silver nitrate solution. After the physical process, the chemical phase (cyanidation) must be implemented, in which the metallic mercury is left in the bottom of the shaking tank. This process occurs through the presence of Zinc in the reaction. The leaching process enables a faster dissolution of Au than Hg.

No. # 2	DATA	FOAM FLOTATION

General Description

This technique presents the most appropriate combination of reagents to recover not only mercury, but also gold and silver, from small mining tailings through the foam flotation process and evaluates their effectiveness in solution. The materials and methods involve a characterization of the samples, the concentration of solid-liquid pulp, an input granulometric phase, a pH regulation by caustic soda an activator by means of lead acetate, and a collector.

Illustrative Diagrams



Pretreatment Systems Required

Tailings pretreatment must be performed before beginning the process**.**

Advantages	Disadvantages
• It can be implemented in the field • High efficiency	• Requires a significant investment to design the field / movable flotation column

Design Features

A flotation column must be provided according to the amount of tailings to be treated and operating conditions must be correctly measured. No cost estimates are not currently available**.**

Expected Returns

From the available data, three-quarters (3/4) of the initial mercury contained in the samples was recovered as well as considerable quantities of gold and silver. Mercury recovery values of up to 75% and over 90% for gold and silver can be recovered by this method. During the field test in the municipality of Cañasgordas, recovery of Hg varied from 16.5% to 49%, recovery of Au varied from 39.5% to 94%, and recovery of Ag varied from 79.5% to 95.5%.

Effects

Management of foam.

Aspects of Operation and Maintenance

The required operating conditions include:

- Granulometry according to each benefit facility sampling (<75 µm);
- Dilution of solid-liquid pulp
- Six foaming flotation tests for each benefit facility
- Sample size: 3 Kg
- pH regulator: caustic soda (NaOH),
- Float pH of 6
- Activator: lead acetate (50 gr / ton of mineral)
- Collector, conditioning time: approximately 9 min
- Metallurgical balance

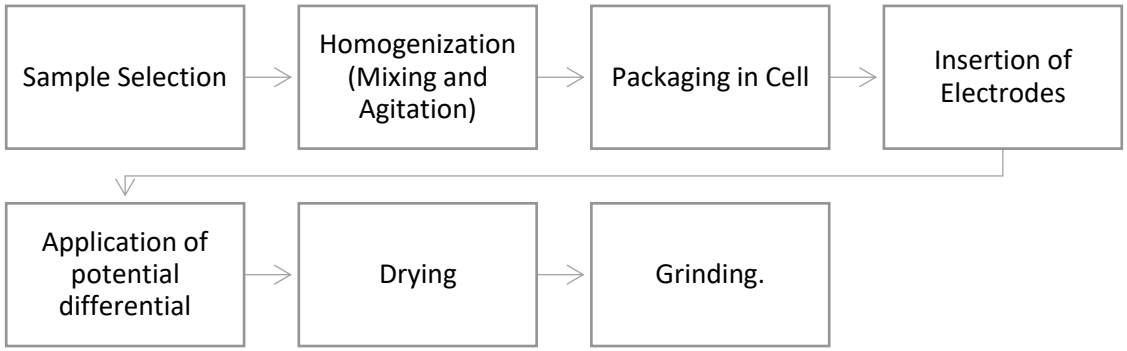
No. # 3	DATA	ELECTROLYSIS

General Description

It is a high energy, natural and analogous technique. This technology is based on an electrokinetic system called ABETOs (Ferric Iron Remediation and Stabilization). The ABETOs system applies a low direct electric potential cd magnitude between two or more iron-rich sacrificial electrodes placed on opposite sides of a contaminated soil mass or sediment.

The electrical potential generates a strong gradient of EH-pH between the two electrodes, promoting an anodic dissolution, the migration of Fe0 and Fe2 + (AQ), and a precipitation force for ferric iron hydroxides, hematites, goethite, magnetite and zero iron, in an almost neutral pH values at the interface of the anodic and cathodic domains. The system uses approximately one tenth of the energy of most conventional electrokinetic systems and has been successfully applied on a pilot stage in a range of contaminated soils and sediments. The system is currently being developed for field conditions with heavy metals in contaminated soils and waste in the United Kingdom in collaboration with Churngold Remediation Ltd (CRL).

Illustrative Diagrams



Pretreatment Systems Required

Soil characterization must be conducted as well as a modification of the area to create the cells in situ (this varies depending on the chemical composition of the soil).

Advantages	Disadvantages
It is a new technique that is based on electrochemical cells. It has been proven successful on a pilot scale in the United Kingdom. It can be tested and managed onsite and requires low energy expenditure.	It is not designed or tested for mercury recovery. As a result, a research study on mercury's behavior in its elemental state during the process would be necessary. Furthermore, Hg recovery would be accomplished using electrodes, which complicates the handling process.

Design Features

- Scanning electron microscopy
- pH tests
- Soil samples
- Laboratory equipment
- Pollutant load specifications
- Thixotropic polyurethane elastomer
- Circulation systems
- Electroosmotic cell

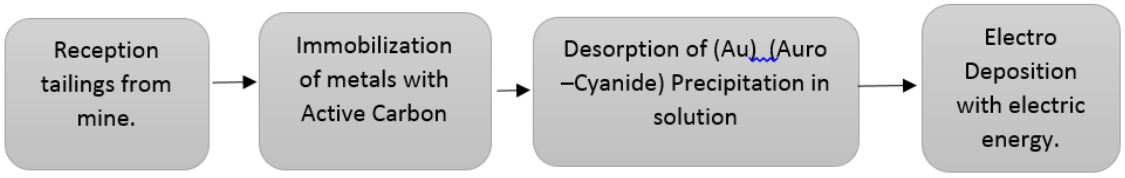
• Matrix electrode (5 anodes and 5 Iron cathodes) • Permit for handling Hg electrodes
Expected Returns
Metallic Hg and byproducts would be recovered as energized and contaminated Hg electrodes, which require final deposition.
Effects
Primary obstacles of the technology include the disposal and controlled manipulation of the Hg electrodes as well as the uncertain efficiency of Hg recovered, given that this technique has been tested primarily with chromium.
Aspects of Operation and Maintenance
More research is required on the use of mercury in the ABETO system. It appears to be a comparatively simple approach with low energy, cost, and maintenance for reducing the environmental risk of CR (VI) and, potentially, Hg. The treatment time and voltage requirements applied will vary as a function of the specific soil's damping capacity and the extent of contamination. The available evidence suggests that this approach can be successfully extended to treat in situ the soils affected by CR (VI) or Hg.

No. # 4	DATA	ACTIVATED CARBON AND ELECTRODEPOSITION

General Description

This technology includes the combination of several alternatives tested independently that are in the adaptation and testing stage. This technology is primarily designed for the recovery of residual gold (Au) in tailings from artisanal mining and not for Mercury (Hg) recovery purposes. However, its adaptation to mercury recovery is extremely viable.

Illustrative Diagrams



Pretreatment Systems Required

Although it does not require any pre-treatment system, significant water flow is necessary during operation.

Advantages	Disadvantages
• Pretreatment of tailings not required • Significant treatment capacity • Recovery of Au and Hg • Low energy use • High gold recovery %	• Desorption process is slow • Cyanide content in the process can generate polluting solutions • High solution content at the end of the process is difficult to deal with • No certain mercury recovery rate %

Design Features

- Total capacity of the plant is estimated at 15 - 20 tons / day
- Capture with activated carbon takes approximately 2 hours
- De-absorption process of metals is a slow operation that takes around 36 hours
- Electrodeposition process that causes a precipitation of the compound of interest (Au - Hg) according to the voltage supplied in the solution. Process in the form of cycle and with average operating time
- Decanting pools or ponds with a capacity of 1,500 tons and a storage capacity of 10,000 tons of tailings
- Pools of poor, previously treated solutions

The adaptation of mercury amalgamating plates will be included in the process to evaluate its effectiveness in mercury recovery.
Currently not a licensed process.

Expected Returns

Concerning gold recovery, there is high certainty of effectiveness; however, the mercury recovered to date has been accidental, without being a principal objective of the process.

Effects

The process of treating the generated solutions should be reviewed thoroughly in order to avoid generating discharges that contaminate soil and water beds.

Aspects of Operation and Maintenance

Limited Operation and Maintenance.

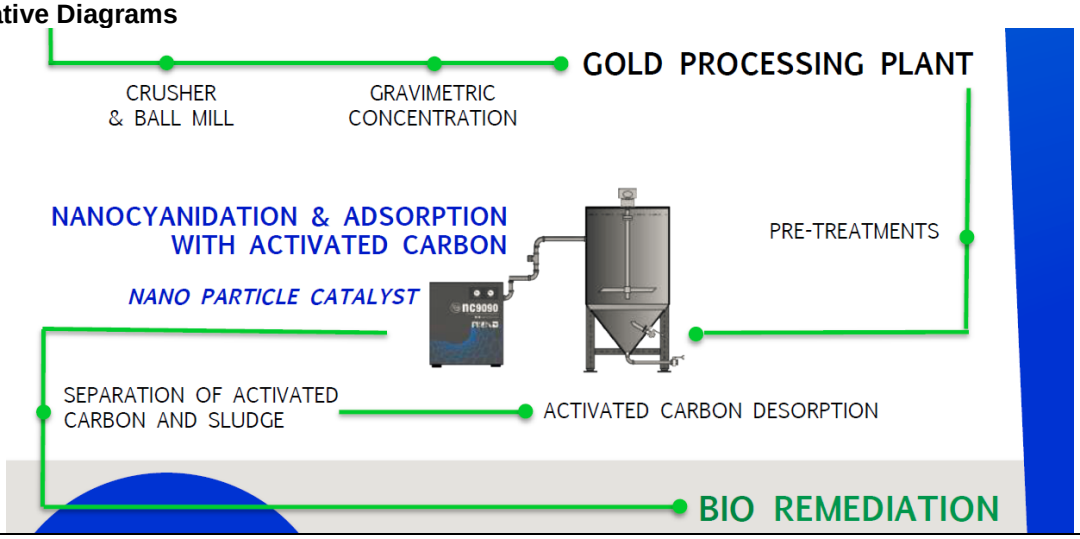
No. # 5	DATA	NANOTECHOLOGY

General Description

The central system consists in leaching mercury with cyanide using a nanocatalyst. The traditional process of leaching does not utilize any type of catalyst and takes approximately 48 hours per batch. The catalyzation with nanotechnology consists in activating the oxygen supply, which is to say that air is passed through the nanocatalysts and activated so it can be injected into the cyanide tanks, where the leaching takes place. This process takes approximately four hours. Lastly, the recovery is finalized by using activated carbon in a desorption process.

The inputs of the process are the tailings originating from artisanal mining with an average concentration of 3 mg/ton of Hg. The process is bumpy and is designed to recirculate as much water as possible. However, when this option is no longer viable, the wastewater is treated by bioremediation. The company has invested in the research and modification of the roots of the Leucaena plant so that they can absorb cyanide. In the pilot, plant there are plantations to which this ferti-irrigation system is applied.

Illustrative Diagrams



Pretreatment Systems Required

It is important to bear in mind that the material separates better the smaller the particle size. Ideally, particles with grain size suited to 200 mesh will be used. Otherwise, a grinding process is necessary.

Ideally, the material is as concentrated as possible to avoid extra costs from chemical consumption during cyanidation. As a result, the pilot plant company has installed a flotation system to concentrate the material. This pre-treatment also eliminates pyrite, which is considered a cyanicide.

Advantages	Disadvantages
• Production time: this method is considerably faster than traditional cyanidation • Low cost • Equipment is easily accessible because it is identical to the traditional cyanidation process	• Technology is intellectual property and is implemented by a company in Colombia • Technology is not sold separately but by contract, which includes the complete consulting service

Design Features

- Flotation system
- Nanotechnology equipment
- Cyanidation system (tanks, agitators, etc.)
- Activated carbon desorption system

Special permits: • Technology is subject to an environmental license
Expected Returns
The studies in the pilot plant demonstrate that, with sludge and contaminated tailings, the process should recover 300 mg of Hg per ton of tailing.
Effects
This technique uses dangerous chemical reagents such as sodium cyanide, which must be treated. The intermediate mercury cyanide is another highly dangerous substance that should not be released into the environment and will therefore require special management and protection measures. The Minamata agreement suggests that all national efforts avoid the use of cyanidation in mining processes where mercury is present.
Aspects of Operation and Maintenance.
• Operation of the pilot plant is simple, with only 1-2 people required • The equipment is commercially available, with the exception of the nanotechnology • The pilot plant can be inaccessible during the winter

No. # 6	DATA	DISTILLATION

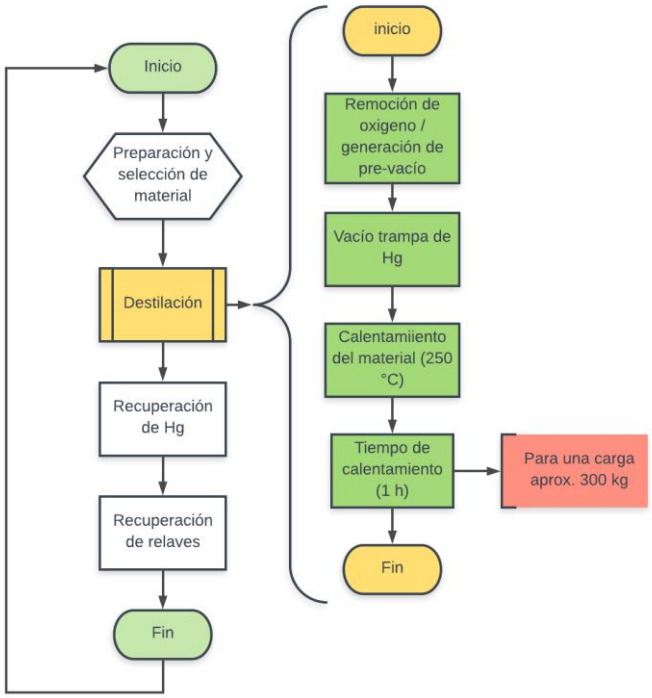
General Description

HG Vacuum Thermal Distillation technology utilizes the pressure difference between Hg vapor and other components present in the contaminated material to facilitate separation. This method is applicable on a variety of materials, including glass, different types of soils, clay, minerals, etc.

In general terms, the distillation system uses a high vacuum and heating system to reach the extraction conditions of the mercury matrix, reaching recovery levels of 99%.

Currently, different vacuum systems exist on the market that can be modified to achieve different application necessities. Basic supplies for the operation of the distillation system are: electric energy sources for vacuum generation and thermal requirements, as well as systems of ventilation and vapor extraction.

Illustrative Diagrams



Pretreatment Systems Required

No chemical pretreatment systems required.

Advantages	Disadvantages

• High Hg0 recovery efficiency • Technology widely used in the field • Equipment is commercially available • Easy deployment • Low level of training • Short operation time	• High work temperatures • Risk of generating emissions from Hg0 • Maintenance costs • Energy costs • Does not recover other metals (Au)
Design Features	
Vacuum distillation does not require technology-related permits or licenses.	
Expected Returns	
• Type of mercury obtained: metallic. • No by-products other than those associated with the matrix • 99% recovery efficiency	
Effects	
Vacuum distillation does not generate side effects in its operation, except for those associated with the sample.	
Aspects of Operation and Maintenance	
The maintenance procedures associated with the operation of the distiller correspond to the maintenance of the vacuum and heating systems.	

No. # 7	DATA	SMART BURNERS

General Description

Smart burners are a separation technique between the contaminated element and the soil. The technology heats the soil through conductivity, which causes the contaminated elements to evaporate. The heated air flows again through the external steel tube and is released at the end of the process. The second step involves recovering the contaminated elements. This is done by absorbing the elements through the holes in the tube adjacent to the heated tube.

A burner can be used to heat up to three tubes. Smart burners can treat mercury pollution and are water resistant. The most recent version of the smart burners can treat contaminated soil from 1 m until 20 m deep.

Illustrative Diagrams

Pretreatment Systems Required

No chemical pretreatment systems required.

Advantages	Disadvantages
• Must be implemented in situ • Capable of treating large areas	• High operating costs due to the need to use combustible gas • CO_2 generation • Equipment must be imported

Design Aspects

- High energy cost due to the large amount of fuel required
- Requires import of equipment.

Expected Returns

It has the capacity to recover mercury from 1-20 m deep by thermal conductivity.

Effects

CO_2 emissions and temperature increase.

Aspects of Operation and Maintenance

Mercury recovery occurs by thermal conductivity to heat the soil, which causes the pollutants to evaporate and the tubes to capture the Hg vapor. The arrangement and depth of the burners is a fundamental factor in the technology's efficiency. The technology also requires fuels, such as diesel fuel, to heat the vapour in each burner. As a result, fuel consumption and emissions in the environment should be considered as an additional negative impact.

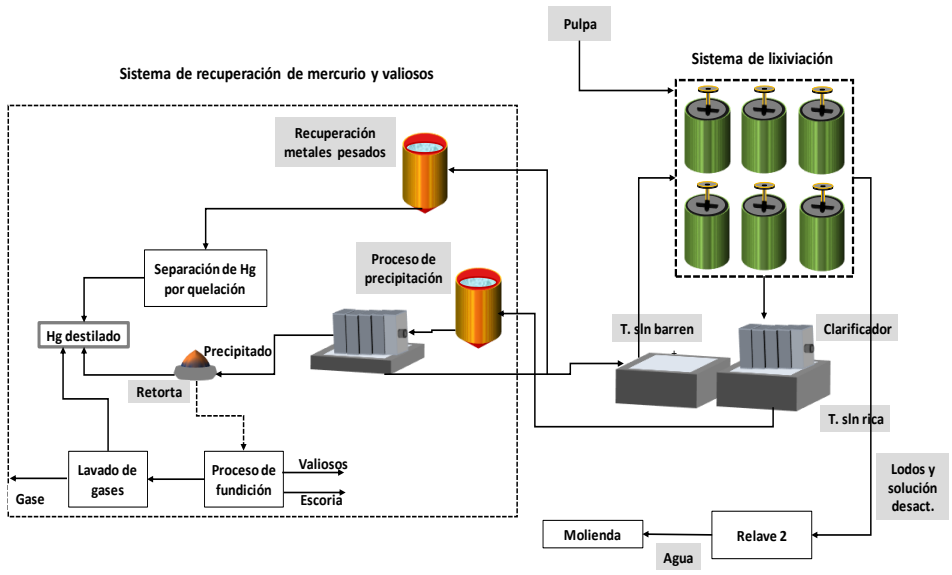
No. # 8	DATA	COMBINED GRAVIMETRIC PROCESS (Coambiental)

General Description

Coambiental's metal recovery process by gravimetric methods begins with the relocation and transportation of sludge from the affected sites to the plant, where the primary sludge collection takes place. This material passes to a stage of dilution and sludge cleaning to initiate a process of re-grinding and gravimetric concentration of Hg.

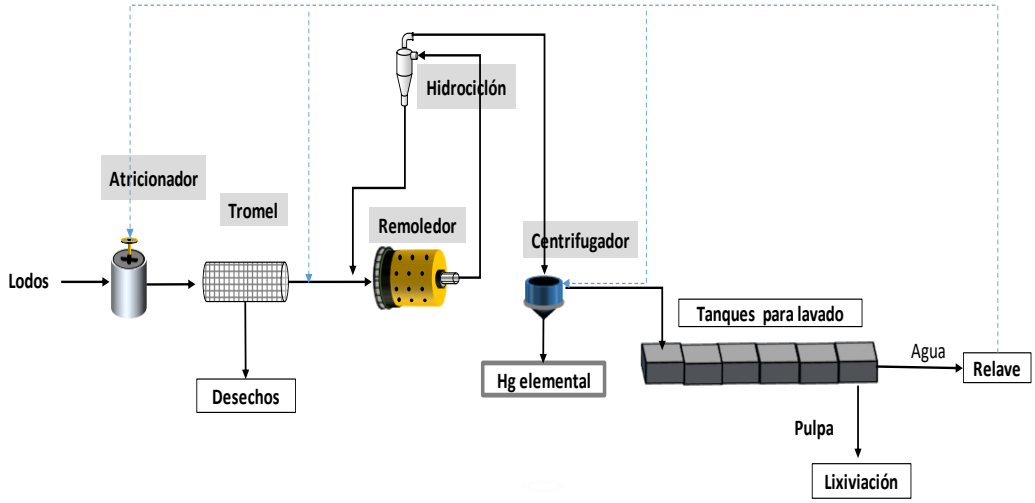
In these phases, the sludge passes through an attritioner, mill and centrifuges that subsequently bring the tailings to a mercury recovery system, which uses a separation process of chelation and smelting to facilitate adequate leaching.

Illustrative Diagrams



Pretreatment Systems Required

A prior sludge cleaning process is required, illustrated by the following diagram:



Advantages	Disadvantages
• Includes gravimetric and leaching processes • The process is implemented and operated in a plant	• Tailings cannot be treated in situ • Management of the cyanidation process.

Design Features

Equipment:

- Attritioner
- Trammel
- Dehydrator
- Hydrocyclone
- Centrifuge
- Washing tanks
- Cast iron retort furnace
- Clarifier
- Mill
- Leaching tanks

Special permits:

- Technology is subject to operation permits

Expected Returns

Its application in the field has been tested primarily in the Department of Antioquia, where it demonstrated mercury recovery efficiencies of 65% and 67% by exclusively gravimetric methods and efficiencies of 23% and 28% using combined gravimetric processes with leaching.

Effects

This technique includes a cyanidation process, during which exit currents may be affected with cyanide.

Aspects of Operation and Maintenance

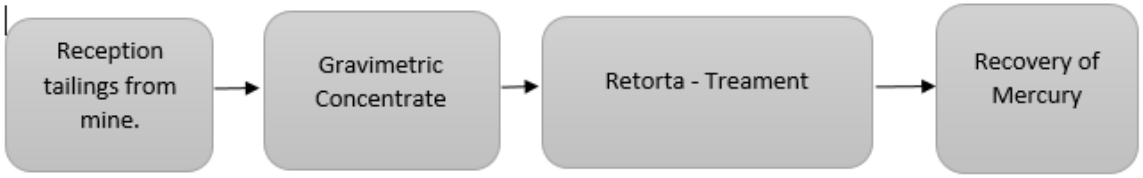
It is necessary to first perform a pre-treatment in the plant, because the process is not designed to work with onsite tailings. Furthermore, a prior preparation of the tailings is required. At the administrative level, the company must have its own operation permits, provided by the corporation of Antioquia.

No. # 9	DATA	IMPROVED GRAVIMETRIC CONCENTRATION

General Description

This technology was developed in Honduras by the company Raptor Mining. It recovers mercury from mining tailings by means of centrifugal, gravimetric and thermal processes such as metallic mercury collection treatment. The technology was designed with the objective of recovering mercury tailings and has a recovery percentage of 97%.

Illustrative Diagrams



Pretreatment Systems Required

No chemical pretreatment systems required.

Advantages	Disadvantages
• High treatment capacity • Hg recovery • Low energy use • High mercury recovery efficiency • Recovery of additional metals • Social involvement with affected communities • Process has been replicated in four additional sites in Honduras • Gold recovery is possible	• High implementation cost ($5 million USD) • No certainty of operating conditions • Insulation capacity of recovered Hg • No final disposal of Hg • No stabilization of recovered Hg

Design Features

- Total estimated plant capacity = 2 ton / hour
- Process equipment includes cylinders and vacuums (details of operation not known)
- Bunker for storage of material in the environmental licensing process

Expected Returns

High mercury recovery efficiency but residual gold recovery rate is currently unknown.

Effects

More information required to define the technique is operating conditions and effects.

Aspects of Operation and Maintenance

Currently unknown.