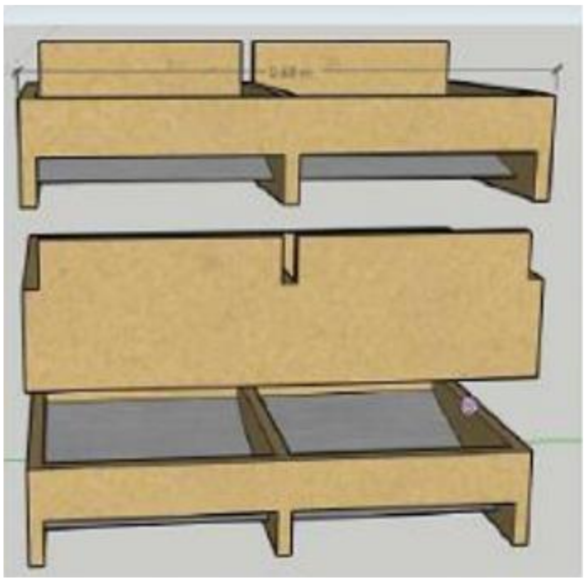
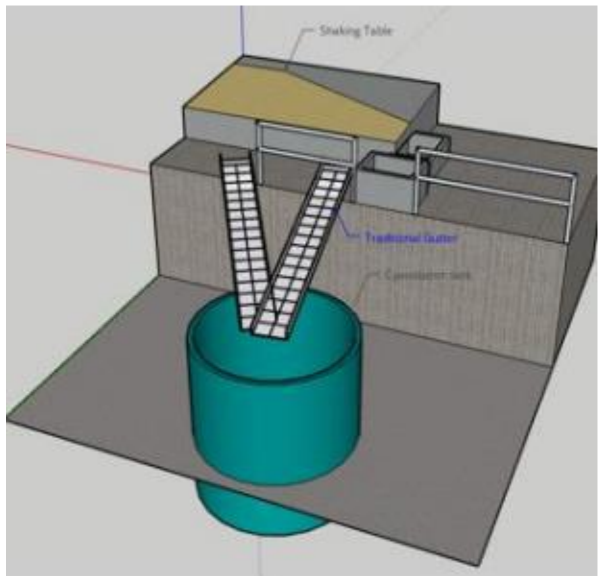
Promoting the recovery and responsible management of mercury in contaminated tailings from artisanal gold mining in Colombia

Implementation and economic plan for the use of copper plates

February 2022





Funded by:

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This publication was funded by a grant from the United States Department of State. The opinions, findings, and conclusions stated herein are those of the authors and do not necessarily reflect those of the United States Department of State.

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1. Introduction

Under the scope of the project *Promoting the recovery and responsible management of mercury in contaminated tailings from artisanal gold mining in Colombia*, financed by the United States Department of State and conducted by Pure Earth, this report presents an implementation plan for the copper plates technology, which was chosen after a review of various technologies by national and international experts as one of the most promising alternatives for the recovery of mercury from contaminated tailings.

The presence of mercury-contaminated tailings in Colombia is an important problem that must be addressed especially in light of data collected during a project about tailings sites identification financed by the United Nations Development Programme (UNDP) and supported by Pure Earth between 2020–2021. Under this project, 34 tailings sites with concentrations of 13–153 mg/kg of mercury (Hg) were identified in the Colombian departments of Antioquia, Bolivar, Cauca, and Nariño. Additionally, concentrations of gold (Au) were found in the tailings, which makes this material attractive to artisanal mining communities and raises the possibility of reprocessing the tailings to extract the remaining gold.

This report presents information drawn from experiences during more than three years of work dedicated to the adaptation and function of the copper plates, which were tested both under laboratory conditions and in the field. During three phases of pilot tests in the field, more than 100 tons of tailings with different characteristics and concentrations of Hg and Au were tested.

2. Objectives

The objectives of the copper plates implementation plan are the following:

- Present the technical criteria for the manufacture and operation of the copper plates for the recovery of mercury from tailings.
- Design the framework of an economic plan detailing the implementation costs of the copper plate technique. This can serve as a reference to calculate implementation of the plates at different scales and capacities.
- Establish a sustainability model of the copper plate technique with consideration for the sustainable development pillars and financial feasibility, keeping in mind the recovery potential of residual gold in the tailings.

To complement these objectives are the following aims:

- Reduce the mercury present in tailings to minimize the negative impacts of Artisanal and Small-Scale Gold Mining (ASGM) on the environment and human health.
- Facilitate the reprocessing of tailings for the recovery of gold found in the tailings.
- Generate a higher degree of awareness among those in the ASGM sector about the importance of eliminating the use of mercury during gold extraction and processing.
- Identify incentives for the mining communities to promote the use of this technology as a recurring and/or permanent practice in their operations.

3. **Mercury recovery in tailings**

ASGM is the livelihood of thousands of artisanal miners around the world. In Colombia, the mining sector directly generates more than 150,000 jobs (Mintrabajo, 2019), of which 72% are considered ASGM. Of these ASGM jobs, 66% correspond to illegal mining (Güiza, 2013), which is the principal source of mercury contamination through tailings that are located throughout the country, harming the environment and human health. An estimated 82% of the mercury released into the environment is from the ASGM sector. Because most of the health effects from mercury are long term, miners generally consider them inexistent. Nevertheless, exposure to mercury can cause significant health issues such as irreversible effects during in-utero development and the first stages of life. Mercury can also affect the nervous, immune, and digestive systems as well as numerous organs such as the skin, the lungs, the kidneys, and the eyes (Organización Mundial de la Salud, 2017). ASGM miners generally do not have the resources to adequately store and treat tailings. Furthermore, though its use is prohibited, mercury continues to be illegally used in various regions of the country. The result is an increasing number of mercury-contaminated tailings in need of attention and proper management.

Mercury is not only used in ASGM but also in industries that produce products such as dental amalgam fillings, thermometers, batteries, and jewels, among others. The recovery of mercury used in these industries would reduce mercury pollution in the air, soil, and water. One example of mercury pollution reduction can be found in the tentative return of coral in the Minamata Bay of Japan, which at one time was highly polluted and is currently in the process of being restored. Recovery of mercury from tailings could help stabilize the microbiological activity that is vital for the food chain and reduce bioaccumulation in fish that easily absorb methylmercury. In this way, mercury, which is concentrated at the top of the food chain in apex predators, such as osprey or humans, can be reduced (UNEP, 2018).

Various promising techniques for the recovery of mercury in tailings exist; nevertheless, criteria such as cost, ease of access, in situ feasibility, unemployment, and complexity, among others, must be considered when selecting the most appropriate technology for artisanal industries. Under this project, mercury recovery technologies were reviewed to identify the one that would be most suited for mercury recovery in tailings. The methodology used in this review consisted of searches in databases such as Science Direct to collect general information on techniques related to the recovery of mercury in tailings. (For more information, see *Technical Report on Mercury Recovery from Tailings* by Pure Earth). From this review, 17 technologies were identified, eight of which were classified as the most promising when the following criteria were applied: the technology had to be at the pilot stage or beyond and the focus of the technology had to be recovery of mercury preferably in elemental form (Hg°). The chosen technologies were:

- Copper plates
- Foam flotation
- Electrolysis
- Activated charcoal and electroplating

- Nanotechnology
- Distillation
- Smart burners
- Gravimetric concentration methods

Upon evaluation of the criteria, the copper plate technique emerged as the best option for mercury recovery owing to its ease of implementation in a variety of situations and terrains. In addition, in comparison to other techniques, the copper plates were relatively low cost.

All chemical forms of mercury represent a hazard. Inorganic mercury, which is obtained when mercury is combined with elements such as chlorine (Cl), sulfur (S), and oxygen (O), can be found in medical equipment, the technology industry, and skin-care products. Organic mercury (e.g., methylmercury) can be found in bactericides and pesticides (ATSDR, 2018). Of the various forms of mercury, the copper plates technology is primarily effective for the recovery of elemental mercury (Hg^{o}), a grey-silver metal which is liquid at room temperature. This type of mercury is used by artisanal miners to make an amalgam with gold and thus extract the maximum possible amount of gold.

3.1. General description of the copper plate technique

As previously mentioned, the use of copper plates for the recovery of mercury in tailings presents sufficient advantages, such as low cost, to allow it to be feasible for use by artisanal miners in the field.

Though the technology presents a significant level of effectiveness according to reports from pilot tests, the adaptation of the technology to other processes, especially physical processes, is recommended to increase the percentage of mercury that can potentially be recovered. This technique has been tested in pilot tests conducted in countries such as Venezuela, Costa Rica, and Brazil. Nevertheless, neither scientific evidence nor reports were available to confirm these tests or give details as to the percentage of mercury recovered.

This technique has been presented by Marcello Veiga, an engineer who is one of the foremost international experts in the field of mining with a focus on mercury recovery. Through documents such as *Alternative technologies for gold yield*, he has contributed to the dissemination of certain ASGM techniques and technologies as a strategy to eliminate the use of mercury in Colombia.

The copper plate technology comprises the use of copper (Cu) plates, set in a stepwise fashion and covered with silver (Ag). These plates work by capturing drops of elemental mercury that adhere to the plates owing to the affinity of silver for mercury. Both silver and mercury are transitional metals and have the ability and tendency to form alloys, which makes the capture possible. A simple diagram of the process of this technology is shown below in Figure 1.

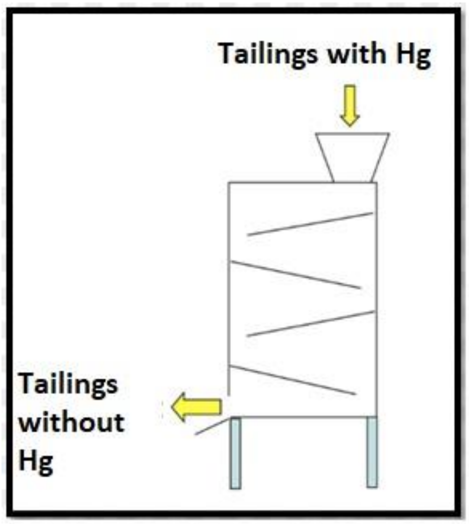


Figure 1. Copper plate technique.
Source: Alternative techniques for gold yield – Marcello Veiga.

3.2. Copper plate preparation

The adaptation and preparation of the copper plates is necessary for the process of recovering mercury from tailings. The plate size is one of the principal factors in the use of the technique. Considering available information, the decision was made to use the recommended plate size of 30 cm x 30 cm. This size allows for easy adaptation of the plates to individual facility processes as well as quick removal of the plates, without affecting the operation times of the miners.

Another variable in the plate design and construction was the plate thickness, which varies between 1.5–2 mm, depending primarily on the availability of the supplier. During the different pilot tests, however, the only contributing factor seemed to be the weight of the plates. The thicknesses seemed to have no effect on the recovery of mercury.

3.2.1. Silver plating

The key component driving mercury capture in this technology is the affinity of silver for mercury. Therefore, it is necessary to electrochemically plate the copper plates with silver, which is a well-known process in the industry (Lagos y Camus, 2017). The main objective of plating is to create a surface made of silver that forms an amalgam between the mercury and the silver superimposed on the copper plate. The principal target is the elemental mercury (Hg^0) found in tailings; however, other types of mercury compounds like mercury oxides can still be captured using this technology.

Considering this, it is necessary to remember that silver is a highly electropositive metal (+0.799V) and is displaced from solutions by practically all metals (Bard & Faulkner, 2001), quickly becoming a black powder with no bonds, as shown by the following reaction:

$$Ag^{+}_{(ac)} + e^{-} = Ag^{0}_{(s)} E^{0} = +0.799V \qquad (1)$$

The only way to avoid this inconvenience is to displace the potential to more electronegative values; for example, through the reduction of the concentration of Ag^{+} ions in the solution. This can be done using complex salts, like double metal cyanides and double ammonia, which is seen in the following reaction:

$$Ag^{+}_{(ac)} + 2CN^{-}_{(ac)} = [Ag(CN)_2]^{-}_{(ac)} \qquad (2)$$

In this way, the ion $[Ag(CN)_2]^{-}$ is not easily reduced because the ligands stabilize the silver ion in oxidation status +1, considerably displacing its potential. Nevertheless, a coating with better quality can be obtained using electrolytes that contain silver from different complexes such as $K[Ag(CN)_2]$, K_2AgI_3, $[Ag(NH_3)_2]Cl$, and $AgBF_4$.

A complex silver compound, such as double metal cyanide with silver and potassium $K[Ag(CN)_2]$, can be characterized by its formation constant that is numerically equal to $K_f = 1.0 * 10^{21}$. The solutions that produce a better shine and quality are those that have big formation constants such as cyanide complexes (Lagos & Camus, 2017).

The ion complexes should continuously dissociate in a watery medium with the presence of an electric potential. The discharge potentials of silver ions vary not only with the nature of the binder but also with other electrolysis parameters (principally, current density) and with the physicochemical parameters of the solution, such as pH, agitation, and temperature (Ortiz González, 2011).

The silver ion complexes move towards the cathode where they will dissociate before reduction over the metallic surface. In this way, the free (or hydrated) ion discharges on the interface gaining electrons originating from the silver atom which reaccommodates in the crystal lattice and forms microcrystals which ultimately produce the metallic shine. It has been proven that cyanidic silver ions can reduce as complexes to generate metallic silver Ag^{o}. In accordance with this, the silver ion does not discharge freely but rather in the form of a complex. It will ultimately produce the following reaction in the cathode:

$$[Ag(CN)_2]^{-}_{(ac)} + e = Ag^{0}_{(s)} + 2CN^{-}_{(ac)} \qquad (3)$$

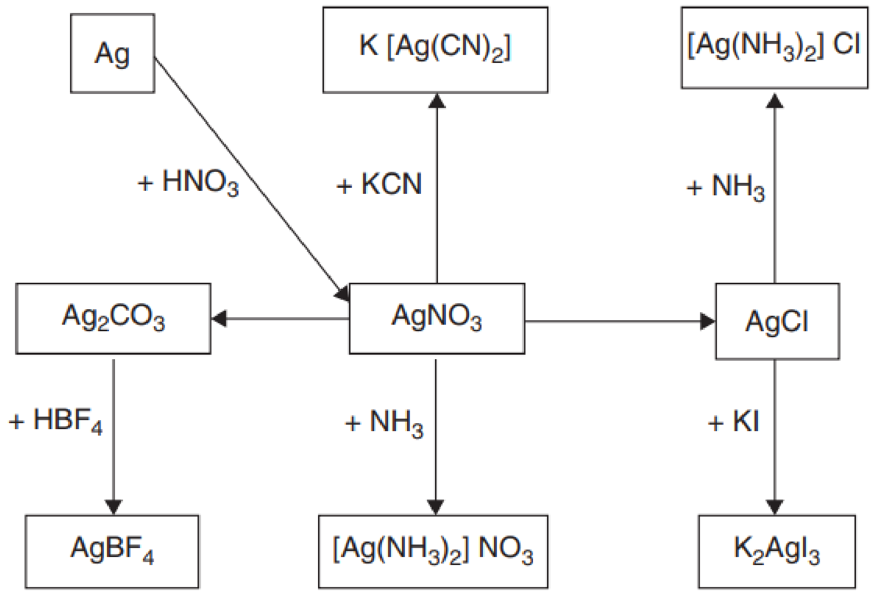


Figure 2. Summary illustration of different silver complexes.
Source: R. Lagos, J. Camus.

As shown in Figure 2, the base for the preparation of different silver electrolytes is silver nitrate $(AgNO_3)$, which is prepared by the following reaction:

$$3Ag + 4HNO_3 = 3AgNO_3 + NO + 2H_2O \qquad (4)$$

As can be seen in Equation 4, toxic nitrous vapors are released and thus the use of a fume hood is recommended.

To conduct the previously described process, the following pathway with the respective reagent amounts is recommended:

Create horizontal grooves and irregularities on the surface of the copper plate using a grinder to decrease the velocity of the displacement of mercury and increase the area of retention.

Remove impurities from the copper plates and from the stainless steel with 25% nitric acid ($HNO3$).

Solution #1: Dissolve 30 g of silver nitrate ($AgNO3$) in 300 mL of distilled water for the creation of a set of four plates.

Solution #2: Dissolve 11.5 g of Potassium cyanide (KCN) in 300 mL of distilled water.

Mix Solutions #1 and #2 (in whichever order) until a white precipitate appears. Do not shake the mixture.

Filter the solution using a coffee filter to obtain the produced precipitate. Filter paper can be used, but this increases filter time.

Filter as many times as needed until the liquid precipitate is clear. The dripping of the first filtration stimulates the reagents that did not previously react, creating more precipitate.

Prepare Solution #3 by disolving 18 g of potassium cyanide (KCN) in 300 mL of distilled water.

Disolve the resulting precipitate from Solutions #1 and #2 in Solution #3 using a glass stirrer.

Fill a 35 x 10 x 35 cm cell with distilled water up to two fingers below the maximum line. Try not to use other types of water which could contain ions that alter the silver-plating of the plates.

Introduce the copper plates (or aluminum) and stainless steel to the electrolytic cell.

Connect the cables of the power source by the following: the red clamp (+) to the stainless steel plate and the black clamp (-) to the copper plate.

Add the prepared solution and connect to a power source 4A. The voltage is adjusted with the current and the charge of the solution in the cell.

Turn on the power source and let it run for 7 minutes. Flip it and then let the power source run for another 7 minutes for a total of 14 minutes per plate.

Remove the silver-plated plate from the electrolytic cell and dry it using a blower, compressor, or dryer.

Wrap the dry silver-plated plates in stretch wrap.

Copper plates are ready for the mercury-capture process

Figure 3. Procedure for the electrochemical plating of the copper plates. Source: Pure Earth.

The mixture of Solutions 1 and 2 for the precipitation of $AgNO_3$ with KCN produces the following reaction:

$$AgNO_3 + KCN \rightarrow AgCN + KNO_3 \qquad (5)$$

The AgCN produced in Equation 5 that afterwards mixes again with the KCN to produce double silver cyanide $[Ag(CN)_2]^-$ is responsible for the coating generated on the copper plate, and the KNO_3 does not enter the electrolytic cell but rather is disposed of by acting like a precipitant.

Below are images of this process:

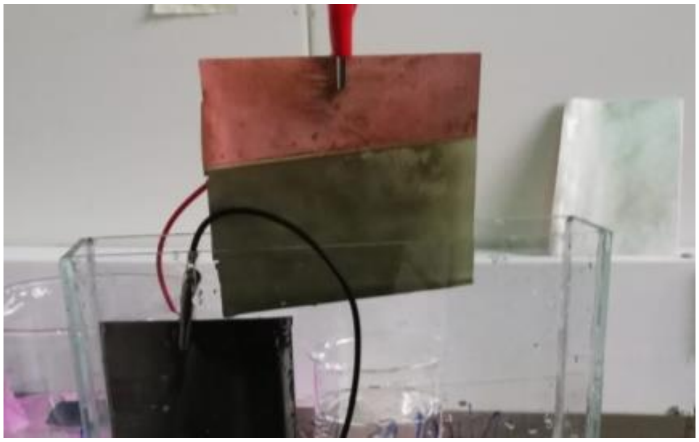


Figure 4. Silver plating on the copper plates with electric potential.
Source: Pure Earth.

Figure 4 shows the copper plate after being subjugated to the silver-plating electrochemical process. The silver layer is now ready to retain the mercury present in tailings. Figure 5 shows how the copper plate looks after the silver-plating process performed by electrolysis is complete.

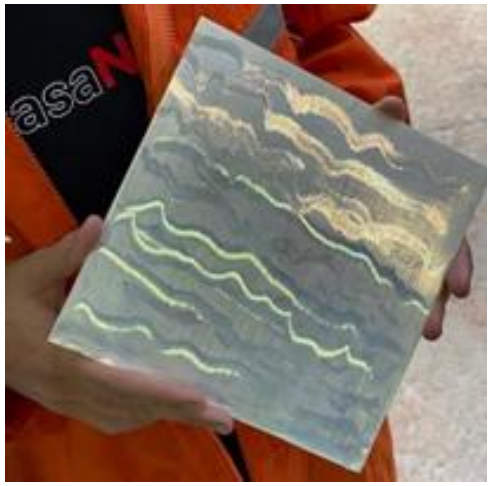


Figure 5. Silver-plated plate with irregular surface.
Source: Pure Earth.

3.3. Guide to implement pilot tests

After the plates have been silver-plated, it is important to construct them in a design such that the tailings material will pass over them and the mercury will be able to be recovered. Next, various designs that were tested during the pilot tests will be described.

3.3.1. Prototypes

The principle of the copper plates is linked to the capture of droplets of elemental mercury on the surface of the plates. Because of this, it is important to consider factors such as inclination angle, percent of solids, type and quantity of flow, and the residency time of the tailings on the surface of the plates to obtain the greatest affinity possible between the silver present in the surface of the plates and the mercury contained in the tailings. Two possible prototypes were suggested according to the results from the copper plate tests pilots. (For more information, see the *Technical Report on the Copper Plate Pilot tests* by Pure Earth.)

Modular-style prototype

This prototype placed the plates according to a modular-style design, which locates the plates in pairs with an incline of approximately 15 degrees, allowing a constant flow between the rows of plates so that the contact area is increased. The number of pairs of plates depends on where they are located.

Considering that each plate has a size of 30 x 30 cm, the total contact area can vary between 3,600 cm^2 for the minimum recommended number of plates (4) and 10,800 cm^2 for the maximum recommended number of plates (12). Figure 6 shows the previously described design.

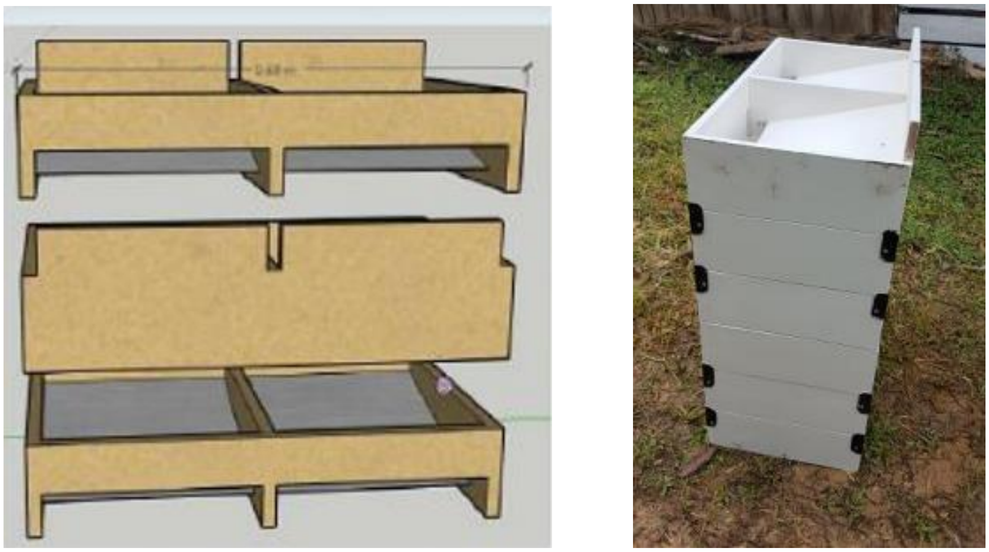


Figure 6. Modular prototype for the copper plates.
Source: Pure Earth.

Advantages of this design include operability and flexibility which facilitates moving the plates from one section of the process to the other. This allows for greater variability and shortens the operation time needed for the tests. Nevertheless, the residency time is a key factor for the effectiveness of the technique, so a disadvantage of this prototype is that it may not be as effective if the quantity of plates installed is low.

Chute-style prototype

This prototype consists of a chute-like design with 30 plates and an expanded net with an incline of 10 degrees. This prototype has three 1.5-meter pieces which are combined to make a 4.5-meter-long piece. Like the modular prototype, each plate is 30 x 30 cm, which equals a total contact area of 27,000 cm^2 or 5 times greater. This design allows for a greater residency time of the tailings on the surface of the plates so that the mercury makes contact with the plates and forms the amalgam with the silver. Similarly, it is important to note the importance of achieving a flow with the highest turbulence possible to increase the efficiency of the process. This prototype is shown in Figure 7.

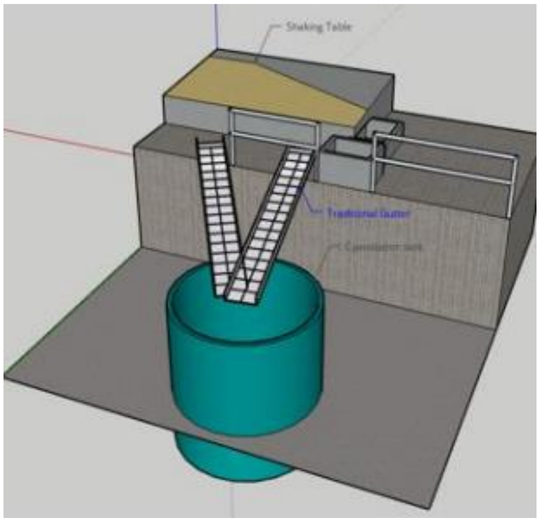


Figure 7. Chute-style prototype of the copper plates.
Source: Pure Earth.

3.3.2. Installation requirements

Considering the importance of the recovery of mercury from tailings, the installation of either of the previously described prototypes is recommended. The selection between the two depends on available space. Although it is possible to install a small model in remote zones, it is recommended that the factory, to maximize benefits, has at least some of the following basic prerequisites:

- Tailings preparation site
- Storage tank (cyanidation type): The Minamata Convention states that mercury should be removed before cyanidation processes occur. For this, it is necessary to have a tank to measure the effectiveness of the plates by sampling the quantity of mercury deposited in the tank.
- Tailings holding facility: A tailings holding facility can ease the implementation of the tests by ensuring a steady supply of material to be used as samples.
- Supply of water
- Supply of energy for pumping processes

3.3.3. Operation procedure

To choose an optimal treatment for the recovery of gold and mercury from the tailings, different steps of the process, summarized in the following flowchart, need to be considered:

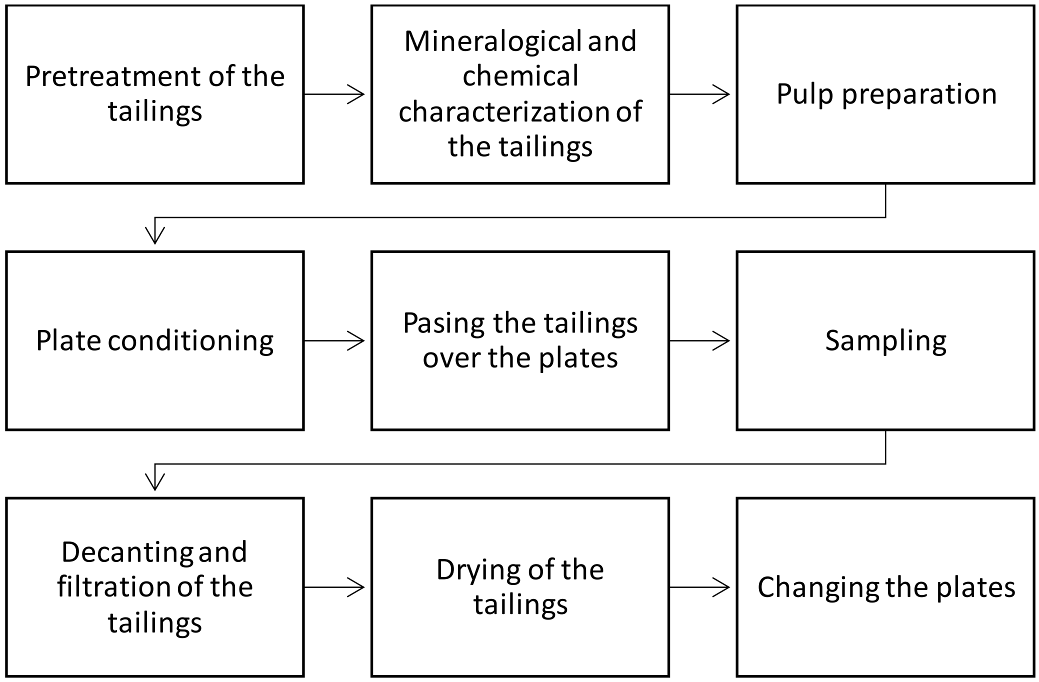


Figure 8. Flowchart of the operating procedures of the copper plates.
Source: Pure Earth.

- **Pretreatment of the tailings**

The pretreatment consists of a classification of the tailings based on particle size. For this, the tailings are sieved in a 30 x 70 net and the material is concentrated on a vibrating table to obtain two types of tailings (concentrated and fine). The fine tailings are transported directly to the copper plates, while the concentrated tailings are first directed to a concentrator and then to the plates. Regardless of classification, the two types of tailings should follow the same sample processing protocol.

- **Preliminary characterization of the tailings**

A mineralogical and chemical characterization of the tailings is recommended to know where and in what quantities the gold and mercury can be found so that they can be processed and extracted correctly. It is important to note that many of the abandoned tailings do not correspond to a single type of mining and therefore, mixtures of different tailings are sometimes found, making characterization even more necessary.

This process consists of three parts:

- Sampling: A correct tailings characterization includes a good design and sampling strategy because this can indicate the location and condition of the tailings.

- Mineralogical characterization: A mineralogical characterization is important to decision-making around the management of tailings; this can identify the presence of minerals rich in metals that are of interest.
- Chemical characterization: This stage permits the identification of the potential presence in tailings of substances of interest for both environmental and health sectors. With this information, the ones that are of interest can be prioritized.

The minerology of the tailings can be done through two tests: the first through the analytic technique of X-ray fluorescence (XRF) using the Epsilon 1 – Panalytical equipment, which reports concentrations of elements in percentages. The second test is done in specialized laboratories and consists of X-ray diffraction (XRD) with the reference equipment Aeris, which is used to detect crystalline structures in the samples and determine which minerals are present.

The chemical characterization can be performed by two analytic methods. The first is related to the determination of heavy metal in tailings using analysis “screening” devices like the Portable X-Ray Analyzer (XRF; brands used in the test were Olympus and Niton). Approximately 10 measurements per sample are recommended. In addition to the equipment mentioned, mercury vapor analyzers such as Lumex, Jerome, or Hermes can be used. Taking samples can be performed by placing approximately 300 g of tailings in one bag, maintaining the bag sealed for 20 minutes, and then measuring the mercury vapor with the Hermes equipment.

The other analytic method relates to atomic absorption with fire assay and cold vapor for analysis of total gold and mercury, respectively. These tests can be performed by accredited laboratories.

- **Pulp preparation**

During pulp preparation, it is important to consider the percentage of solids with the objective to avoid bottlenecks or the retention of material that is not desired. Therefore, a solids concentration of 25–40% in the pulp is recommended.

To move the tailings solution to the copper plates, it is necessary to have a pump with the capacity to transport solids at a high enough power (around 520 kW) to obtain the maximum possible efficiency of the plates.

- **Plate conditioning**

In addition to the copper plate preparation previously mentioned in Section 3.2, the position of the plates should be considered to obtain the maximum yield throughout the process. Therefore, it is necessary to select the best design, modular or chute, based on the criteria of the conditions observed in the field and the recommendations of this document.

- **Passing the tailings over the plates**

As previously mentioned, the pulp (mixture of tailings with water) must maintain a constant flow over the plates to avoid possible bottlenecks or retention of undesired material. Nevertheless, this flow should be as turbulent as possible. Because of this, the tailings should pass over the plates at the rate of 1.5 L/min in triplicate.

- **Sampling**

To measure the recovery of mercury and the amount of gold in the tailings, samples should be taken in containers or buckets that allow for the collection of approximately 500 mL of pulp at the beginning and end of the plates. This process should be done continuously based on operation time to sample during different moments of the process.

- **Decanting, filtration, and drying of the tailings**

After sampling, the solution should decant for approximately five hours, then the tailings should be filtered and dried for an average of six hours in a desiccator. The dry samples can then be analyzed by the XRF technique with the portable equipment, atomic absorption in the laboratory, and for mercury vapors with the HERMES equipment.

- **Changing the plates**

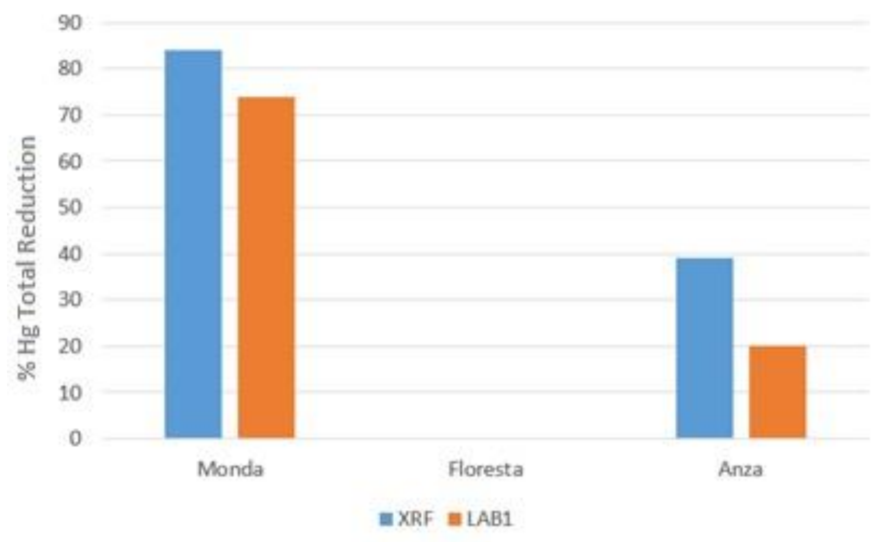
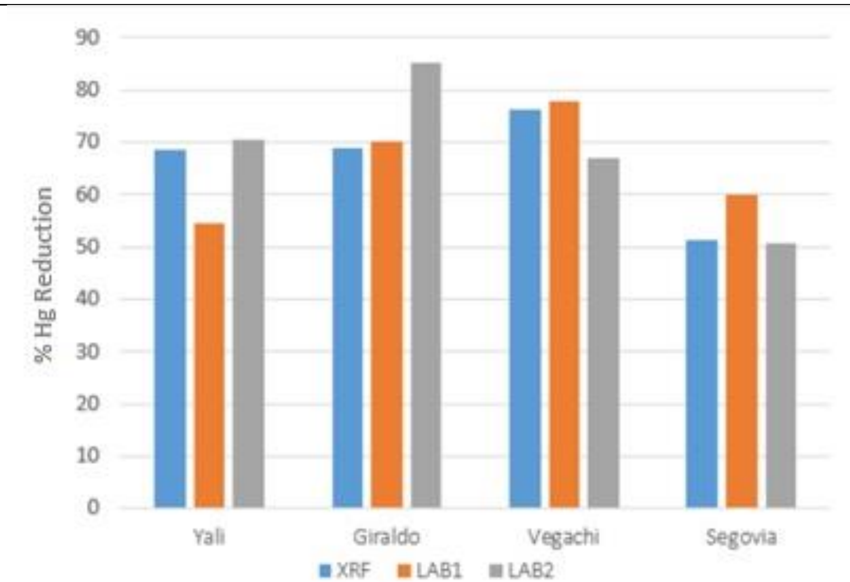
Finally, to increase the yield of mercury removal from the tailings, the plates should be changed every two tests of approximately seven tons per test on both sides of the plates. This step is necessary because of the oxidation that the plates present. This oxidation is governed by the age of the tailings; the older the tailings are, the more oxidation occurs on the plates.

3.4. Mercury recovery results

To test the effectiveness of the copper plates on the recovery of elemental mercury (Hg^o) that may be present in the tailings reprocessed by the ASGM sector to obtain gold, various pilot tests were conducted in the field. These pilot tests were split into three phases. The results from each phase are presented in Table 1.

The percentage of total mercury reduction is the most important factor because the principal objective is to reduce the greatest quantity of mercury before the tailings enter the process of cyanidation. As can be seen in Table 1, there is a significant reduction in each phase of the percentage of mercury present in the tailings.

Table 1. Results from the pilot tests, split into three phases.

Phase I	
Phase II	

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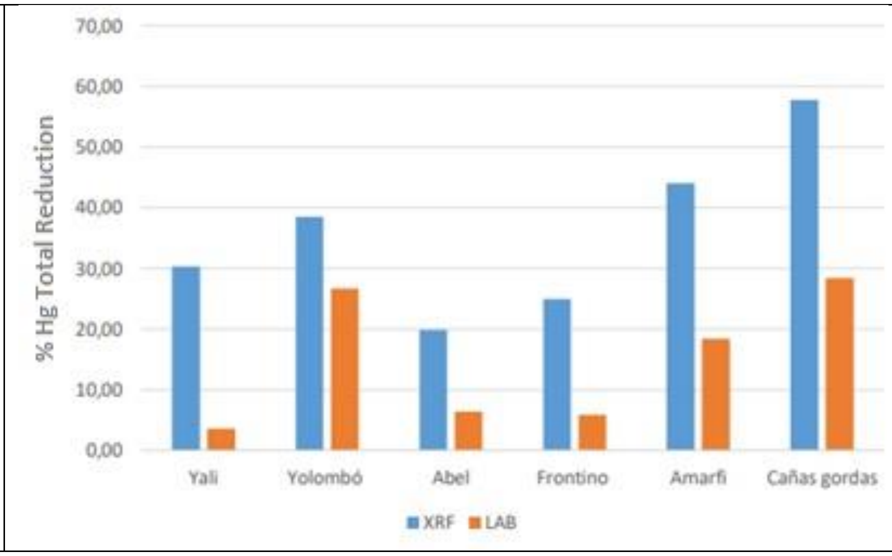
<td>
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4. Economic plan

To establish the viability of the implementation of the copper plates project, with the end goal of recovering mercury from contaminated tailings, the methodology of project financial evaluation was applied.

As a starting point, an investment project is defined as a plan that is assigned a determined amount of capital as well as various inputs to produce a good or service (Meza Orozco, 2017).

The lifecycle of an inversion project has four stages: idea, pre-inversion, inversion, and operation. After identifying the problem or business opportunity, the principal goal of the formulation stage is to determine the amount of initial inversion, income, and costs of the project through a series of sequential studies, such as market, technical, administrative, and financial studies.

The financial study seeks to determine the viability of the project considering the information contained in the other studies by determining the initial inversion, calculating the income, and determining the costs, which results in the net cash flow. These flows allow for the completion of the financial evaluation of the project by applying tools such as the Net Present Value (NPV) or the Internal Rate of Return (IRR). For the project to be viable, it needs a positive NPV or an IRR greater than the discount rate.

In the following section, this methodology will be developed for the copper plates technology, using the information collected from the results of the pilot project split into three phases. This pilot project was conducted in the Juan Diaz tailings processing plant, so there could be variations in cost with respect to the implementation of the plates in other tailings processing plants. Information was also gathered from the 2018 Cost Model used by the Colombian Geologic Service and the Ministry of Mines and Energy, which used the mine of

La Llanada in the Department of Nariño as a reference (Servicio Geológico Colombiano, 2018).

4.1. Copper plate implementation costs

An initial inversion is needed for the implementation of the copper plates, which is divided into two phases: the plating phase and the installation phase. The costs are as follows:

Table 2. Costs of equipment and reagents for the plating phase.

PLATING PHASE

EQUIPMENT DESCRIPTION	SPECIFICATIONS	COMMERCIAL VALUE (COP $) *	QUANTITY	TOTAL COMMERCIAL VALUE (COP $)
Glass cell	4 MM 35*35	55,000	1	55,000
Glass cell	4 MM 35*10*35	97,000	1	97,000
Mts cable	#8	5,000	10	50,000
Beaker	250 ml	6,303	2	12,606
Beaker	400 ml	8,655	3	25,965
Beaker	2000 ml	35,294	2	70,588
Bag	25 x 2	800	2	1,600
Stirrer	Glass	3,529	2	7,058
Sheet	300 x 300 mm	11,500	3	34,500
Stretch film caliber	-	43,900	2	87,800
Filter paper	-	3,900	3	11,700
Coating	TAMI Darnel	6,800	1	6,800
Gloves	Extra large	1,700	4	6,800
Gloves	Medium	11,000	2	22,000
Gloves	Small	3,500	2	7,000
Thermometer	Digital	75,000	1	75,000
Gloves	Large	2,500	2	5,000
Blade disc	-	4,300	6	25,800
Sandpaper	#100	1,600	5	8,000
Universal bracket	-	33,193	1	33,193
Clamp	Double for pipettes	21,849	1	21,849
Stretch wrap	-	11,400	1	11,400
Nitric acid	50%	14,874	3,8 L	14,874

Distilled water	-	40,756	40 Kg	40,756
Silver nitrate	In crystals 99%	1,546,218	500 g	1,546,218
Potassium cyanide	-	20,168	500 g	20,168
Dual power source		1,100,000	1	1,100,000
Machinery and equipment total for plating phase				**3,398,675**

The plating phase is related to the equipment and reagents necessary for the electrochemical plating of the copper plates (Ver 3.2.1).

Table 3. Costs of machinery and equipment for the installation phase.

INSTALLATION PHASE

EQUIPMENT DESCRIPTION	SPECIFICATIONS	COMMERCIAL VALUE (COP $ *)	QUANTITY	TOTAL COMMERCIAL VALUE (COP $)
Pressure tube	2 x 1	16,900	2	33,800
Set of 8 cloths	Microfiber	22,900	1	22,900
Ball valve	PVC 2 L	27,100	4	108,400
Elbow tube	90 x 2	8,800	3	26,400
Tee tube connector	PAVCO	14,150	4	56,600
Female adaptor	2:00 p. m.	9,400	2	18,800
Male adaptor	2 PR	6,550	2	13,100
Lock	Red 3 dial	31,900	1	31,900
Lock	Suitcase TSA	48,900	1	48,900
Plugs	2"	4,167	6	25,002
Elbow tube	45 x 2	12,100	4	48,400
Volumetric flask	500 ml amber	36,000	3	108,000
Copper sheet	0.60 m	50,623	16	809,968
Wood compartments	With waterproof paint	-	6	900,000
Bioremediation mud xKg	With heavy metals	1,495	990	1,480,050
Copper wire rolls xKg	60 cm x 1 mm	36,990	28,7	1,061,613
Copper wire rolls xKg	60 cm x 0.9 mm	39,950	67,48	2,695,826
Manufacture and supply of a modular type channel	4.50 m long x 60 cm wide. Two sides 15 cm high divided in 3 equal parts: 1.50 m long, 60 cm wide, 15 cm sides	1,428,000	1	1,428,000

Machinery and equipment total for installation phase	**8,917,659**

The total initial inversion is COP **$12,316,334.**

4.2. Costs estimations for a processing plant

To estimate the costs for a tailings processing plant in Colombia, the Juan Diaz tailings processing plant was used as a reference. This plant is in the municipality of Yalí in the department of Antioquia. Below, a description can be found of the parameters that were considered for the formation of a financial plan to estimate project costs and viability:

4.2.1. General variables

The general variables applied in the production plan of the plant in Yalí are the following:

- **Project lifecycle:** To establish the viability of the project, the lifecycle is set at 5 years.

- **Discount rate:** The discount rate used in these calculations is 20%. This variable refers to the percentage that the investor wishes to recover. The value of the discount rate must be less than the IRR for the project to be viable.

- **Machinery lifespan:** Because of depreciation effects, the effective lifespan of the machinery is 10 years.

- **Inflation:** An inflation value of 5% is used for 2021 which will affect overall prices in 2022. Because this variable is controlled by the Banco de la República (Republic Bank), it can be assumed that inflation will decrease to 3.5% in 2022–2023 and 3% in 2024–2025.

- **Price of gold:** For 2021, the price of gold was calculated as the average price paid by the Banco de la República for a gram of gold between January 2000 and December 2021. For the other years, the growth rate was set at 6.5% by using an autoregressive model with the assumption that intermittent interruptions will continue in general productive processes in the economy due to the effects of COVID-19. These interruptions lead to consistently high estimates for the price of gold.

- **Minimum wage raise:** For 2022, the government of Colombia raised the minimum wage by 10.04%; nevertheless, for the upcoming years, the more conservative value of 1% of the projected inflation was used.

4.2.2. Benefits

The calculations considered the following by the employer for benefits: 12% for pension, 8.5% for health insurance, 6.96% for professional risk insurance, 4% for family compensation funds, and COP $400,000 for the supply of clothing, personal protective equipment, and other provisions.

4.2.3. Production variables

- **Value of the tailings:** The estimated value for the purchase of tailings is COP $200,000 per ton. The transportation of the tailings is estimated at COP $400 per ton per kilometer. The estimated distance of travel is 300 kilometers, meaning that COP $120,000 is needed for the transportation of each ton of tailings.

- **Plant operation:** The plant operation is set at 8 hours per shift, one shift per day, and 25 days of operation per month.

- **Processing volume:** The processing capacity is 7.5 tons per day for a total of 187 tons per month.

- **Gold recovery:** According to the tests conducted in different phases of the project, the gold content in tailings is 5 grams per ton and the percentage of gold recovery is 79.77%, resulting in a recovery of approximately 4 grams of gold per ton of tailings.

- **Utilities:**

  - **Electricity cost**

    Formula to calculate the monthly electricity bill:

    $$Cost\ of\ Electricity\ (\$) = Electricity\ Consumption\ (KWh - month) * Rate\ (\frac{\$}{KW}),$$

    where the rate is COP $630 per kilowatt.

  - **Water cost**

    Formula to calculate the monthly water bill:

    $$Cost\ of\ water\ (\$) = Monthly\ water\ consumption\ (m^3) * Rate(\frac{\$}{m^3}),$$

    where the rate is COP $1,043 per cubic meter.

The Juan Díaz tailings processing plant disregards the cost of water because they can obtain water from a nearby source; nevertheless, it is important to consider this factor in future models.

- **Costs:** Indirect costs are set at 10% of direct costs. Equipment maintenance costs are 0.5% of indirect costs. Given that the infrastructure needed for tailings processing is already in place, the opportunity cost is COP $40,000,000. The opportunity cost is defined as the earnings from the rent of the plant and its equipment. Usually, this opportunity cost is not considered in financial plans, but it should be considered in subsequent models.

- **Final disposal of the copper plates:** Upon processing the tailings, the copper plates would then be considered hazardous waste. To establish the final disposal costs, the initial weight is set at 0.8 kg and final weight at 1 kg, which represents a recovery of 0.2 kg of mercury per plate. The use rate is assumed to be 42 plates per year which equals 30 used for the chute-style model and 12 for the modular-style model. The price of hazardous waste management is COP $1,500 per kilogram.

- **Taxes:** According to regulations, income tax is 35% and the royalty rate is 4%.

4.3. Profit layout

As previously explained, the timeline of the project is 5 years; nevertheless, the model uses year 0 as the time in which the inversions are made. Therefore, year 6 corresponds to the payment of taxes generated in year 5.

Considering this, the following section describes each component of the cash flow:

4.3.1. Inversion

Inversion is necessary for the installation and function of the elements that allow for the plating of the copper plates which are used for the recovery of mercury found in tailings.

4.3.2. Non-taxable income

For the current plan, the sale of gold can be considered non-taxable income. Gold production is constant and relates to the quantity of tailings processed per year multiplied by the total recovery of gold, which equals 8,949.74 grams. Gold price tendencies are described in the description of the parameters.

Table 4. Non-taxable income.

TAXABLE INCOME PROJECTION

CONCEPTO	UNIDAD	0	1	2	3	4	5	6
Annual Gold Prouction	g		8,949.74	8,949.74	8,949.74	8,949.74	8,949.74	
Annual Total Income by Gold Sell	**COP($)**		**$ 2,001,877,623**	**$ 2,211,042,834**	**$ 2,442,400,558**	**$ 2,697,954,765**	**$ 2,979,849,258**	
% Annual variation				10.45%	10.46%	10.46%	10.45%	

4.3.3. Deductible expenses

The variables that form this line item are adjusted yearly based on estimated inflation with the exception of salaries that are adjusted by the minimum wage increase for each period. Deductible expenses comprise:

- **Cost of raw materials:** The cost of raw materials consists of two components, the cost of the tailings and the cost of the transportation of the tailings. The total annual cost is calculated by multiplying this value by the processing volume during this period.

- **Inputs:** The input category consists of components necessary for the process of gold extraction and mercury recovery from the tailings, such as chemical elements, copper plates, and materials for the chute- or modular-style models.

- **Human resources:** This line item includes salaries, benefits, social security, and parafiscal contributions for all permanent employees of the process of gold extraction and mercury recovery.

- **Industrial safety:** This includes all elements required for the workplace safety of the workers**.**

- **Maintenance:** As explained in the description of the parameters, this represents 0.5% of the total cost of the machinery.

- **Laboratory tests:** This line item is necessary, given the importance that these tests have in measuring different aspects of the process. Included in these tests are atomic absorption for metals, fire assays, and mineralogical characterization, among others.

- **Utilities:** The category consists of the water and electricity needed for the treatment of the tailings. Its use is proportional to the quantity of tailings processed.

- **Depreciation:** For this project, depreciation is not included because the machinery and installations are considered an opportunity cost.

- **Indirect costs:** The indirect costs, as explained in the description of the parameters, are calculated as 10% of the direct costs.

Table 5. Deductible expenses.

PROJECTION OF DEDUCTIBLE EXPENSES								
CONCEPT	UNIT	0	1	2	3	4	5	6
TOTAL DEDUCTIBLE EXPENSES			**$ 1.758.179.687**	**$ 1.822.506.317**	**$ 1.889.209.945**	**$ 1.948.933.365**	**$ 2.010.570.373**	
Raw Material Cost			$ 753.984.000	$ 780.373.440	$ 807.686.510	$ 831.917.106	$ 856.874.619	
Tailings			*$ 471.240.000*	*$ 487.733.400*	*$ 504.804.069*	*$ 519.948.191*	*$ 535.546.637*	
Transport			*$ 282.744.000*	*$ 292.640.040*	*$ 302.882.441*	*$ 311.968.915*	*$ 321.327.982*	
Supplies			$ 263.562.259	$ 272.786.938	$ 282.334.481	$ 290.804.515	$ 299.528.651	
Copper Plates disposal			$ 66.150	$ 68.465	$ 70.862	$ 72.987	$ 75.177	
Human Resource			$ 253.667.363	$ 265.082.394	$ 277.011.102	$ 288.091.546	$ 299.615.208	
Health and Safety			$ 13.816.356	$ 14.299.929	$ 14.800.426	$ 15.244.439	$ 15.701.772	
Mantenance			$ 155.002.649	$ 160.427.742	$ 166.042.713	$ 171.023.994	$ 176.154.714	
Lab Tests			$ 74.785.609	$ 77.403.106	$ 80.112.214	$ 82.515.581	$ 84.991.048	
Public Services			$ 83.460.784	$ 86.381.911	$ 89.405.278	$ 92.087.436	$ 94.850.060	
Depreciation								
Indirect Costs			$ 159.834.517	$ 165.682.392	$ 171.746.359	$ 177.175.760	$ 182.779.125	

4.3.4. Taxes

Starting in 2022, income tax is estimated at 35%. Note that the income tax incurred in the present term will be paid in the next term.

Additionally, generated royalties are calculated at 4% on top of the 80% of the price of gold for each period.

4.3.5. Cash flow

Using the previously described variables, the Net Cash Flow can be calculated. For year 0, the negative value corresponds to the project inversion and for year 6, the negative value refers to the income tax for year 5.

The flows from years 1–5 are calculated by including earnings from gold sales, subtracting the expenses generated during the production process, discounting the payment of taxes, and applying the opportunity cost. Finally, for year 5, a salvage value corresponding to 10% of the initial value is estimated for the machinery.

Table 6. Cash flow.

CONCEPT	0	1	2	3	4	5	6
(-) INITIAL INVESTMENT	$ (12.316.334)						
(+)TAXABLE INCOME		$ 2.001.877.623	$ 2.211.042.834	$ 2.442.400.558	$ 2.697.954.765	$ 2.979.849.258	
(-)DEDUCTIBLE EXPENSES		$ 1.822.239.771	$ 1.893.259.688	$ 1.967.366.763	$ 2.035.267.918	$ 2.105.925.549	
Operational Costs		*$ 1.758.179.687*	*$ 1.822.506.317*	*$ 1.889.209.945*	*$ 1.948.933.365*	*$ 2.010.570.373*	
Royalties		*$ 64.060.084*	*$ 70.753.371*	*$ 78.156.818*	*$ 86.334.552*	*$ 95.355.176*	
(-)DEPRECIATION							
(=)PROFIT BEFORE TAXES	$ (12.316.334)	$ 179.637.852	$ 317.783.146	$ 475.033.795	$ 662.686.847	$ 873.923.709	
CAUSED TAXES		$ 62.873.248	$ 111.224.101	$ 166.261.828	$ 231.940.397	$ 305.873.298	
(-)PAID TAXES			$ 62.873.248	$ 111.224.101	$ 166.261.828	$ 231.940.397	$ 305.873.298
(+)DEPRECIATION							
(-)OPPORTUNITY COST		$ 42.000.000	$ 43.470.000	$ 44.991.450	$ 46.341.194	$ 47.731.429	
(+)RESCUE VALUE						$ 59.308.110	
NET CASH FLOW	$ (12.316.334)	$ 137.637.852	$ 211.439.898	$ 318.818.244	$ 450.083.826	$ 653.559.993	$ (305.873.298)
NET PRESENT VALUE	$675.821.254						
TIR	1171%						

As a result of the financial evaluation, Table 6 shows that from the first year of the project, the Net Cash Flow presents values that not only recover the initial inversion but generate earnings. These financial indicators can be used in addition to the NPV and IRR to support the viability of the implementation of the copper plates.

5. Conclusions

- The implementation of the copper plates reduces by up to 80% the amount of mercury found in tailings, which signifies a reduction in the amount of contamination to the environment and risk to human health.
- The incorporation of the copper plates in the tailings process is viable and profitable, not only benefiting the environment and human health, but also potentially economically benefiting the involved miners due to the positive NPV and the IRR higher than the discount rate.
- The reprocessing of tailings for the recovery of gold can be facilitated with the copper plate technique because during the cyanidation process, the amount of mercury involved has been reduced, increasing the quantity of gold able to be recovered.

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