Processing Centers in Artisanal and Small-scale Gold Mining: Evolution or More Pollution?

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Abstract

This article discusses the technical evolution observed worldwide in the artisanal and small-scale gold mining (ASGM) sector. At first glance, the centralization of mineral processing activities in local centers seems to rationalize the production and educe the dispersion of polluting tailings in rural areas. However, the rise of processing centers around the world is taking advantage of the ignorance and lack of capital of the artisanal miners. These centers receive gold ores from miners and process using poor grinding and amalgamation processes to extract less than 30% of the gold. As payment, miners leave the tailings (residues) at the centers which are processed by cyanidation to extract residual gold. The cyanidation of Hg-contaminated tailings produces mercury-cyanide complexes that are not always recovered in the process of activated carbon or zinc precipitation. As a result, tailings discharged into the local water streams carry mercury either as soluble cyanide complexes or Hg droplets. Some technologies to extract gold in small-scale to replace amalgamation are discussed and the cyanidation of concentrates in small-ball mills is highlighted as the most promising one. Any technique to replace mercury should invest in gravity or flotation concentration in order to reduce the mass of material to be leached or melted. This reduces dramatically capital and operating costs. There are a few processing centers, in particular at the South of Ecuador, doing responsible and cleaner gold extraction. They are integrating miners in the evolution process and creating a new breed of professionals in the small gold industry. The proliferation of these centers is possible but private capital is the main key factor since most Governments of developing countries do not have the understanding and the capacity to change the behavior of artisanal miners.

Keywords: *gold, mining, mercury, cyanide, technology*

1 The Need for Cleaner Production

In virtually all developing countries approximately 30 million individuals extract more than 30 different minerals in small-scale using rudimentary techniques. Gold is the preferred mineral since the metal price quintupled in the last 10 years. It is estimated that between 10 and 15 million people are directly involved in this activity causing high levels of river siltation, mercury pollution and other environmental problems (Swain et al., 2007). There is a clear lack of understanding by the dominant society and authorities on the work of the informal or small-scale or artisanal miners. In the large majority of more than 70 countries where these gold miners operate, the regulations are extremely fuzzy. Despite the ignorance about this sector, most Governments believe the way to resolve the pollution problem caused by these gold miners is the formalization. Interestingly, the root of the informality is usually the poor relationship between Ministries of Mines and Ministries of Environment in developing countries. An example is found in Brazil where in 2010 the Ministry of Mines granted 284 mining titles for artisanal miners in the Tapajós "Garimpo" Reserve but they do not have environmental permits (DNPM, 2010). Sousa and Veiga (2009) reported that out of 141 artisanal mining sites visited in the Tapajós Reserve, only 0.7% had environmental permits in good standing. In Peru the situation is not different. The Peruvian Ministry of Mines, with support of the United Nations, is encouraging formalization of more than 300,000 Peruvian artisanal miners believing this will bring technical, environmental and social obligations to the artisanal miners (PMEM, 2011). Formalization is in the agenda of all Ministries of Mines in developing countries. While this provides the miners with legal mineral titles that can be negotiated, with no presence of the Governments in remote rural/mining regions, no technical assistance, and no economic incentives, formalization is seen by miners as a way of the Governments to charge taxes.

In general, legislations do not provide adequate framework to make small, artisanal or informal miners more efficient and cleaner gold producers. The official mechanisms for a small or artisanal or informal miner to obtain environmental permits are so complicated that they prefer to be illegal. An example of this is the mercury and cyanide use in Brazilian mines. The Decree 97634 of 1989 of April 10, 1989 and Decree n° 97507 of February 13, 1989 establish that all miners have to obtain a special authorization from the Federal Environmental Agency (IBAMA) to use both chemicals. The process is so complicated that virtually all miners do not have such permits. As there is no enforcement, the laws are simply ignored by gold miners (Sousa and Veiga, 2009).

After four decades of intensification of artisanal and small-scale gold mining in virtually all developing countries, the environmental, social and health situation of these miners has not improved much. As the simple and inefficient amalgamation techniques usually extracts less than 30% of gold from the ore, some smart individuals are learning, copying and adapting processing technologies to extract gold from large industrial mining companies. The main hurdle in accelerating this technological evolution is still the lack of technical assistance and capital. As a consequence, the technological transition is still "cripple", and this has been causing large environmental and health problems. There are problems in technology transition that goes beyond simple educational and demonstration of new techniques. This deals with the fact that those individuals with more knowledge and resources are taking advantages of the poorer and simpler miners. In other words, information and capital about more efficient techniques does not flow democratically among the artisanal and small mining sector. This is the case of the propagation of processing centers.

2 "Evolution" and Pollution of the Processing Techniques

The idea of having processing centers was introduced in some countries in the 1980s and 1990s. Miners take their ore to a facility where gold is extracted by specialized operators. In 1991, the Government of Venezuela prohibited all amalgamation activities on board of dredged. Three processing centers were created by the Government and private investors to receive gravity concentrates of alluvial ore and extract the gold with amalgamation in rolling barrels. The idea was applauded by many experts and during the existence of the centers, substantial reduction of mercury discharges into the Caroni River was observed (Veiga, 1997).

In Africa, the Shamva Center in Zimbabwe, built in 1989, supposed to process ore from 40 gold mines in the region. This project was a collaboration of the National Miners Association of Zimbabwe with the UK Non-Government Organization ITDG (Intermediate Technology Development Group, nowadays known as Practical Action). The main environmental benefits were to move away tailings from rivers and discourage miners from using mercury The center was active for many years but the main hurdles were the distance from the mines and the lack of efficient process to extract fine gold (Simpson, 2007).

The original idea of the Shamva Center proliferated worldwide. The merit of the idea was clear: those with no capital to purchase their own pieces of equipment to crush, grind and process gold, take their ores, mined for two or three weeks, to these centers where the owners provide, for “free” or for a symbolic fee, the whole service to generate, in short time, a bar of gold in the miners’ hands. As a payment, miners leave their tailings (waste) in the centers’ facilities. The “catch” of this system is the fact that these centers barely grind the ore in order to liberate fine gold particles before processing. In all centers they use mercury to trap the gold from concentrates or from the whole ore. With this inefficient processing technique, the gold recovery is usually below 30% and in some rare cases can reach 50%. Then, the centers’ owners use better techniques to extract at least 90% of the gold from the tailings left behind. The process is unfair with the miners and also extremely polluting as the material being re-processed is contaminated with mercury.

Worldwide, all Hg-contaminated tailings left in processing centers are leached with cyanide in large tanks. In some countries there are agitated tanks but in many places the simplest cyanidation way is the vat leaching or “percolation”, as it is popularly known. Without proper aeration, the percolation process lasts up to 50 days as observed in the Brazilian Amazon and gold recovery can be as low as 50% when the gold particles are not exposed to the cyanide (Sousa et al., 2010). Once the gold is in the cyanide solution two techniques can be used to recover it: 1) adsorption of gold onto activated carbon or 2) gold precipitation with zinc.

In Zimbabwe, percolation is widely used followed by adsorption on activated carbon. There are about 1000 small-scale gold mining sites and almost 250 processing centers in the country in which 117 are registered in the Kadoma-Chakari region (Metcalf, 2008). Miners take low gold grade material (3 to 15 g Au/tonne) to the custom centers to be ground in stamp mills (1 tonne/h) below 1 mm followed by either concentration in a locally manufactured Knudsen-type centrifuge or amalgamation of the whole ore in copper-amalgamating plates. These are copper plates of 2 to 3 m^2 covered with a layer of mercury. Miners pay typically US$ 1 to 3 per hour of services which definitely does not cover the operating costs. When the low speed centrifuges are used, the concentrate is constantly discharged and manually amalgamated. As miners do not have analytical control of the adequate concentrate discharge time, they add 50 to 150 g of mercury into the centrifuges hoping to trap more gold. The process does not become more efficient. In fact part of the mercury is dispersed as droplets and lost with tailings. In the case of copper-amalgamating plates use, due to the attrition of the material with the mercury layer, about 20 g of Hg is lost per tonne of material processed (Billaud et al, 2004). Mercury losses in Zimbabwe are about 25 tonnes/a and it is estimated that around 70% of this mercury is lost to tailings that eventually undergo cyanidation in vats with 20 to 70 tonnes of material (Metcalf and Spiegel, 2007). The gold-loaded cyanide (pregnant) solution percolates the coarse-grained material and is filtered at the bottom of the vats by cotton rags and sand columns. Then the clear Au-pregnant solution passes through 3 or 4 columns of PVC loaded with activated carbon to adsorb gold and some mercury. The Au-barren solution is then re-circulated to the vats or simply discharged to water streams. The Au-loaded activated carbon is transported to the capital, Harare, to be stripped by two or three companies. There is only a colorimetric qualitative control of the gold dissolved in six days of percolation and it seems that the processing centers' owners have high trust in the stripping companies as they do not question the gold recovered by them. The amount of mercury dissolved is unknown. The cyanide percolation of tailings from copper-amalgamating plates has also been witnessed in Brazil, Chile, Laos and Venezuela. Recently, the Government of Guyana prohibited the use of copper-amalgamating plates in the country.

In the South of Ecuador, miners bring their ores to one of the hundreds processing centers in the region. When the gold ore is low-grade and the amount of material to be processed is large (40-90 tonnes) the material is processed in Chilean mill processing centers. A Chilean mill consists of two or three heavy cement wheels with steel rims connected to a 20 HP electric motor. The wheels rotate over a 25 cm wide, 2-inch thick steel plate to crush and grind the material below 0.2 mm. The ground material is then concentrated in sluice boxes with wool carpets and the concentrate is amalgamated. As only a small amount of concentrate, around 20 kg, is amalgamated, the mercury losses with tailings represent only 1.4% of the mercury introduced in the process. The amount of gold extracted fluctuates between 40 and 50%, which is better than what it is seen in other centers with more rudimentary grinding-concentration processes. When the ore is rich and the amount of material is low (1 or 2 tonnes), miners prefer to take their ores to "chancha" centers. "Chanchas" (as known in Peru and Ecuador) or "cocos" (in Colombia) are small ball or pebble or rod mills (capacity ranging from 70 to 200 kg of ore) filled with one pound of mercury to amalgamate the whole ore. This rudimentary amalgamation process is not efficient since mercury is pulverized when the ore is ground. Only 30 to 40% of the gold in the ore forms amalgam and is recovered. The main environmental problem is that about 20 to 30% of the mercury introduced in the system is lost with tailings (Velasquez et al, 2010). In the Department of Antioquia, similar process is used and up to 82% (average of 15 centers was 46.3%) of the mercury introduced in the "cocos" is lost with tailings (Ibrahim Salih, UNIDO Mercury Project in Colombia, personal information). Tailings with up to 5000 mg/kg of Hg were observed in Colombia (Veiga, 2010). This inefficient process of whole ore amalgamation is also seen in North Sulawesi, Indonesia (Castilhos et al., 2006) and about 30% of the mercury introduced in the mill is lost. This whole ore amalgamation process in ball mills has also been seen in the Department of Piura, Peru.

In the cyanidation process, mercury, as gold and other metals, forms soluble complexes with cyanide, such as $[Hg(CN)_4]^{2-}$ which is stable at pHs above 8.5 and $Hg(CN)_2$ (aq), stable at pH below 7.8 (Flying and McGill (1995). Gold cyanide complexes formed during the leaching step are adsorbed on activated carbon and removed from the leaching system without the need of filtration. As the species $Hg(CN)_2$ is more easily absorbed on the activated carbon than $[Hg(CN)_4]^{2-}$ (Adams, 1991), and the gold cyanidation process occurs at pH between 10 and 11, it is expected that little mercury reports to the activated carbon. In this situation, the pulp of ore left behind when the gold was extracted with carbon is rich in mercury-cyanide complexes. This was actually observed in Portovelo, Ecuador, where only 3.72% of the mercury introduced in the cyanidation tank was removed by the activated carbon. Nearly all gold was adsorbed on the carbon, but the large majority of the mercury remained with the contaminated tailings which have been discharged to the water streams. In the tailings, mercury is left behind as small droplets (43%) or in solution as cyanide complexes (51%) (Velasquez et al, 2011).

Gold can also be extracted from the cyanide solution by precipitation with metallic zinc (known as Merrill-Crowe process). As previously described, the leaching process is either conducted in vats or in agitated tanks. In the latter, as observed in Ecuador, the process is halted after 12 hours of agitation and the solids settle. The

Au-pregnant solution is siphoned and passed through PVC columns filled with zinc shavings where gold is precipitated. The cyanide solution returns to the tanks and another cycle or 12 hours of agitation starts. The process lasts 5 days and around 90% of the gold is extracted together with 40% of the mercury from the contaminated tailings. As the kinetics of mercury leaching is slower for mercury than for gold, mercury cyanide keeps forming when the miners discharge the pulp. The gold precipitation with zinc supposes to be conducted under vacuum but miners do not have this knowledge and lose 6% of the gold in solution (not precipitated with zinc). The same is observed with mercury and 10% of the mercury already in solution is not precipitated. However the precipitated mercury is released to the atmosphere when miners irresponsibly burn the zinc shavings to obtain metallic gold (Velasquez et al., 2011).

Any cyanidation of Hg-contaminated tailings seems to be a relevant source of pollution as mercury cyanide is formed and released to the environment. It is well known that mercuric species are easily methylated in the environment (Jensen and Jernelov, 1969). However it is not well-understood whether the mercury cyanide species are methylated in the sediments or directly bioaccumulated in aquatic organisms, but in many sites where Hg-contaminated tailings are leached with cyanide, fish contains high levels of mercury (McDaniels et al., 2010). Rodrigues et al (2004) analyzed 31 samples of carnivorous fish from a small lagoon at the Brazilian Amazon that was receiving effluents from a heap-leaching cyanidation operation. The average total mercury concentration of the samples was 4.16 ± 5.42 mg/kg and a small fish (15 cm) sample showed levels of 21.9 mg Hg/kg (Sousa and Veiga, 2009), probably a new world record.

So, it is clear that the transition from mercury to cyanide technology cannot be partial, since mercury-cyanide complexes exacerbate the pollution. The labour division between “rich” processing centers’ owners and “poor” miners introduces a huge hurdle for the evolution of the mercury-free technologies and for equitable division of the gold production.

3 No Magic Bullets...but We Try

In spite of many other issues in artisanal and small-scale gold mining such as water siltation, tropical diseases, deforestation, prostitution, drugs, child forced labor, etc., mercury pollution still occupies the first place in research and intervention projects since the effects of metallic mercury in the environment is complex. Another reason is that most mercury used by gold miners in developing countries comes from developed countries. Most assistance projects with focus on mercury bring solutions to reduce exposure to mercury vapour. Retorts are definitely important for health reasons, but the large majority of mercury is lost when the whole ore is amalgamated. International technical assistance is important but it is rarely sustainable. Hilson et al (2007) has criticized in particular the low effectiveness of the measures implemented or demonstrated by international agencies to gold miners to replace mercury. The sustainability of such measures is also poor due to the lack of presence of Governments in a mining region.

Artisanal, informal or small gold miners are the main consumers of mercury, using and losing almost 1000 tonnes of metallic mercury per annum or more than 30% of all mercury annually used by different industrial applications (Swain et al., 2007). Mercury emitted to the atmosphere and released to the environment has serious environmental and health implications. Many techniques to introduce cleaner gold mining have been proposed but most of them are “sophisticated” or unfamiliar to miners or involve specific (or proprietary) reagents not usually accessible to all miners. Hinton et al. (2003) stressed that any change in artisanal gold mining technology should be accompanied by a rapid rate of return, increased simplicity, and low investment. The cleaner gold production by miners (or processors) depends basically on access to technology, education of operators and capital. This latter is probably the most critical factor, since these miners rarely have access to bank loans. In addition, the mercury replacement cannot reach all types of artisanal miners. The target for mercury replacement technologies should be the largest mercury consumers, the processing centers.

Technically speaking, the amalgamation process is simple, since mercury combines with gold to form a wide range of compounds from $AuHg_2$ to Au_8Hg (Taggart, 1945). The inefficiency of the process occurs because most miners do not know three basic conditions to have good gold recovery by amalgamation: 1) gold must be liberated, i.e. not locked within other minerals, 2) gold must be concentrated to be amalgamated, 3) mercury must be clean to trap gold particles. To address the first problem, miners should invest in expensive grinding and classification circuits, which is beyond their financial and technical capabilities. The second condition brings a significant reduction of mercury use. When only gravity or flotation concentrates are amalgamated the use of mercury is substantially reduced because the mass of material to be amalgamated is at least 1/10 of the original mass of the ore. Regarding the third condition, miners do not suspect that when mercury is oxidized, it does not trap gold (even from a good concentrate) efficiently. As a result, amalgamation tailings have hundred of grams of gold per tonne of concentrate. Dr Pantoja, in Colombia, came up with a ingenious method to activate (clean) mercury with table salt and a small radio or motorbike battery. The sodium amalgam formed is much more effective in amalgamating gold than oxidized mercury (Pantoja and Alvarez, 2000) and reduces substantially the mercury losses by "flouring" (formation of many Hg droplets). But this is not a panacea, since not all gold in the concentrates is liberated, then even a good amalgamation with sodium-amalgam is not 100% efficient.

Based on these three conditions, the best investment that a miner can do, is in the first and second conditions. Once a good concentrate is obtained, with good gold recovery and reasonable gold grade, there are many methods to extract gold from concentrates without using mercury. One method in evidence is the direct melting of the concentrates with borax at 1064 ^{o}C (Geus, 2010; Amankwah et al., 2010). This is much more efficient than amalgamation but there is a problem: the gold concentrate must be rich (thousands of grams per tonne). If the concentrate is not rich, gold can be lost to the slag. So, for reaching high grade gravity concentrates, the gold recovery is usually low, and this does not translate into more profits to miners, not encouraging them to adopt this cleaner method. Miners in Indonesia, North Sulawesi using similar method, observed that some gold was trapped in the slag and they used to crush the slag followed by amalgamation. For most alluvial ores, where gold is usually liberated, the concentrates can be very rich and direct smelting is very useful and efficient.

Similar to the direct melting process, a research institute of South Africa, MINTEK, developed a process named iGoli, to dissolve gold from rich gravity concentrates with hypochlorite in acidic medium followed by precipitation with sodium metabisulphate (Mahlatsi and Guest, 2003). The process is not simple for artisanal miners requesting rich concentrates and chemical reagents, which are not familiar to miners. For organized small miners, this can be an interesting option, but still more sophisticated than direct melting.

Another elegant solution to extract gold from concentrates was proposed by the Center of Mineral Technology (CETEM) in Rio de Janeiro and tested in a pilot plant (Sobral and Santos, 1995). This is a electrolytic process in which the concentrates are added to a tank with table salt. By electrolysis of the sodium chloride, a mixture of sodium hypochlorite-chlorate is formed and more than 95% of the gold dissolves within 4 hours to be collected on a cathode. The chlorine solution can be recycled. So the process may be relatively inexpensive but the availability of salt or seawater is needed. The main drawback is the need for trained personnel to control operating variables (pH, current density, etc.) (Veiga and Meech, 1999).

There are other leaching methods using alternative chemicals such as thiourea, thiosulphate, bromine, etc. that can be used to replace amalgamation of concentrates but those methods are neither easily adapted for artisanal mining conditions or the reagents are not widely stable and locally available (Hilson and Monhemius, 2006). An interesting case is the Haber Inc. technology (Haber, 2008) to leach gold with a proprietary "green" reagent. The method successfully tested in Suriname and Ghana has a great potential to grow but miners must depend on acquiring the undisclosed reagent from a single supplier.

In most alternative gold extraction processes reviewed, the bottle neck is not the leaching or melting steps but the concentration process to obtain concentrates with reasonable gold grade and recovery. A small plant leaching gravity or flotation concentrates needs half of the capital and operating costs of a plant leaching the whole ore. This is also much more environmental friendly since just a small portion of tailings has contact with chemicals.

Cyanidation is the most promising process to replace amalgamation. Firstly because nearly all 2000 organized industrial mines around the world no longer use mercury but cyanide alone. Secondly, because many small miners are already using cyanide and are familiar with the chemistry of the process. The main problem, like all the methods mentioned above, is knowledge and capital to invest in good grinding circuits, concentration equipment and leaching tanks. Many miners do not grind properly the material before cyanidation as grinding requests the highest capital and operating costs in mineral processing plants. However there are some ideas already tested in the field that can replace the use of mercury and reduce the need for high costs for grinding and concentration. The technique named mill-leaching (Veiga et al. 2009) eliminates completely amalgamation. It introduces cyanidation to leach only gravity concentrates into small-ball mills. So, in some regions, the capital cost to adopt this technique is virtually none since miners can use their "chanchas" and "cocos". This was demonstrated to miners in Ecuador, Colombia and Brazil. Miners continue using their grinding methods with hammer or Chilean mills and a medium gold-grade concentrate is obtained by a small Canadian Icon centrifuge which has capacity of 2 tonnes/h of material. In South America, these centrifuges cost around US$ 7000. Three centrifuges in series may increase the gold recovery to 60-80% depending on the ore mineralogy. More liberation, definitely can increase gold recovery, but very fine particles (-0.040 mm) are hard to be concentrated. In these cases, a secondary concentration with flotation can also be used. In the Icon, the centrifuging force is at least 150 times higher than the gravity force (usually used by miners in rudimentary gravity concentration equipment) and this favours concentration of unliberated gold particles. The concentrates from the centrifuges represent less than 1/100 of the mass of the original material and the cyanidation tanks do not need to be large. In the mill-leaching process, cyanide, lime, peroxide, activated carbon (in a PVC cartridge) and balls or rods are added to a small ball or rod mill. The unliberated gold of the concentrates becomes exposed and leached during grinding. Around 98% of the gold from concentrates is leached and adsorbed on the carbon in less than 24 hours. The use of oxidizing agents can reduce the leaching time substantially. The desorption process is done in a ice cooler at 90 ^oC and gold is precipitated with zinc powder (Sousa et al. 2010). In this case, like in the direct melting and iGoli processes, the efficiency of the gravity and/or flotation concentration rules the gold recovery of the process, but the difference is that the mill-leaching process does not need concentrates with very high gold grades.

4 A Light at the End of the Tunnel

It is recognized the environmental and health effects of the misuse of mercury and cyanide by the owners of processing centers (Velasquez et al., 2011). In spite of the proliferation of these centers with no concern for the environment, it has been observed a few small gold plants in the South of Ecuador with processing capacity of 100 to 200 tonnes or ore/day doing a very efficient and responsible work. Engineers (many from Peru), operate either cyanidation of the whole ore or gravity and flotation concentration followed by cyanidation. At least four good plants are examples for the other miners in Portovelo, Ecuador. Partnerships of foreign companies with artisanal miners have also been formed to bring capital and to improve working conditions. Owner of the processing centers are acquiring their own mines or making agreements with the miners to integrate their productions. The gold production ranges from 300 to 1000 g Au/d. This provides jobs for a large contingent of local people and sustains other social activities in the community. Cyanide tailings are properly managed, impounded, and treated with hydrogen peroxide. Other minerals such as copper and silver are also extracted.

Some processing centers became organized small operations by investing as much as US$ 1 million. The plants were paid in less than one year and have been generating cash flow that allows the investors to continue geological exploration and/or prospecting new gold deposits. Some Canadian junior companies are also creating partnerships with local miners to form small, but very profitable and cleaner operations. This evolution process also allows the use of alternative techniques discussed above which are not quite tested in large scale but are proved feasible for small-scale operations. This seems to be a prosperous future to transform artisanal, disorganized, informal gold miners into business citizens. This transformation is coming thanks to the private sector and more knowledge acquired by the miners due to the presence of good private technical people interested in small mining business. Unfortunately most Governments are not participating or even understanding what is going on. A large amount of well structured small mining companies means more jobs and better use of the natural resource since small deposits are not interesting for large mining companies.

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