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Clean Artisanal Gold Mining: A Utopian Approach?

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ABSTRACT

Artisanal and small-scale mining (ASM) provides an important source of livelihood for rural communities throughout the world. These activities are frequently accompanied by extensive environmental degradation and deplorable socio-economic conditions, both during operations and well after mining activities have ceased. As gold is easily sold and not influenced by the instability of local governments, it is the main mineral extracted by artisanal miners. Mercury (Hg) amalgamation is the preferred gold recovery method employed by artisanal gold miners and its misuse can result in serious health hazards for miners involved in gold extraction, as well as for surrounding community inhabitants, who may be exposed to mercury via the food chain. The rudimentary techniques characteristic of ASM result in a number of occupational hazards, other although most risks are primarily attributed to machinery accidents and ground failure, such as landslides and shaft collapses.

Several technologies and methods commonly utilized by large-scale mining operations can be downsized to smaller scale operations. However, the likelihood that miners will adopt these large-scale methods, or those developed specifically for ASM, depends upon some key factors. For an artisanal miner, these factors include: (1) increased or comparable simplicity, (2) quick recovery of the economic mineral, and (3) demonstrated financial gain. Other practical aspects, such as the availability of materials (chemicals, steel rods, piping, generators, etc), capital and operating cost requirements and access to technical support, also influence acceptance of new techniques.

This article will review four inter-related areas: first, the limitations and benefits, for ASM, of a number of specific technologies; second, the role of Processing Centers in education, information dissemination and provision of "clean" services; third, benefits and challenges associated with formalization of ASM activities; and fourth, the contribution of ASM to the development of sustainability of communities, primarily through diversification of livelihoods. The appropriate application of technologies, particularly given the diversity of ASM communities around the world, will also be explored.

Keywords: Artisanal mining; small-scale mining, mercury pollution; mineral processing; clean technologies, processing centers.

1. INTRODUCTION

Artisanal mining is an essential activity in many developing countries as it provides an important source of livelihood, particularly in regions where economic alternatives are critically limited. The International Labour Organization estimates that the number of artisanal miners is currently around 13 million in 55 countries. It has further been extrapolated that 80 to 100 million people worldwide are directly and indirectly dependent on this activity for their livelihood [1]. With increasing population, particularly in developing nations, many speculate that involvement in these activities is likely to escalate. Unfortunately, these activities are frequently accompanied by extensive environmental degradation and deplorable social conditions, both during operations and well after mining activities have ceased. Given the number of people directly or indirectly reliant on artisanal mining activities and the magnitude of resulting impacts, *appropriate* measures must be developed and implemented to mitigate associated problems.

This paper focuses on potential technical solutions for the minimization of ecological and human health impacts derived from artisanal mining. However, the negative consequences of this activity are not a product of poor technical practices alone; the socio-economic circumstances driving this activity must also be addressed for any measure, technical or otherwise, to have any enduring contribution to ASM communities. Based on past efforts to develop and implement clean ASM technologies, it is evident that in addition to taking into account community-specific conditions, appropriate clean technologies must satisfy the following criteria:

1. Economically beneficial – The technology must be inexpensive to operate and it must generate obvious financial benefits.
2. Simple – The technology must be easy to use and would ideally utilize readily available resources.
3. Expedient – The economic mineral must be efficiently recovered.

In this discussion, special emphasis is placed on the treatment of gold-bearing ores. This is primarily as gold is, by far, the main mineral extracted by artisanal miners, but also because the environmental impacts generated by artisanal and small-scale gold mining, specifically related to the discharge of mercury into the environment, warrant special consideration. Many of the technologies and issues discussed, however, are applicable to other minerals, and could therefore be considered in this general context.

2. CURRENT PRACTICES IN ARTISANAL GOLD MINING

The nature of ASM activities must be well understood to successfully apply any measure to a given operation. ASM can be illegal or legal, formal or informal, and can involve extraction of primary or secondary ores. As well, not all ASM activities are defined by the size of the operation, but may be better characterized by the lack of long-term mine planning/control and use of rudimentary techniques. In many regions in the Brazilian Amazon, for instance, a single mining operation moves as much as 4 million m³ of material annually.

ASM usually involves the extraction of secondary gold from alluvial, colluvial or elluvial material, (i.e. free gold that is easily concentrated by gravity processes). For soft materials, such as weathered ores, miners typically employ hydraulic monitors, which involve the high-pressure application of water to 'fluidize' loosely consolidated materials. For alluvial ores, dredging of the river bottom sediments is the preferred method. Hydraulic monitoring typically results in extensive environmental degradation due to the sheer volume of material fluidized, the amount of water used and the lack of containment structures. Typical impacts include the modification of hydrologic regimes through creation of vast tailings "beaches" and diversion of rivers. In the north of Mato Grosso State, south of the Amazon basin, the impact caused by diversion of one river extended for more than 30 km.

Extraction of gold associated with primary ores (e.g. sulphide associated gold, often found at depth) can be far more complicated. Blasting with dynamite may be required and, if the operation is not limited to a small-scale excavation at the surface, underground tunnelling presents additional challenges (e.g. ventilation, hauling, tunnel stability, etc). Some operations extract gold from quartz veins, which may contain extremely high grades (>10-20 g Au/tonne). Most gold is not occluded in sulfides and can be extracted by amalgamation or cyanidation without prior sulfide oxidation. Experienced miners can recognize that once gold associated with *pyritic* quartz veins is encountered, this signifies the beginning of the end of their activities. Without access to technical support, desperate miners invest in "miraculous" solutions to extract gold from sulfides with results often ranging from ineffective and costly to environmentally destructive.

Historic gold mining activities of colonial North America are very similar to artisanal practices employed for subsistence purposes today - both are characterized by very rudimentary and labour intensive equipment and methods. Mechanization significantly modifies ASM operations as resource extraction can take place in a much shorter time frame. As miners seek opportunities elsewhere, this practice results in rapid abandonment of communities, in addition to the degradation of huge expanses of land associated with the excavation of even greater volumes of earth. Miners are eager to re-invest profits in expensive excavators, bulldozers and trucks, or look to private investors to scale-up production. Access to modern equipment, however, does not necessarily equate to efficient resource extraction. The situation in Poconé, Brazil exemplifies what can occur when mechanization is not accompanied by appropriate use of technology. At the beginning of the 1990s, more than 4,500 miners in 100 sites were mining low-grade quartz veins in highly weathered rock using trucks and shovels. In the absence of geological information and traditional mining concepts such as planning, all of the capital invested in equipment was quickly lost. Even miners who had previously produced 10 tonnes of gold were facing bankruptcy. Because funding in Poconé and other locations is obtained outside of traditional financing systems, miners pay a high price for these failed ventures, in some cases, with their lives.

Plate 1 - Miners in Ikabaru, Venezuela, using hydraulic monitor together with bulldozer.

Mechanization has also been important in increasing the productivity of hydraulic monitors and dredging operations. While processing alluvial-colluvial terraces, hydraulic mining operations frequently use bulldozers and excavators to remove soil and waste material. At the beginning of the Amazon gold rush, mercury was commonly spread on the ground in the belief that mercury moved throughout the dirt to capture all available gold. This resulted in enormous mercury losses; in some cases up to ten parts of mercury per one part of gold produced. Hydraulic operations usually employ riffled or carpeted sluice boxes to concentrate gold prior to amalgamation (Plate 1). In some cases the whole ore is amalgamated directly in sluices on which mercury has been spread (Plate 2). The heavy mercury-gold amalgam that forms 'sinks' and is retained behind riffles or in carpet fibres. In these operations, large amounts of mercury are directly discharged with tailings.

From sophisticated barges to rafts floated by air-filled steel drums, miners around the world use many types of equipment to dredge river-bottom sediments. The "Guyanese missile", a significant improvement on current methods, is a cutter-head system that penetrates through a hardpan crust to access the

Plate 2 - Fluidized ore is pumped to sluice box. Mercury is either spread on the ground (above) or on riffled sluice box (below)

underlying gold-rich gravel. This reduces the amount of fine sediments dispersed throughout the river and avoids the fatalities that commonly occur when men outfitted with crude diving gear 'vacuum' bottom sediments through a pipe. Diluted pulps of gold-rich gravel (usually 5% solids) are sent to the on-board sluice boxes. Tailings from sluices are discharged back to the river generating a large silt plume. Other gravity separators, such as jigs or centrifuges, are virtually never used to concentrate dredged ore. Gravity concentrates from sluices are sometimes amalgamated on-board using high-speed blenders, which discharge mercury-rich amalgamation tailings directly into rivers [2]. This practice creates "hot spots", i.e. sites with extremely elevated mercury concentrations. At the beginning of the 1990s, on-board amalgamation using copper plates was also very popular in Latin America. Until 1991, more than 200 barges dredging the Caroni River in Venezuela discharged about 5 tonnes of mercury into the river as a result of the use of copper-amalgamating plates [3]. This method loses popularity as miners realize that gold is lost with mercury due to friction between gravel and amalgamated copper surface.

Currently, skilled miners only amalgamate gravity concentrates (i.e. ore which has been crushed and separated by weight), a practice that contributes to significant reductions in mercury consumption and emissions. Approximately 14 grams of mercury are required to amalgamate 1 kg of concentrate (ratio Hg:concentrate ≈ 1:70) [3]. The undesirable mineral portion is separated from the gold-mercury amalgam by panning either in 'waterboxes', in pools excavated in the ground or at creek margins. The heavy mineral-rich amalgamation tailings frequently contain 200 to 500 ppm of residual mercury, which create 'hot spots' when discharged into adjacent water bodies.

Excess mercury is removed from the amalgam by an ancient filtration process of hand-squeezing through a piece of fabric. The excess mercury, usually more than 90% of the mercury employed in the amalgamation, is re-bottled and used again. Once the amalgam is obtained, which typically contains ~60% gold, it is retorted or simply burnt in a pan or shovel using a blowtorch. The amalgam decomposition process (with or without retorts) produces a sponge-like gold *doré* that is sold to gold shops in nearby villages or melted on-site.

3. CONSIDERATIONS FOR IMPROVEMENT AND IMPLEMENTATION OF APPROPRIATE TECHNOLOGIES

Formal, large-scale mining operations employ a number of innovative and efficient technologies, but most have not been effectively adapted or transferred to ASM operations in the developing world. Technical alternatives derived from formal mining, or developed specifically for ASM, must be thoroughly examined, pre-tested, appropriately modified and successfully transferred (e.g. through educational programmes) before ASM is likely to transform into an environmentally sound and socio-economically sustainable activity.

To an extent, the adoption of new artisanal mining technologies has many parallels to the current movement towards voluntary initiatives. The success of voluntary initiatives, which are measures undertaken by organizations or individuals in lieu of or as a complement to regulations, is driven by the fact that *obvious benefit(s)*, in addition to diminished ecological and human health risks, must be derived from any modifications to practices [4].

For an artisanal miner, this means a method must be fast, easy and cheap, i.e. any change should be accompanied by a rapid rate of return, increased simplicity and a low investment (or reasonable investment countered with appreciable returns). An artisanal miner will not pay out a dollar for a piece of equipment or technique that does not return two dollars [5]. Other practical aspects, such as the availability of materials (chemicals, mechanical components such as piping, generators, etc) and operating costs influence the adoption of any new technique. In order for a technology to be successful, i.e. in that it is accepted and effectively applied by miners, any measures should be pre-tested and accompanied by sufficient training [6]. If a measure has been effectively demonstrated, miners will inevitably be encouraged to continue implementing the method and may be willing to attempt other "innovations."

Consideration of the diversity of backgrounds (cultural, religious, economic, etc), level of knowledge and varied perceptions of individuals in ASM communities is fundamental to the successful development and implementation of technical assistance projects [7]. Many miners are farmers, who mine on a seasonal basis to supplement their incomes. Other small miners work in more organized, albeit often superficial partnerships, with mechanized equipment and greater access to resources. Some communities are completely marginalized and operate in a state of virtual lawlessness, with rampant drug and alcohol abuse, gambling, child prostitution and diseases, while other communities, although generally poverty stricken, maintain a greater level of organization and sense of community. Varying degrees in permanence, adaptability to new methods, and other issues (age, gender), should also be considered in evaluating techniques. As it is well demonstrated that programmes developed by the people participating in them (i.e. bottom-up measures) tend to be most effective and enduring, alternative technologies would likely be most successful if members of the local artisanal mining community were directly involved with the development of any initiatives.

In addition to socio-economic conditions in ASM communities, the geological characteristics of each deposit also differ, thus, it is unreasonable to advocate a universal technical solution for all ASM activities. In the recent Workshop on Artisanal and Small-scale Mining sponsored by Mining, Minerals and Sustainable Development (London, Nov. 19-20, 2001), it was evident that the production level and technological knowledge of miners in and throughout South America, Africa, Indonesia, China, Philippines and Africa can vary significantly, thus any solution must be tailored to meet local needs. It was also made apparent that efforts related to bringing solutions to the ASM sector are minuscule when compared to the resources allocated to monitoring and characterization of ecological and human health impacts caused by poor ASM practices.

There is consensus among researchers, however, that the introduction of simple solutions to improve gold recovery and reduce mercury emissions *is* possible. Priester *et al* (1993) published an extensive review of technologies used in ASM and discussed their technical appropriateness to small deposits around the world [8]. In addition to the appropriate use of various clean technologies, some fundamental information not directly related to extraction techniques (e.g. health and waste management issues) must also be conveyed to miners. The topics outlined below consist of key gaps identified in ASM and possible measures to support the development of environmentally sound and sustainable operations:

1. Determination of mineable reserves
2. Gold liberation with comminution
3. Improvement of gravity concentration
4. Introduction of alternative processes
5. Employment of safe cyanidation procedures
6. Employment of safe amalgamation practices
7. Health and Safety Precautions
8. Ecological and human health impacts of mercury and cyanide misuse
9. Responsible waste management and reclamation practices
10. Establishment of processing centers
11. Development of organizations and partnerships
12. Advancement of sustainable livelihoods

Mineable reserves

Establishing mineable reserves is vital to creating a sustainable operation as it: enhances the link between miners and the land they work; promotes planning that may be accompanied by an extended mine life; and it can be used to obtain funding from formal financial institutions, and therefore may encourage operation within a regulatory framework [9]. Currently, the prevailing tendency is to employ methods that make the most money in the shortest period of time, even in larger-scale ASM operations using highly mechanized techniques.

A simple sampling program using auger drilling can be used to efficiently determine a minimum gold reserve that will support at least medium-term mine planning. The effectiveness of this measure has been demonstrated in Bolivia. As chemical analysis to establish gold grades is complicated and costly, panning of a 20-kg sample is sufficient to evaluate gold grades by counting visible specks. Formal exploration companies evaluating alluvial and elluvial material use a similar procedure.

Based on more realistic reserves, rudimentary mining methods evaluations and scheduling can be conducted. Even a basic mine plan will encourage consideration of safety precautions and improve miners' capacity to anticipate problems. Concepts ranging from assessments of various mining methods, equipment maintenance, rock mechanics/stability and safety issues (ventilation, transport) should be introduced to miners. Production methods, including pre-concentration and pre-fragmentation, could even be coupled with mine plans to reduce transportation and mineral processing costs.

Comminution

Comminution involves crushing and grinding of ore to reduce particles to a size suitable to liberate gold from gangue minerals through further processing (e.g. gravity concentration). Crushing and grinding are relatively simple mechanical processes, but are the most expensive unit operations in mineral processing. In ASM scenarios, comminution processes are severely limited by the availability of resources such as electric generators, fuel, steel rods or balls, and

Plate 3: Quimbaliti Crusher in Peru (Photo courtesy of F. Hrushka)

drums, particularly if these components require frequent replacement. As most gold lost in tailings from ASM is in the coarse fraction (>1mm) due to poor liberation, and the fine fraction (<0.074 mm) due to limitations in most gravity processes, it is apparent that more effective comminution practices can improve recoveries.

A number of crushing methods are used by artisanal miners throughout the world to process primary ores (e.g. quartz associated gold) including hammer mills (Kenya, Bolivia, Venezuela, Brazil), ball mills (Philippines, Tanzania), muller mills (China, Venezuela, Chile) and the locally developed Quimbaliti crusher/grinder (Peru) (Plate 3). As they are simple, robust, and capable of reducing ore to a treatable size using a single unit, stamp mills are also in widespread use [10]. However, stamp mills cannot handle large volumes of material and may require upgrades to higher capacity units (e.g. jaw crushers and ball mills). Simple sledgehammers are common tools in less mechanized artisanal operations.

Hammer mills are the most used grinders in Latin America due to their ability to accept large pieces of rock (as large as 10 inches), to operate dry or wet and to process large volumes of ore (as much as 100 tonnes/h). Using swing hammers, these mills rotate at speeds as high as 6000 rpm shattering ore to a size sufficient to pass through the output sieve. Quartz vein ores and their weathered portions can be discharged to screens of 1 or 2 mm. [11]. As this type of equipment was developed to mill soft rocks, such as limestone, miners change hammer heads every 8 hours when milling hard rock.

Even using highly mechanized methods, most gold is not liberated through these comminution methods. Gold-laden tailings are subsequently re-processed, often using the same circuit. In many mining sites in the Amazon, fathers leave tailings for sons for re-processing, who subsequently leave more for the next generation. Although this practice can allow multiple generations to subsist, this hereditary activity is not in agreement with 'Best Practices' or the principles of sustainable development. The best use of the natural resource implies efficient application of techniques that allow reasonable gold recoveries with minimal energy consumption and waste generation.

Although material derived from comminution processes is suitable for other mercury-free concentration methods, mercury is still frequently added during crushing and grinding, gravity concentration or after. The ratio of mercury used to gold produced, can be as high as 40:1, as can be the case for the quimbaliti crusher [12]. In general, however, it has been found that when the whole gold ore is amalgamated, the ratio of mercury lost to gold produced is around 3:1, compared to a ratio of 1:1 when mercury is used with ground ore [3, 9].

Gravity Concentration

Attempts to introduce gravity concentration equipment to artisanal miners, such as shaking tables, spirals, automatic panners, centrifuges, etc., to eliminate mercury amalgamation have not succeeded. These methods, which use gravity to separate particles on the basis of density or size to obtain a metal-rich final concentrate, can reduce mercury consumption, but they are still not effective enough and further concentration with mercury is generally needed.

Gravity separation methods important in ASM are described in Box 1.

Gravity separators, centrifuges in particular, have a demonstrated capacity to concentrate fine gold, increase gold recovery and reduce the volume of material requiring amalgamation. The primary obstacle to widespread use of the most well known centrifuges (e.g. Knelson and Falcon) is cost. At least four manufacturers in Brazil are producing crude and slightly less efficient replicas of the Knelson concentrator, enabling increased use by artisanal miners and improved gold recoveries (Plate 4).

Plate 4 - Weathered ore is ground below 1 mm in a hammer mill then fed into two 32 tonne-

Alternative Processes

Depending on the skills and financial resources of miners, other beneficiation techniques can be used. For instance, **froth flotation** is the main process used by conventional mining companies to concentrate minerals, including gold. Chemical surfactants are used to recover fine mineral particles from slurry by adsorbing to a particle surface and rendering it hydrophobic. In gold flotation studies by Lins *et al*. (1994), concentrates were upgraded from 13 g Au/tonne to 3,000 g Au/tonne at 82% recovery using xanthate collectors [13]. Unfortunately, it is not trivial to submit 2-3 kg/tonne of concentrate to direct melting. Flotation using wooden cells or columns is being conducted in Poconé, Brazil. Although flotation is a relatively complex process, it has enormous potential to concentrate fine gold, achieving grades around 200 g/tonne, and reduce the volume of material to be amalgamated or submitted to cyanidation. Education of more skilled miners in this process should be promoted at some locations.

Some concentration processes have been devised based on site-specific mineralogy. **Magnetic removal coupled with blowing and tapping,** which has been employed in ancient times in Ghana and the surrounding region, involves the separation of most heavy minerals from a gold concentrate using a hand magnet, followed by blowing and tapping of up to several kilograms of concentrate [14, 15]. The magnet removes magnetite and hematite is separated by blowing and tapping, leaving gold behind (99.9% recovery). As this method is less expensive, faster and more effective than amalgamation at recovering fine gold, it is a promising alternative. The unique mineralogical characteristics of gold deposits in Ghana, specifically the presence of flaky hematite, make this technique feasible. Wind blown separation has also been documented as a concentration process in Namibia, for instance, wherein women at the Uis tin mine lay out small wooden trays of crushed ore to be windsieved by the hot desert breeze [16]. The presence of mica as the main impurity makes this unconventional technique viable.

An innovative **salt-electrolytic process** to leach gold and residual mercury from concentrates has been developed by the Brazilian Center of Mineral Technology (CETEM) and tested in a pilot plant in the Tapajós region of Brazil [17, 18]. Using an electrolytically generated sodium hypochlorite-chlorate solution, more than 95% of gold and mercury is dissolved and collected on a graphite cathode within 4 hours. The solution is recycled, minimizing effluent discharge, and plastic tanks are used, reducing investment and replacement costs. The process has shown positive results in the oxidation of gold-bearing sulfide concentrates using seawater as the initial electrolyte. The main drawback of this method is the need for trained personnel to control operating variables (pH, current density, etc.) [3].

Coal-oil agglomeration techniques have some potential, although they still require more skill and investment than amalgamation practices. Experiments have shown that 90% of gold can be recovered when agglomerated coal and oil (5mm diam) are contacted with pulp derived from gravity concentration [3]. Another process developed by Envi-Tech Inc., Edmonton, Canada involves intense agitation of a concentrate-proprietary adsorbent mixture for 5 to 10 minutes [19]. Subsequent separation of gold from the adsorbent is conducted using froth flotation methods.

Box 1 - Gravity Separation Methods

Sluice Boxes
- Riffled sluice boxes or carpeted sluices or trenches are angled such that heavy particles of gold settle out behind riffles or in carpet fibres.
- As the material must be fluidized in order for this process to work, artisanal miners commonly use substantial amounts of water and modify the hydrologic systems (e.g. river diversions, tailings beaches).
- The most commonly employed method (simple, cheap and fast).

Jigs
- Jigs induce density and size stratification of particles through a pulsating (up and down) motion.
- A simple configuration consist of a screen overlying a tank containing liquid and a means of generating relative motion between the liquid and material on the screen (air, water or mechanical), regulating water flow and recovering product.
- Due to the limited number of moving parts and their simplicity, little maintenance is required.

Shaking Tables
- Shaking tables involve the generation of motion on an angled surface covered in parallel riffles, which induces separation of particles based on their densities and particle sizes.
- Efficiency is limited by the tendency of large high-density particles to have velocities comparable to small low-density particles when similar forces are applied. This results in high gold concentrations in the middlings (particles containing non-liberated gold).
- Simple, easily modified and separation can be directly observed. However, limited to specific range of grain sizes, capacity is limited (~1.5 t/h), recirculation of middlings required.

Centrifugal Concentrators
- Centrifuges have the potential for primary concentration of fine gold or cleaning ordinary gravity concentrates.
- Process uses a fluidized bed spinning-bowl that generates a centrifugal force that can reach up to 200G and can process up to 100 tonnes of solids/h. Concentrates can reach grades above 20,000 g gold/tonne in two stages (rougher and cleaner) and can be directly smelted, potentially avoiding an amalgamation step.
- Tend to be costly, but can be highly effective in terms of recovery and reduced mercury consumption.

Cyanidation:

Most organized mining companies use cyanide to dissolve fine gold present in low-grade ores or in flotation concentrates. When properly implemented, cyanidation can yield high gold recoveries, but for artisanal miners the process requires much more skill and investment than simple amalgamation. Gold is recovered from the gold-cyanide complex ($Au(CN)_2^-$) in leachate through precipitation on the surface of fine zinc particles or adsorption onto natural or synthetic activated carbon. Coconut shell, for example, has the high ion exchange capacity and porous structure needed for adsorption of gold and gold complexes [20]. Carbon-in-pulp or carbon-in-leach processes are rapidly replacing these recovery methods as they do not require the same degree of filtration and clarification and are effective for clayey surface deposits.

Certain operating parameters, particularly pH and dissolved oxygen, must be maintained to efficiently and safely practice cyanidation. In order to prevent the loss of cyanide by hydrolysis and generation of harmful hydrogen cyanide gas (HCN), agents such as lime (CaO) are added to the solution to maintain a high pH. Although sodium or calcium hydroxide is also effective at increasing pH, they have been demonstrated to inhibit gold dissolution, particularly at extremely high pH (>12). Lime has also been shown to enhance settling of fine ore particles so that clear pregnant solution can easily be separated from cyanide ore pulps. Oxygen is essential for gold dissolution in cyanide solutions and it has been found that cyanide concentrations can be reduced by up to 25% if oxygen levels are high [21]. Thus, simple oxygenating mechanisms, such as spargers, used in the leaching process may reduce cyanide consumption.

Although it is not widespread, artisanal miners are currently practicing cyanidation in a number of countries including Peru [12], Ecuador [22], Colombia [23], Brazil [3], Philippines [24] and China [25]. Increased use in the Philippines has been primarily attributed to support from large mining companies, who have provided both engineering expertise and capital, and the government, through provision of gold assaying services, chemicals or facilitated borrowing agreements [7]. Other key factors include the practice of purchasing or selling tailings, the presence of informal financing agreements between miners and gold buyers, and the availability of chemicals (sodium cyanide, zinc, activated carbon).

Amalgamation Practices

Unskilled artisanal gold miners prefer amalgamation, as it is simple, cheap, quick and effective (mercury can extract more than 90% of gold from concentrates). Because the level of environmental pollution and related human health impacts strongly depend on the amalgamation method employed, “cleaner” measures should be promoted.

Plate 5 - Decomposing amalgam using a blowtorch

Amalgamation is efficient for particles coarser than 200 mesh (0.074 mm) and for liberated or partially liberated gold [26]. With gold recoveries in excess of 90%, amalgamation can be improved when concentrates are processed in **rolling barrels** [27]. Two hours of operation provides good recovery but also increases the "flouring effect" (loss of mercury through formation of 'inactive' droplets), as is the case in when amalgamation is performed in ball or rod mills. Some possible solutions are: shorter amalgamation periods, use of large rubber balls to promote contact between mercury and gold particles, and application of oxidizing (e.g. $KMnO_4$) or complexing (chlorides) reagents to clean gold surfaces and avoid mercury flouring [28]. Although chemical reagents can improve gold and silver recovery, they may promote metallic mercury dissolution and loss. Adding one gram of **sodium hydroxide** (NaOH) to every kilogram of concentrate to be amalgamated can easily improve the effectiveness of the method. In many Latin American operations, amalgamation in rolling barrels takes place in 30 to 50 minutes with the addition of 1 part of mercury to 100 parts of concentrate [3].

Due to the inefficient use of traditional copper plates by artisanal miners, two Brazilian companies have manufactured special **silver-based amalgamation plates**. As these plates have had considerable success in cleaning mercury-contaminated tailings, they also have potential for the amalgamation of gravity concentrates. Gold amalgamates with mercury on the plate surface and is subsequently scraped off and subjected to decomposition processes. Due to abrasion from sand and gravel on the plate surface, whole ore amalgamation will release mercury and is therefore not recommended. Electrolytic silver plates have been used in Bolivia and Brazil, but their price is high and their efficiency in terms of mercury retention is not known [29].

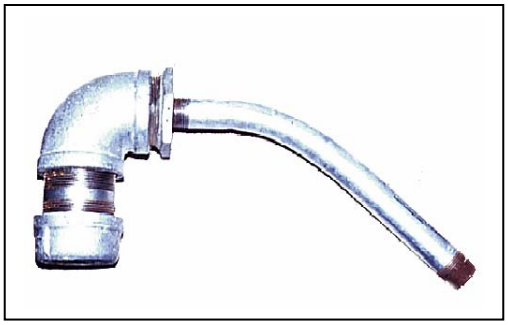

Plate 6 - Homemade retort (developed by Hypolito) made of plumbing connections

Amalgam decomposition can be done by retorting or through chemical processes, such as using nitric acid (30%). Nitric acid is very efficient but dangerous, as highly toxic forms of mercury can be generated in the process. In the acidic solution, mercury is predominantly found as mercury pernitrate ($Hg(NO_2)_2.H_2O$), whose fumes are fatal to humans at concentrations of only 0.05 mg/m³ of air. When mercury pernitrate contacts alcohol, fulminate ($Hg(CNO)_2$) can be produced. This readily explodes when dry and is used in blasting caps and detonators. Although most mercury in solution can be recovered by precipitation with aluminium (or iron or zinc or copper) wires, artisanal gold miners in Colombia and Guyana directly discharge mercuric solutions into watercourses [30].

The preferred method for amalgam decomposition is open-air burning (Plate 5). When this is conducted, as much as 50% of the mercury initially introduced into the amalgamation process is released to the atmosphere. However, when amalgamation is conducted properly and **retorts** are used, very little mercury is lost (as low as 0.05%) [31]. A retort is a container in which the gold-mercury amalgam is placed and heated; volatile mercury travels up through a tube and condenses in an adjacent, cooler chamber [9]. More than 95% of mercury can be recovered through retorting and it therefore contributes to significant reductions in air pollution and occupational exposure. There are a variety of retorts on the market, some made of stainless steel while others use inexpensive cast iron. A homemade retort can be built with standard plumbing pipe for less than US$10 (Plate 6) [32]. Intermediate Technology Development Group (ITDG) has been promoting this retort in Africa, Philippines and South America.

UNIDO has distributed a number of Thermex glass retorts in Africa and the Philippines. As miners can observe mercury being released from the amalgam and condensed, they trust that all gold is recovered in the process. Due to the low capacity (<30 g of amalgam), high cost (~ 1 oz gold), breakability and lack of spare parts, this alternative is not particularly popular.

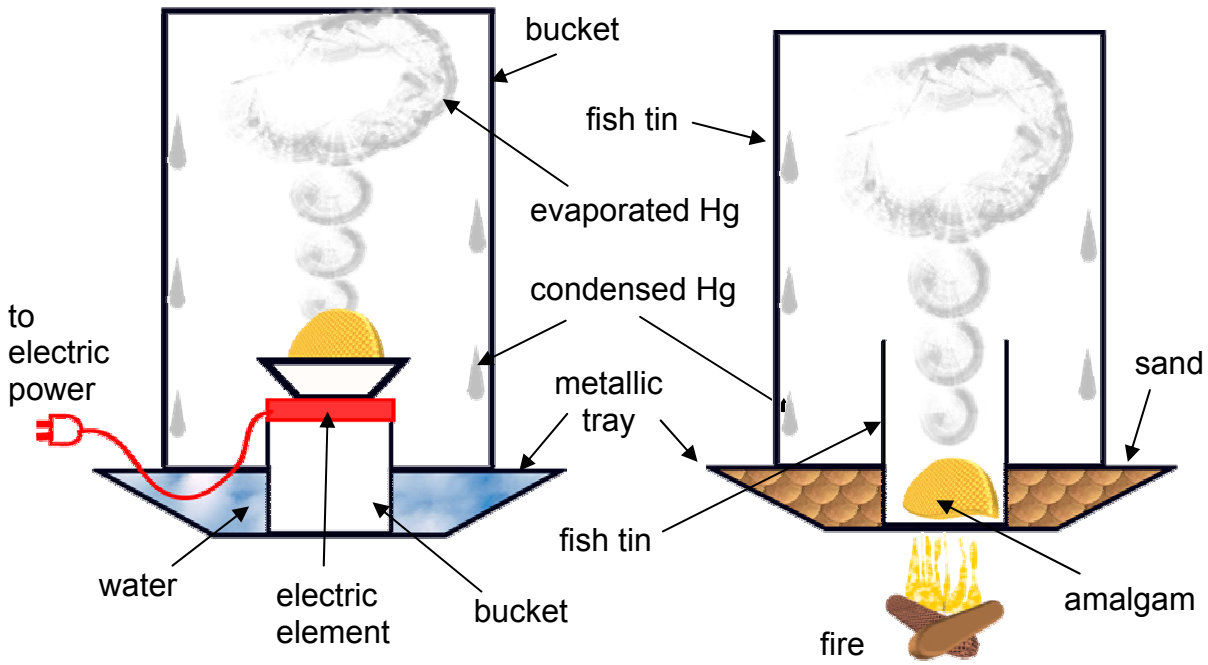

Figure 1 - Two-bucket retort (left) and tin-fish-tin retort (right)

A less expensive option for retorting has been applied in Papua New Guinea and China [24, 25]. The Chinese two-bucket retort consists of a metallic bucket and a bowl filled with water (Fig. 1). A larger bucket covers the first bucket containing the amalgam. The PNG "tin-fish-tin" retort employs the same concept, but uses fish tins and wet sand instead of water. In both cases, the amalgam is heated using wood, charcoal or electric element and mercury vapours condense on the cover-bucket walls.

A crude method of retorting has been described in the "Gold Panner's Manual", a favourite of North American weekend prospectors [33]. This simply involves "baking" the amalgam in the scooped out cavity of a potato. Readers are advised to not eat the potato after processing.

Despite the introduction of retorts through many programs (CETEM, UNIDO, Projekt-Consult GmbH, ITDG, Organization of American States, etc) and obvious benefits associated with their use, artisanal miners are reluctant, primarily due to a lack of concern for environmental and health impacts relative to other issues (i.e. the ease and speed of open-air amalgam burning) and the negligible costs savings from mercury recovery. Many miners in Suriname, Guyana and Venezuela report that bandits often attack during amalgam decomposition, thus a fast process can be crucial in some locations.

It is fundamental that any initiative related to distribution of retorts should be accompanied by a strong educational program. Information packages (e.g. pamphlets, comics) must consider issues such as illiteracy rates, which can be high in many regions, and other social and cultural issues. In 1985, the Secretary of Mining of Goiás State, Brazil, started a campaign promoting retorts that included a brochure illustrating the effects of mercurialism. Impotence was stressed as one of the initial symptoms, which is somewhat inaccurate and therefore questionable from an ethical standpoint, but was extremely effective in capturing the attention of miners. In general, the amount of money and effort spent in education of miners is considerably lower than those of other approaches, such as enforcement and monitoring.

Mercury recovered by retorting often does not have the same amalgamating properties as new mercury. In many South America countries, miners simply discharge retorted mercury. The most efficient way to reactivate the surface of mercury is by using an ultrasonic bath, such those used by dentists, wherein mercury droplets coalesce in seconds (~US$200-400). A much less expensive method involves electrolytic activation using table salt and a simple battery to dissolve mercury oxides from the mercury surface [34]. Any activation method should be accompanied by a process to retain the contaminated water effluent for example using lateritic material or activated charcoal. Despite the small amount of effluent, some soluble mercury could be transformed to more toxic forms once discharged into the environment.

At the end of the amalgamation process, miners sell their gold *doré* to jewellers, banks or gold dealers in nearby villages. These shops melt the *doré* containing about 20g of mercury per kg of gold [3] to volatilize (i.e. vaporize) the remaining mercury and any other

impurities. Mercury levels inside these shops are extremely elevated. Fume hoods – if they are used at all -- are usually rudimentary, consisting of only a fan that blows mercury vapours into the ambient atmosphere. As evidence suggests that most volatilized mercury is deposited near the emission source, exposure to mercury vapour is extremely high for people living in close proximity to gold shops.

In 1989, a Brazilian company, Apliquim, developed a mercury condensing fume-hood consisting of a series of condensing plates coupled with iodide impregnated activated charcoal filters (Figure 2). This equipment reduces mercury emissions by more than 99.9% [27]. Less than 40 $\mu g/m^3$ of mercury was detected in the interior of a gold shop using the prototype, compared with measurements as high as 300 $\mu g/m^3$ in unprotected shops [35][1]. A similar idea is being used in Venezuela where a gas scrubber (shower) using a potassium iodide solution cleans the fumes from the melting furnace. Introduction of effective fume-hoods to gold dealers is essential to reduce poisoning of operators and urban citizens.

Health and Safety Issues

A number of hazards exist in both surface and underground ASM operations. Although the chemical dangers, in particular associated with mercury and cyanide misuse, first come to mind, most occupational hazards result from poor physical conditions. In 1997 alone, 37 of 53 mining-related deaths in Zimbabwe mines were attributed to ground failure, shaft collapses and machinery accidents [10]. In Chinese small coal mines, at least 6000 miners die annually [1]. In Hunan province alone, 70% of the 232 coal mine related deaths were attributed to methane or coal dust explosions. Hydraulic monitoring of secondary deposits can also be extremely unsafe, as a potential exists to undercut hill slopes and generate landslides. This was the case in Filadelfia, Colombia, where 51 miners were killed on November 22, 2001. Poor lighting and ventilation, electrocution and explosives misuse are other frequent causes of accidents [8]. Dust producing silicosis and noise pollution are also pervasive problems. Although accidents are underreported due to the illegality of ASM, ILO (1999) states that non-fatal accidents in ASM are still 6 to 7 times greater than in formal, large-scale operations [1].

These tragic conditions are likely more a consequence of economic demands, which result in inadequate equipment and neglect of safety measures (e.g. shaft supports), than lack of expertise, although insufficient training and awareness are undoubtedly critical factors. A joint project between the Canadian International Development Agency (CIDA), the British Columbia Ministry of Energy and Mines, and the Peruvian Ministry of Energy and Mines includes a component addressing management of health and safety issues in ASM. A detailed handbook entitled "Safety and health in small-scale surface mines" by Walle and Jennings (2001), produced by the International Labour Organization, includes simple illustrations and examples for communication of safe mining methods [36].

Impacts of Mercury and Cyanide Misuse

The toxic forms of mercury of greatest concern in ASM are mercury vapour and an organic form, methylmercury [37]. Mercury vapour released during amalgam decomposition can be hazardous to artisanal miners or individuals working or living near gold shops. Chronic vapour exposure can result in symptoms ranging from psycho-pathological, such as depression and exaggerated emotional response, to gingivitis and muscular tremors. Exposure to acute levels can produce dysfunction of kidneys and urinary tract, vomiting, and potentially death.

Metallic mercury discharged into the environment (air, water, tailings) can be transformed into methylmercury, which is readily bioavailable and may be present in increasing concentrations up levels of the food chain, particularly in aquatic systems (i.e. it is biomagnified). Individuals reliant on fish as a primary food source may be particularly susceptible to accumulation of dangerous levels of methylmercury. In cases of acute intoxication, muscular atrophy, seizures and mental disturbance are prominent. Methylmercury is easily transferred from women to the foetus, with effects ranging from sterility, spontaneous abortion, to mild to severe neurological symptoms.

Due to the importance of amalgamation, convincing miners to use less mercury due to health hazards is difficult [1]. Lack of sanitation, widespread disease (malaria, cholera, STDs, etc.) and limited access to health care providers have resulted in generally poor health conditions in ASM communities. Consequently, any program directed at reducing the comparatively invisible health impacts from mercury will be received with minimal success if the program does not comprehensively address these community issues also. On average, ~40% of artisanal miners are women [38], thus a gender sensitive approach is necessary to promote women's involvement in the development and introduction of measures. As women have little knowledge of the hazards associated with mercury (and they are less suited to labour intensive mining methods), they often are selected to work in the processing aspect of ASM (including amalgamation). They are also predominantly responsible for food preparation, and as women of childbearing age and children are particularly susceptible to methylmercury exposure from fish, some educational programs should be specifically directed towards women.

[1] background in cities is 0.01 $\mu g\ Hg/m^3$, limit for public exposure is 1 $\mu g\ Hg/m^3$ and limit for industrial exposure is 50 $\mu g\ Hg/m^3$.

A major concern with the promotion of cyanide use by artisanal miners relates to its toxicity. Cyanide is an effective asphyxiant and hydrogen cyanide gas (HCN), which is generated at pH below ~11, can be fatal to humans at concentrations around 250 ppm (276 mg/m³ at 25°C) in air. Ingestion of cyanide in solution (CN^-) can induce death at about 1 to 3 mg of cyanide per kg of body weight [39]. Due to the risks from cyanide misuse, the pH of cyanide leaching solutions must be carefully kept around 11 and 12 with the addition of lime (CaO).

Despite the dangers associated with cyanide, in areas where it is extensively used by artisanal miners human fatalities from cyanide exposure are relatively minimal, particularly when compared with mercury or other hazards. In Zimbabwe, for example, artisanal miners use about 5000 tons of cyanide annually, but less than one fatality every 40 years is attributed to cyanide poisoning [40]. Cyanide can be transported and stored relatively safely as sodium or potassium cyanide salt. If spilled, the immediate effects are dramatic, but cyanide generally does not remain biologically available in soils and sediments as it quickly complexes with trace metals, volatilizes or is metabolized by microorganisms. Some metal-cyanide complexes in aquatic systems, however, can remain stable for extended periods of time. As ASM waste containment practices tend to be insufficient, support (training and resources) for construction of safer cyanide ponds may be needed.

Waste Management and Reclamation

Typically, solid or liquid wastes generated by artisanal miners are carelessly discharged to the nearby environment. Simple settling ponds or tanks are relatively low-cost, easy to construct and are conducive to the segregation of tailings or potentially toxic chemicals (e.g. cyanide). Also, water separated from solids in settling ponds can be re-used in processes. The benefits of flocculants were brought to the attention of miners in an experimental processing centre established by CETEM in Poconé, Brazil in 1989 [11]. Some miners recognized the value of using these chemicals in settling ponds as the rate of water reclamation doubled.

As transportation of tailings is easier in a fluidized form, solid separation from fluids best takes place in sedimentation ponds or lagoons. Ideally, artisanal miners will select a site that is topographically amenable to tailings containment, for example, adjacent to hillslopes, and downgradient from the processing site. Dams should be constructed to inhibit tailings dispersion and mobilization into waterways. Due to the potential magnitude of impacts from dam failure, consultation with qualified technical experts is *strongly* recommended throughout dam design and construction. Extensive geotechnical and geochemical expertise is needed to properly segregate waste generated from ASM and mitigate related hazards – it is quite apparent that methods of disseminating and promoting responsible waste management practices to artisanal miners need further attention.

An alternative to small separate tailings impoundments has been proposed at Potosi, Bolivia where 8000 miners were producing ~1500 t/day, which was processed at 40 separate flotation plants [41]. In 1996, MEDMIN proposed a collective dam to receive tailings from the plants and an extensive consultative process and feasibility studies were undertaken. The German Financial Corporation (KfW) intends to fund the final design and construction (~US$ 4.5M) of the San Antonio Tailings Dam, which will commence construction in 2002. This sort of "community" tailings dam project may prove to be a model for other locations where a number of operations are active in a localized region.

In addition to pollution from various chemicals (mercury, cyanide, oils, etc), ASM can impact ecosystems through water siltation, hydrologic modifications and extensive deforestation. The forest destruction caused by artisanal miners is minimal in comparison with agricultural activities, but nevertheless is a notable contributor. The main physical impact of ASM is usually associated with careless tailings disposal that silt up watercourses and divert rivers. Reclamation and revegetation projects with direct participation of artisanal miners have been conducted in Brazil and Venezuela. In 1991, the U.S. Forest Service Department trained Venezuelan professionals in revegetation of ASM sites. Using mulches and a straw "carpet" with biodegradable plastic, the technique was transferred to miners to reclaim steep hills. As most tropical countries are rich in lateritic soils with a thin veneer of organic soil, the earthworm-generated organic matter significantly improved soil quality. The local Association of Miners was fundamental in conducting these projects.

Another interesting example comes from Alta Floresta, an extensively mined region in the Brazilian Amazon. As ASM declined during the 1990s, populations drastically decreased from 120,000 to 38,000 and Alta Floresta was condemned to become a ghost town. Commercial goods from the region were not accepted in other centers due to the risk of mercury contamination. The local Government, together with Agriculture Cooperatives, developed solutions to return the region to its original vocation: agriculture and farming. Among other ideas, the use of abandoned open pits for aquaculture was well received by the population. The newly established Aquaculture Association brought incentives to locals and miners who found new reason to reside in the region. In conjunction with this initiative, the State University of Mato Grosso and the Oswaldo Cruz Foundation have undertaken a meticulous monitoring program to assess mercury in the area [42].

Processing Centres

Methods such as centrifugal concentrators, which can yield high recoveries even when compared with current environmentally destructive techniques (i.e. mercury amalgamation), continue to be overlooked by artisanal miners [7]. As these methods are generally more complicated and often require greater capital costs, processing at a central location may be beneficial for miners. These centers may also promote formal economic arrangements or attract private investment, either of which can be conducive to increased support from technical expertise (e.g. consultants) and acceptance by society and regulators. With this, there is a greater likelihood of incorporation of these miners within a legal framework [9].

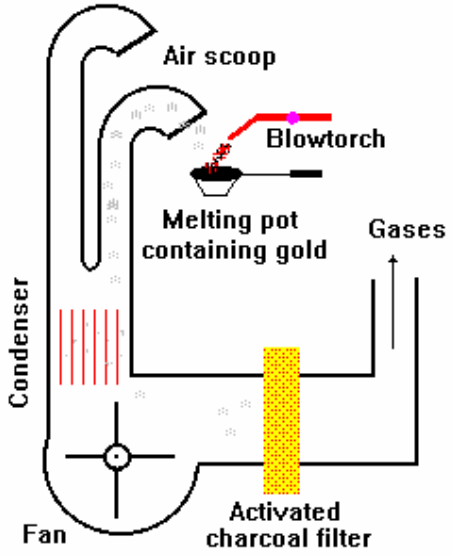

Figure 2 - The Apliquim fume hood

An example of effective and creative amalgam processing is currently being applied in Venezuela, where **Amalgamation Centres** have been constructed to increase gold recovery and reduce mercury emissions [3]. Miners bring their gravity concentrates to these private or state-owned centres to be properly amalgamated, retorted and melted by specialized operators. In the government-owned Amalgamation Centres in Venezuela, the service is free. Veiga and Beinhoff (1997) describe the many techniques that can be implemented to improve operation of Amalgamation Centres in detail [43].

The concept of Processing Centres was successfully applied to **Shamva Mining Center** in Zimbabwe, which was established by the Intermediate Technology Development Group (ITDG) in 1989. This facility provides access to a central mill for about 200 miners. In addition to processing services, the Shamva Center also provides drilling and blasting services, ore transportation and technical support in areas such as mine planning, mining method selection, mine safety and pollution control [7]. Shamva also supplies information on legal issues, geology and metallurgy and the selection and purchase of technical equipment. A particularly interesting characteristic of the Shamva Center is that local miners are responsible for their own ore throughout the milling process, although a plant manager provides supervision and assistance. Miners pay ~US$6 per hour (~US$4/t) to use the plant and take away the gold recovered (on average ~5g/t). Other payment agreements (e.g. based on estimated gold per tonne of unprocessed ore) resulted in disputes and were unsuccessful. Tailings generated from ore concentration contain gold that has been occluded in particles or is sulfide associated – this gold (~1 g/t), which is recovered using cyanide, is a primary revenue source for the Shamva Center. Ownership of the Center has recently been transferred to a commercial company, Shamva Mining Center (Pct) Ltd.

Experiences at cooperatives, such as the Shamva Mining Center in Zimbabwe, have demonstrated that the concept of shared mining equipment is feasible and these centers can provide an important basis for training in processing methods as well as other fields (e.g. exploration, health and safety, etc). Using Shamva as a model, similar centres have been implemented by government, NGOs and private companies in other locations in Zimbabwe, as well as in Burkina Faso, Ghana, Mali and Tanzania [44]. In another example, Proyecto Gama (Gestión Ambiental en la Minería Artesenal) has recently begun the design and engineering of a **mercury-free artisanal processing plant** in Peru [12]. Gama intends to provide technical support for the project, but the cyanide plant will be constructed and operated by artisanal miners.

A similar project has been proposed to the Surinamese Government by Healy and Veiga (1997) [45]. The **Experimental Mining Centers** (EMCs) proposed for the interior of Suriname would primary function to provide training and assistance and encourage the transformation of these activities to a legal, ecologically responsible and economically sustainable employment opportunity for the impoverished people of the region. Specific mining claims would be designated as experimental mining areas, wherein miners would be exposed to concepts of geological exploration, ore reserve estimation, mining and concentration techniques, environmental impact, water reclamation, tailing pond building, revegetation, safety issues, bookkeeping, etc., contiguous with gold production. In addition, the Center could improve the economic and social welfare of artisanal miners and their families by providing advice on obtaining legal mineral titles, financial support, mine planning, occupational exposure precautions, initiating alternative economic activities and family matters.

The goals of EMCs are similar to the environmental programme *Manejo Integrado del Medio Ambiente en*

la Pequeña Minería (MEDMIN) (Integrated Environmental Management of Small Miners) sponsored by the Swiss Agency for Development and Cooperation [29]. This programme, which contributed approximately $4 million over six years, has involved education programs combined with technical and environmental studies at the San Simón small mining area in Bolivia. It has been estimated that San Simón was discharging about 1,900 kg of mercury into the environment (air, tailings, water) per month. An alternative to the mercury-intensive milling process was devised using 6m long sluices lined with specific types of carpets. As gold recoveries were comparable and in some cases higher using the mercury free process, the local small mining Association was encouraged to sign an agreement with MEDMIN, its primary goal being mercury reduction, and a pilot plant was subsequently constructed. Although mercury amalgamation is still used in this plant, only a maximum of 3% is lost. With the new plant, gold recovery has increased by ~10% and costs decreased by 10% - it is not surprising that local miners have been willing to re-evaluate their practices and commit to mercury reductions.

A UNIDO supported Processing Center will soon be initiated in the Tapajós region, Brazil. Covering 100 km² and involving 90,000 miners throughout the 1990s, Tapajós is the world's largest artisanal gold mining reserve. More than 1000 tonnes of gold has been produced and an equivalent amount of mercury emitted to the environment since 1958 [46].

Organization and Partnership

In many operations, the ability to exploit more complicated deposits (e.g. primary ores, typically at depth) is limited not only by technical capability (i.e. expertise and mechanization), but access to capital to acquire technical resources [9]. Financial institutions are unlikely to lend money in the absence of proven reserves and a credible reputation. Due to the obvious risks associated with ASM, if funds are provided, interest rates tend to be exceptionally high. The role of alternative lending organizations (e.g. IFC, NGOs) may be crucial to the advancement of ASM operations. Alternative means to obtain financing include joint ventures, leasing of equipment and equity participation [41].

Organizing ASM activities, for instance through creation of Miners' Association, has been recognized as a key step in mitigating the risks from this activity. This is attributed to, in part, improved access to formal funding sources and the introduction of clean techniques. Most ASM meetings in the mid-1990s focused on formalization of activities. If miners could obtain legal titles, they would be required to satisfy legal requirements for environmental practices, something that necessitates a degree of organization [9]. However, any legalization strategy must consider that (1) miners will undoubtedly work outside of a regulatory framework if obvious benefits cannot be derived from operating within it [47] and (2) many miners do not have the resources or skills to effectively participate. Skills in many areas, including basic literacy to bookkeeping, as well as technical expertise, require supplementation. History has taught us that it seems more practical to organize and then legalize than vice-versa.

The Kias Explorer's Association at the Kias Mine in the Philippines is an example of miners uniting to operate within a legal framework in order to sustain viable livelihoods [48]. Financing for the association is generated from membership dues, milling fees and the provision of labour and energy (diesel engines) by individual miners. Miners, who previously had basic mining skills or were self-taught, work in small cooperatives ("companhias") that typically operate separate gravity separation methods (ball or rod mills and sluices). Cyanidation units and electrowinning are carried out at a central facility. Payment is through profit sharing or on a per diem or output basis. Although mercury is not used at Kias and the Association is involved in environmental endeavours like a local tree planting program, waste is discharged into the environment at any opportune location, illustrating a common shortcoming in the ASM sector. Practical assistance is needed in a number of areas, including financing, energy sources, safety issues and equipment to viably mine a deep deposit.

Development of organized ASM requires a systematic approach that is appreciative of the challenges facing artisanal miners. Key steps identified by a UNIDO Expert Group (1997) include: legalization and development of appropriate regulation of ASM activities and training of key government and institutional representatives; a site-specific assessment of the viability of certain technologies given the environmental, social and economic conditions; and the design and implementation of appropriate technologies [49]. Elements of this approach are shown in Figure 3 and discussed in greater detail in work by Veiga and Hinton (2002), Veiga (1997), Dahlberg (1997), Bugnosen *et al.* (2000), Barry (1995) and Davidson (1995) [3, 6, 9, 47, 49, 50].

Development of Sustainable Livelihoods

In a detailed report on sustainable development in artisanal mining presented at a UNIDO Expert Group Meeting, Dahlberg (1997) articulated the value of artisanal mining in terms of *alleviating poverty and contributing to the development of rural communities* [49]. It is apparent that ASM can provide a viable means of employment for a limited number of people. However, ASM can also contribute to sustainable development of the surrounding community by using approaches similar to those adopted by many large-scale, formal mining companies; this primarily consists of support for auxiliary enterprises (e.g. jewellery production) and agricultural development. This utopian image of artisanal mining communities working together with a common vision is, however,

highly improbable, at the very *least* until any type of organization of mining activities has occurred.

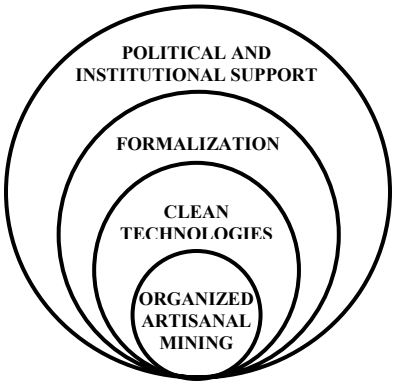

Figure 3: Key Elements of Organized Artisanal Mining

Few livelihood diversification initiatives have been implemented in ASM communities, but the importance of this issue has prompted a number of related programs. The UN Department of Economic and Social Affairs (DESA) has developed a program to produce policy options and best practices for poverty eradication, privatization, sectoral interlinking and privatization in ASM [51]. This project will be conducted in conjunction with the UN Development Programme (UNDP), who has also outlined a strategy for the development of sustainable livelihoods and in ASM communities [38, 52].

One positive example can be found in the Tapajós region, Brazil, where the end of easily extractable gold has driven small entrepreneurs to invest in cattle farming, palm tree and "açaí-nut" production. In order to support transportation of agricultural products, roads were constructed or upgraded. This is a significant improvement as, in mining times, all transportation was by airplane. Governments and NGOs are also implementing jewellery schools in existing mining areas to add value to the miners' product.

Large-scale mining companies can play an important role in promoting sustainability of ASM communities. Prompted by reports of invasions and violence from artisanal miners, many companies have recognized that ASM represents a socio-political risk that must be considered through all phases of a project. In response to disruption of ASM activities and dislocation of people resulting from expansion of a nearby mine in Mali, the Sadiola Gold Mining Project was created by Anglo Gold. This project provides technical assistance and resources to further ASM, as well as alternative revenue generating activities, such as agriculture, jewellery production and fabrication of dyes and soaps [53].

One of the best-documented examples of coexistence between company and artisanal miners is Placer Dome's Las Cristinas Project in Venezuela. Movement of miners to lands owned by Placer Dome Inc. stimulated support for a technically assisted partnership with local miners, including development of a semi-mechanized, environmentally sound mine [54]. The company recognized the socio-economic importance of the miners in the region and created mechanism to help them organize and access better technology. This type of partnership should be promoted but it is important that large companies are well prepared to understand the complexity of the ASM world.

4.0 CONCLUSIONS

It seems a utopian concept, but the principles of sustainable development could, in fact, be applied to the organization of ASM and creation of better living conditions in communities facing immense social, environmental and economic challenges. Sustainable development in mining involves the realization of a net benefit from the introduction of mining through to the closure of the mine and beyond [55], but it is evident that the tools to do so are lacking at all stages of ASM.

With the scarcity of easily extractable gold ores, artisanal miners in many countries have begun to work with more complex, often deeper ores that require greater investment and expertise. Unskilled miners first use greater quantities of mercury to increase gold recovery and, when this proves ineffective, later seek technical assistance. Normally, this support is not available. Engineering companies usually refuse to help artisanal miners and hiring consultants is costly. Local governments are not prepared to provide specialized personnel or appropriate technology, and research institutions primarily offer high-tech methods. In these situations, artisanal miners will adopt an alternative technique out of necessity, but it will not necessarily be safe or particularly effective. Clean ASM is a possible option but requires assistance from governments, technical experts, researchers and NGOs to transfer information to miners and create demonstration projects.

Although it is evident that ASM can be an important catalyst for other entrepreneurial activities, the potential benefits from this activity have not been fully explored. Measures such as the development of alternative economic activities (e.g. jewellery, agriculture, etc) and formalization itself could significantly contribute to community development. Any efforts by external parties (e.g. NGOs, government) are more likely to succeed where structured, locally based organizations or associations are present and measures to support formalization of activities and related development initiatives are driven by members of the ASM community (i.e. bottom-up measures). As this is commonly not the case, measures to enhance the capacity of the

community to develop formal partnerships or cooperatives and explore community strengths and opportunities must be undertaken.

Capacity building exercises in the developing world must be conducted with thoughtfulness and sensitivity. Lessons learned in mining and similar sectors in developing nations have indicated that local individuals and/or groups should participate in assessments of indigenous knowledge, community strengths and risks, resource factors (availability, quality, public services, etc), as well in development of any programmes. It is also essential that the ASM community is incorporated, wherever possible, into the decision-making process when external parties undertake technical, social and/or environmental studies and initiatives.

Simple techniques such as homemade retorts, can be brought to the attention of miners but individual or isolated solutions have not been durable, particularly in the absence of strong educational support. Processing or Experimental Mining Centers have a demonstrated ability to reduce mercury emissions and establish concepts of organization and citizenship in an ASM community. In the next decade, the formal gold mining companies of the world are expected to amalgamate into few gigantic organizations, adsorbing any remaining mid-sized companies in the process. With proper support, ASM could occupy the gap between small and large-scale mining and contribute to the development of resilient, sustainable communities.

REFERENCES

1. International Labour Office (ILO), 1999, Social and labour issues in small-scale mines, Report for the Tripartite Meeting on Social and Labour Issues in Small-scale Mines, Geneva 17-22 May, 1999.
2. Pfeiffer, W.C.; Malm, O.; Souza, C.M.; Lacerda, L.D.; Silveira, E.G.; Bastos, W.R., 1991. Mercury in the Madeira river ecosystem, Rondônia, Brazil. Forest Ecology and Management, v38, p. 239-245.
3. Veiga, M.M., 1997, Introducing new technologies for abatement of global mercury pollution in Latin America. Ed. UNIDO/UBC/CETEM, Rio de Janeiro, 94 p.
4. Moffet, J. and Bregha, F., 1999, Non-regulatory Environmental Measures, Ch. 2, *Voluntary Initiatives*, R.B. Gibson, ed., Broadview Press, Ltd., Orchard Park, NY, pp. 69-92.
5. Priester, M., 1995. Small-Scale Mining in Latin America. SMI Bull. n.8, p.1.
6. Barry, M., 1996. Regularizing Informal Mining: A Summary of the Proceedings of the International Roundtable on Artisanal Mining, *IEN Occasional Paper*, No. 6.
7. Bugnosen, E., 1997, Technological Options in Abating Mercury Pollution Caused by Small Scale Gold Miners, *In* Introducing New Technologies Technologies for Abatement of Global Mercury Pollution Derived From Artisanal Gold Mining, UNIDO Headquarters, Vienna, Austria, July, 1997.
8. Priester, M., Hentschel, T., and Benthin, B, 1993. *Tools for Mining: Techniques and Processes for Small Scale Mining*, Berlin, Gate / GTZ.
9. Veiga, M.M. and Hinton, J.J., 2002, Abandoned Artisanal Gold Mines in the Brazilian Amazon: A Legacy of Mercury Pollution, *Natural Resources Forum, JNRF*: 26:1, February 2002
10. Holloway, J., 1998, The Button Gold Mine, Zimbabwe, *In:* Small-scale gold mining: Examples from Bolivia, Philippines & Zimbabwe, International Labour Organization (ILO), www.ilo.org/public/english/dialogue/sector/papers/goldmine.
11. Centro de Tecnologia Mineral (CETEM), 1989, Poconé Project, Annual Report, Rio de Janiero, Brazil (In Portuguese).
12. Hrushka, F. and Medina, G., 2001, Peru: Integrated Environmental Management of Small Scale Mining (GAMA), Book of Abstracts from the 6th International Conference on Mercury as a Global Pollutant, Minimata, Japan, October, 2001, p. 195.
13. Lins, F.F.; Monte, M.M.; Hamelmann, C.R.; Middea, A., 1994. Amalgamation in Small Gold Operations: Alternatives and Treatment of Hg-Contaminated Soils and Effluents. Proc. International Symposium on Extraction and Processing for the Treatment and Minimization of Wastes, 123rd Congress of TMS, The Mineral, Metals and Materials Society, S. Francisco, CA, Feb. 27-Mar. 3, 1994
14. UNIDO, 1997, Expert Group Meeting on UNIDO High Impact Programme Introducing New Technologies for Abatement of Global Mercury Pollution Derived From Artisanal Gold Mining, UNIDO Headquarters, Vienna, Austria, July, 1997.
15. McCracken, D., 1995, *Gold Mining in the 1990's: The Complete Book of Modern Gold Mining Procedures*, Keene Engineering Company, Inc., 296pp.

16. Ericsson, M., 1996. Women in Small Scale Mining in Namibia, *CRS Perspectives*, No. 52, pp.18-20.

17. Souza, V.P., 1991. Tailing Decontamination by Electrolytic Process. In: Poconé, um Campo de Estudos do Impacto Ambiental do Garimpo, p.95-113. Ed. M.M. Veiga e F.C.R. Fernandes. Rio de Janeiro, CETEM/CNPq. (in Portuguese).

18. Sobral, L.G.S.; Santos, R.L.C.; Hempel, M.; Thöming, J., 1996. The Electroleaching of Residues Containing Mercury. Part I: Kinetics Aspects. Paper presented at Clean Technology for the Mining Industry, Univ. Concepción, Chile.

19. Envi-Tech, 1997. Field Testing of Envi-Tech Adsorbent Technology for Gold Extraction of Gold. Project Summary. Leaflet of the presentation at CANMET, Ottawa, March 07, 1997.

20. Haupt, C.D., Mistry, M., and Wilde, J., 2001, Development of Measures to Minimize Adverse Ecological Effects Generated by Abandoned Mines in Developing Countries, Institut Für Bergbaukunde I, Aachen, Germany, 160p.

21. OGSI, Oxygen Generating Systems Inc, 2001, www.ogsi.com/library/mining.pdf, Mining Application Note.

22. Vaca, G.A., 1992. Gold Mining in Ecuador and its Impacts. In: Proc. 2nd International Conference on Environmental Issues and Waste Management in Energy and Minerals Production. v.2, Ed. R.K. Singhal et al., Calgary, Alberta, 1-4 Sept. 1992, p.969-984. (in Spanish)

23. INGEOMINAS-Inst. Investigaciones en Geociéncias, Mineria and Química, Min. Mines and Energy, 1995. Colombia, a Gold Mine. 25 p. (in Spanish)

24. Susapu, B., 2001. Milne Bay, Papua New Guinea. Paper presented at MMSD (Mining, Minerals and Sustainable Development Project.). November 19-20, 2001, London, UK. 5 p.

25. Gunson, A.J. and Veiga, M.M., 2001, Mercury and Artisanal Gold Mines in China, Book of Abstracts from the 6th International Conference on Mercury as a Global Pollutant, Minimata, Japan, October, 2001, p. 197.

26. Wenqian,W. and Poling, G.W., 1983. Methods for Recovering Fine Placer Gold. CIM - Canadian Inst. Mining and Metallurgy Bulletin, v.76, n.860, p.47-56.

27. Veiga, M.M. and Fernandes, F.R.C., 1991. Aspectos Gerais do Projeto Poconé.In: Poconé, um Campo de Estudos do Impacto Ambiental do Garimpo, p.1-25. Ed. M.M. Veiga e F.C.R. Fernandes. Rio de Janeiro, CETEM/CNPq (in Portuguese).

28. Taggart, A.F., 1945. Handbook of Mineral Dressing, Ores and Industrial Minerals. New York, John Wiley.

29. Hentschel, T. Roque, D., Taucer, E., 1998, Small Scale Gold Mining at San Simón, Bolivia, *In:* Small-scale gold mining: Examples from Bolivia, Philippines & Zimbabwe, International Labour Organization (ILO), www.ilo.org/public/english/dialogue/sector/papers/goldmine.

30. Corponariño, Cooporación Autonoma Regional para el Desarrollo de Nariño, 1995. Evaluation of Social and Environmental Consequences of Mining with Excavators in Department of Nariño. Convenium Canada-Colombia, Fidufes-Corponariño. Doc. prepared by INCOAMPRO (in Spanish).

31. Farid, L.H.; Machado, J.E.B.; Silva, O.A., 1991. Emission Control and Mercury Recovery from Garimpo Tailing. In: Poconé: Um Campo de Estudos do Impacto Ambiental do Garimpo, p. 27-44, M.M.Veiga, F.R.C. Fernandes (eds), CETEM/CNPq, Rio de Janeiro, Brazil (in Portuguese).

32. Veiga, M.M.; Meech, J.A.; Hypolito, R., 1995. Educational Measures to Address Hg Pollution from Gold Mining Activities in the Amazon. Ambio, v. 24, n. 4, p. 216-220.

33. Basque, G., 1991. *Gold Panner's Manual*. Sunfire Pub. Ltd., Langley, BC, 108p.

34. Pantoja, F. and Alvarez, R., 2001, Techniques to Reduce Mercury Emissions in Gold Mining in Latin America, Book of Abstracts from the 6th International Conference on Mercury as a Global Pollutant, Minimata, Japan, October, 2001, p. 215.

35. Malm,O.; Pfeiffer, W.C.; Souza, C.M.M.; Reuther, R., 1990. Mercury Pollution Due to Gold Mining in the Madeira River Basin, Brazil. Ambio, vol.19, n.1, p. 11-15.

36. Walle, M. and Jennings, N., 2001, Safety and Health in Small-scale Surface Mines: A Handbook, International Labour Office (ILO) Working Paper 168, ILO Publications, Geneva, Switzerland, 48p.

37. Hinton, J.J. and Veiga, M.M., 2002, Earthworms as Bioindicators of Mercury Pollution from Mining and Other Industrial

Activities, Geochemistry: Exploration, Environment and Analysis, in press.

38. UNDP, 2001, Artisanal Mining for Sustainable Livelihoods, www.undp.org/sl/Documents/General%20info/Artisinal_mining/artisinal_mining.htm, November 3, 1999.

39. Lodgson, M.J., Hagelston, K., Mudder, T.I., 1999, The Management of Cyanide in Gold Extraction, International Council on Metals and the Environment, Ottawa, Ont., April, 1999, 40p.

40. Holloway, J., 1997, Environmental Management Systems for Small Scale Gold Mines, *In*: Introducing New Technologies for Abatement of Global Mercury Pollution Derived From Artisanal Gold Mining, UNIDO Headquarters, Vienna, Austria, July, 1997.

41. Hentschel, T, Hrushka, F., and Priester, M., 2001. Draft Global Report on Artisanal and Small-Scale Mining, Working Paper for Mining, Minerals and Sustainable Development, November, 2001, 59 pp.

42. Farias, R.A., Hacon, S., Caires, S.M., Rossi, A.P., Campos, R., Argento, R., Castro, S.E., 2001, Evaluation of Contamination by Mercury in Fish Farming in Garimpo Mining Area in the Northern Region of Mato Grosso, Brazil, Book of Abstract from the 6th International Conference on Mercury as a Global Pollutant, Minimata, Japan, October, 2001, p. 214

43. Veiga, M.M. and Beinhoff, C., 1997. "UNECA Centers, a Way to Reduce Mercury Emissions from Artisanal Gold Mining and Provide Badly Needed Training". *UNEP (United Nations Environment Programme) - Industry and Environment*, Oct-Dec. 1997, v. 20, n.4, p.49-51.

44. Mugova, A., The Shamva Mining Center Project, Paper presented at MMSD (Mining, Minerals and Sustainable Development Project.). November 19-20, 2001, London, UK. 6 p.

45. Healy, C. and Veiga, M.M., 1997, The Foundation for Experimental Mining, *Appendix in* UNIDO Special Report on Artisanal Gold Mining Activities in Suriname, December, 1997.

46. Veiga, A.T. and Veiga, M.M., 2000. A Proposal for Rehabilitation of Degraded "Garimpo" Areas in the Amazon. Proc. of Iberoamerican Workshop on Mine-closure. 9 p. CD ROM. CYTED. La Rabida, Spain, Sept. 25-29, 2000. (in Portuguese).

47. Bugnosen, E., Twigg, J., and Scott, A., 2000, Small-scale Mining Legislation and Regulatory Frameworks, UNEP, Industry and the Environment, Vol. 23, Special Issue, pp. 50-53.

48. Bugnosen, E., 1998, The Kias Gold Mine, Philippines, *In:* Small-scale gold mining: Examples from Bolivia, Philippines & Zimbabwe, International Labour Organization (ILO), www.ilo.org/public/english/dialogue/sector/papers/goldmine.

49. Dahlberg, H., 1997, The Transformation from Artisanal to Small Scale Gold Mining: An Outline for Sustainable Development, *In* Introducing New Technologies for Abatement of Global Mercury Pollution Derived From Artisanal Gold Mining, UNIDO Headquarters, Vienna, Austria, July, 1997.

50. Davidson, J., 1995, Enabling Conditions for the Orderly Development of Artisanal Mining with special reference to experiences in Latin America, International Roundtable on Artisanal Mining, Washington, D.C., May 17-19, 1995.

51. DESA, The UN Department of Economic and Social Affairs, 2000, Poverty Eradication and Sustainable Livelihood, *DESA News*, Volume 4, Issue 2, April-May 2000, www.un.org/esa/desa42.htm.

52. Labonne, B., and Gilman, J., 1999, Towards Building Sustainable Livelihoods in Artisanal Mining Communities, Tripartite Meeting on Social and Labour Issues in Small Scale Mines, Geneva, Switzerland, 17-21 May, 1999.

53. Keita, S., The Contribution of Sadiola Gold Mining Project to Poverty Reduction and the Development of Local Mining Communities, Paper presented at MMSD (Mining, Minerals and Sustainable Development Project.). November 19-20, 2001, London, UK. 6 p.

54. Davidson, J., 1993, The Transformation and Successful Development of Small-scale Mining Enterprises in Developing Countries, United Nations Interregional Seminar on Guidelines for the Development of Small/Medium Scale Mining, Harare, Zimbabwe, 15-19 February 1993.

55. Veiga, M.M.; Scoble, M.; McAllister, M.L., 2001. Mining with Communities. Natural Resources Forum, v. 25, p. 192-202