Global Mercury Project

Project EG/GLO/01/G34
Removal of Barriers to Introduction of Cleaner Artisanal Gold Mining and Extraction Technologies

Manual for Training Artisanal and Small-Scale Gold Miners

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Less mercury, more gold and better health
(Gold in a shop in Kalimantan, Indonesia)

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Chapter 1
Introduction to Effective Training Strategies

This chapter is designed to be an introduction to training strategies for people teaching artisanal miners and their families both health-related and technical information and skills. This includes peer-educators, technical experts with little or no teaching experience, as well as those accustomed to teaching in academic settings.

It is hard to characterize a general type of artisanal miner's family. In some regions artisanal mining is a secondary source of income for farmers, but in parts of the globe, artisanal mining is the main subsistence activity. Artisanal gold miners are typically poor, hard working, illiterate, with little or no formal education, under health stresses, malnourished and often somewhat transient. As we consider successful approaches to education, it is helpful for us to remember that miners want to earn more money, and want their families to be healthier and more stable. Therefore, they can be enthusiastic learners.

It is also critical to remember that many may have had no experience of being a "successful learner". Being acknowledged as being good at learning is critical to being confident enough to ask critical questions when we do not understand something. It is also important to establish the link between learning information and changing behaviors. Our goal in training mining families is behavior change. Whether it is using a new piece of equipment effectively, being able to do maintenance on equipment to ensure long-term use, or beginning to take the time to establish burning areas in villages, our primary focus is on establishing behavior change that enhances health and wealth.

Who are successful trainers?

It is helpful to first have a look at ourselves. Are we people who learn best and easiest how to do things by reading a book, by watching someone else do something first, by trial and error, by talking to friends about it or by looking at images? Do we learn best in a loud and crowded room or in a quiet and calm atmosphere? One thing we know about teachers is that we like to teach in the same style and atmosphere in which we learn best. However, if we only teach in the style that we identify with most, we are often ineffective for a majority of students. Hence, learning to teach outside our natural comfort style is critical.

Next, let's look at ourselves as learners. Do we learn material well if there is no clear positive outcome for us as individuals? The answer is no. Why do we learn how to use the new machine at work? We do this possibly because we will loose our job if we don't. Pretty clear. Why do we learn how to maintain and fix the latest machine at work? We do this possibly because there is a chance of promotion if we do. Why do we get good scores in school? We do this probably because we want to earn a degree or have a certain job in the future. When planning training programs for mining communities, we need to offer them knowledge and skills that they value. In other words we need to have the question, "Why do these people want to learn this material and new skill set?" answered by the community itself. So, setting up time to listen to questions, needs, stories about failed training programs in the past, as well as what has worked in that community is necessary while in the planning stage of the training.

How many times do we need to hear, read or discuss something before we really 'know' it? How much of what we learn do we remember? How many times do we need to practice a new skill before we feel comfortable with it? Think about how to learn to ride a bicycle. Remember those crashes? When planning trainings, it is essential that we only teach material that is essential in order for real changes to take place. What we do not want to happen is for a person to leave a training remembering only the theory about mining engineering or medical terminology. This information is interesting, but does not give the people any new skills or behavior change experience. If people only remember 10% of what they are told, then we want to make sure that the critical material is told ten times rather than other interesting background material we might really like to teach. A good rule of thumb for teaching skills is 1 part of information to 7 parts of practice.

Think back to the last time you tried to change one of your behaviors. Possibly, beginning to exercise or giving up cake and chocolate. Did it take a lot of effort? Was it easy? My guess is that it was at least a significant challenge. Behavior change to the point of habit development is very difficult, even if we know exactly why it is a good idea. Understanding this and being supportive over time of efforts to change, and understanding failed attempts results in better sustainable change than in any way suggesting that people are bad or hopeless for not changing. As we all know from experience of receiving such negative messages, these messages can be very subtle. However, being listened to about why our efforts were not successful encourages future attempts. Would it have been easier for you if all your friends and acquaintances had been engaged in the same change at the same time? Chances are that it would have been. This is because people learn behavior change best in a social context.

Our job as trainers is to provide appropriate information, time for skills practice, time to listen to individual and community concerns, time to consider obstructions to success. Community change evolves from community planning and ownership of the information over time. Maintaining a positive supportive attitude while working with a community makes all the difference.

What is a successful curriculum?

Successful curricula incorporate strategies that have been proven by research to support long-term health enhancing behavior change. Important components are: training of local natural leader 'heroes'; widespread training of affected community members; and community development with local traditional, professional and elected leaders.

The Global Mercury Project is currently piloting a mining community curriculum derived from research-based strategies. "Protect Myself, Protect My Children" is described below and is an example of a skills based health enhancing behavior change curriculum.

The major focus of "Protect Myself, Protect My Children" is the practice of specific demonstrable skills to prevent exposure of miners and their families to mercury. A primary goal of prevention efforts with mining families is to educate them about exposure risks, to provide access to affordable safety and mining equipment, and to practice behaviors that reduce or eliminate the risk of mercury poisoning. A secondary goal of prevention effort with mining families is to reduce the level of poverty experienced by artisanal miners and educate them about ways to extract more gold from the ore and to develop and practice more efficient behaviors and skills. "Protect Myself, Protect My Children" was developed with the specific intent of influencing artisanal miners behaviors related to extraction of gold from ore. This curriculum is designed to be embedded in the context of local community health and technical programs and is particularly appropriate in areas where multiple health related issues, poverty, malnutrition and lack of health care and/or education coexist.

In order to achieve the two goals of the program, "Protect Myself, Protect My Children" has three main components:

1. The train-the-trainer components are workshops specifically tailored for the needs of the local nurses/healthcare workers and technical experts. Participants demonstrate teaching skills and core competencies in technical and health related areas.

2. The training component for miners and families comprises workshops provided by the above-mentioned healthcare workers and technical experts in the field at the transportable demonstration units (TDUs). Sites vary but include mills, small mines and villages. TDU trainings include: education regarding health hazards related to mercury exposure; demonstrations of appropriate gold processing equipment and health seeking behaviors; access to local micro credit and business skill development for participants. Material specific to the needs of women and young children is included. Participants demonstrate new replicable skills related to safer and more productive mining for individuals and whole communities.
3. The community component addresses local receptivity to mercury specific information, local attitudes and beliefs regarding possible changes, provision of resources and local action plan. This supports local leaders and decision-making processes in regards to micro credit, supply issues and specific health and educational concerns. Participants demonstrate pro-change leadership behavior and work for mobilization and continuity at community levels.

This curriculum is designed specifically for areas where normal behavior results in immediately dangerous environmental mercury exposure and contamination creating individual and whole community health hazards. These normal behaviors include frequent inhalation of mercury fumes when burning amalgam, ingestion of mercury-contaminated food (e.g. fish), exposure to contaminated living areas and lack of personal protective equipment. One of the objectives of this “norm and skills based curriculum” is to change what people perceive as normal behavior. One of the premises is that in order to do so, social issues must be acknowledged, primarily that of poverty. More effective mineral processing equipment and protective equipment are provided and micro credit is available to enable miners to change behaviors with as much support as possible.

Research tells us that there are a few critical characteristics required by a curriculum that are effective in promoting positive behavior change. With reference to “Protect Myself, Protect My Children”, (PMPC), these characteristics are:

A. Effective programs include a narrow focus on reducing risky behaviors. PMPC does this by focusing upon safer mining practices specifically.

B. In general, effective programs are based upon theoretical approaches that have been demonstrated to be effective in influencing other health risk behaviors, e.g., social cognitive theory, social influence theory, social inoculation theory, cognitive behavioral theory, and the theory of reasoned action. PMPC is based on these also.

C. Effective programs employ a variety of teaching strategies designed to involve the participants in ways that they can personalize the information. Trainers reach participants through active learning methods rather than didactic instruction. In PMPC, participants are involved in experiential classroom and community activities: Small group discussion, simulations, brainstorming, role playing, practice, feedback/coaching, identifying barriers and creating solutions, use of safety equipment, use of mining equipment, and goal setting.

D. Effective programs provide basic information that participants need in order to assess personal risks and avoid unnecessary behaviors. Typically this information is not unnecessarily detailed or comprehensive. Instead, the programs emphasize the basic facts needed to make behaviorally relevant decisions. PMPC provides functional knowledge in regards to avoiding/reducing mercury exposure.

E. Effective programs include activities that address social pressures on related behaviors. PMPC does this in several ways. It discusses situations that result in inhalation or ingestion of mercury in or near homes (e.g., lack of protective wear, disposal of tailings and associated chemicals near villages, and acceptance of unnecessarily low recovery of gold from their ore).

F. Effective programs reinforce clear and appropriate values in order to strengthen individual and group norms supporting health-seeking behaviors. The PMPC curriculum conveys the message that child/community health is both vital and possible.

G. Effective programs provide modeling and practice of specific skills including hands on and communication/negotiation skills. PMPC provides information about these skills, models effective use of the skills, and provides opportunities for skill rehearsal and practice (e.g., use of mining equipment, role-play and written practice).

H. Effective programs provide training for the educators implementing the curriculum. The PMPC train the trainer component provides background information, teaching strategies, rehearsal and practice with equipment, materials and teaching units along with feedback and coaching.

How do we recognize successful implementation?

It is recognized that there is no one ‘magic bullet’ for complex social problems, but when implemented in a culturally specific context, the PMPC curriculum can be an effective strategy to address cultural beliefs, socio-demographic status, women’s autonomy, economic conditions, physical and financial accessibility, community stability, and disease patterns/health service issues. In regions where this curriculum is appropriate, harm reduction is the goal rather than harm elimination. Success of “Protect Myself, Protect My Children” is based on specific appropriate indicators of positive behavior change.

Basic knowledge for trainers

- The goal of training is sustainable, positive behavior change
    - In some situations, “harm reduction” is the best approach
- Behavior change is difficult and involves many steps and practice
- Use effective teaching strategies that involve participants
    - Focus on essential information and skills that help learners make real changes
    - People learn in different ways so try to use a range of teaching styles, not just the ones that you identify with most
    - Remember to give 1 part information to 7 parts action (skills practice or discussion)
- Allow time for individuals to assess personal and family risk
- Include time to consider social pressures NOT to change
- Behavior change is easier for groups than individuals
- Identify and support natural community leaders

Chapter 2
Gold Ores, Mineralogy and Liberation

Gold occurrence

Gold is a rare element. The average concentration of gold in the Earth's crust is 0.004 g/tonne (i.e. 0.004 grams of gold in one tonne of rock). A gold deposit becomes interesting for economic exploitation with grades usually above 0.2 g/tonne. A rich deposit has gold grades above 10 g/tonne. The extraction of gold does not depend only on the gold grade but also the mineralogy of the gold (i.e., how the gold occurs in the ore), as well as on the access and infrastructure of the site.

It is very common to say, "A miner found a gold vein". In fact gold mineralization occurring in hard rocks is usually associated with quartz veins that can be as thin as a few centimeters and as wide as several meters. Inside the Earth's crust, gold is dissolved in hot silica-rich fluids. When the host or wall-rock suffers a geological fracture or accommodation, room is opened up for the gold containing hot liquid or vapor to come up and penetrate into the cracks and fractures. When the fluids cool down, gold-mineralized quartz veins are formed. This has happened millions to billions years ago. In some cases the hot fluids reacts with the wall rocks. In these cases, gold mineralization is not restricted to the quartz veins but can be found in the host rocks, especially when these contain dark minerals, which are more reactive. Quartz veins can be very deep and can extend for kilometers. It is not uncommon to find quartz veins without gold because the fluids that form the quartz veins often do not contain any gold. When gold occurs disseminated throughout the host rocks, it is usually finely distributed in the minerals that form the rock.

Gold can occur as very fine particles, as fine as 0.001 mm, which are very difficult to concentrate. When the gold-bearing rocks are eroded or weathered, unconsolidated sand or gravel placer deposits rich in gold can be formed. Sometimes this unconsolidated material reaches present day streams, but sometimes it stays near the uplands in terraces or beaches formed by ancient streams that no longer exist. With time, unconsolidated sand and gravel eventually turns into hard rock, hardened over millions of years by geological processes. It is often possible to see the round pieces of quartz and other hard minerals embedded in a matrix of fine minerals in these ancient "conglomerates".

Gold minerals

Fig. 2.1 - This gigantic gold nugget (60.8 kg) was found in Serra Pelada, Brazil *(photo A.R.B. Silva)*

Gold can occur as a pure mineral or be combined with other metals such as silver, copper, mercury, palladium, tellurium, etc. The term "carat"[1] is used to describe the purity of gold and is based on a total of 24 parts. Pure gold is known as 24 carat. In 18 carat gold, for example, 18 of the 24 parts are gold and the remaining 6 parts are another metal, such as silver or copper. The properties of pure gold are altered when it contains other metals. For example, 24 carat gold is too soft to make long lasting jewelry. The international price of gold is usually related to pure gold. The purity or fineness of gold is expressed in parts per 1000 (fineness of 1000 is 100% gold). The most common unit for measuring the weight of gold is the "troy ounce". One troy ounce of gold weighs approximately 31.1 grams. The price of gold is established daily by the London Exchange Market and the gold buyers around the world apply this price when they buy pure gold from miners. However, gold dealers usually do not pay the miners the same gold value as a bank because gold produced by artisanal miners is still impure (usually with fineness of about 900, or 90% pure). The value of a gold nugget is usually higher than the amount of gold contained because nuggets are rare and collectors around the world pay more for them. When a gold nugget is found, this can sometimes be an indication that the primary gold deposit is nearby (gold nuggets do not travel too far because gold is a heavy mineral). Sometimes gold is formed as a secondary mineral. For example, in a deposit rich in iron oxide-hydroxides (yellow-red-brownish-earthy type of material), gold can "grow" as it precipitates from the fine iron hydroxides, forming large nuggets (Fig 2.1) such as the Canaã nugget weighing 60.8 kg found by the artisanal gold miners in Serra Pelada, Brazil in the 1980s. Actually the Canaã nugget was part of a larger gold nugget weighing 150 kg that broke in pieces when it was removed by the miners. Secondary gold nuggets are usually very pure

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[1] A unit of weight for diamonds, pearls and other gemstones. 1 carat = 200mg or a unit used to measure the purity of gold:
1 carat = 1 out of every 24 parts is gold
2 carat = 2 out of every 24 parts is gold
24 carat gold is pure gold

(>99%; note: ">" = "more than"; "<" = "less than") because they have been "refined by nature" (i.e. gold was naturally dissolved, adsorbed and precipitated). When gold is produced by artisanal miners, usually the fineness (purity) of the gold is known by the local gold dealers. It is possible, however, to find gold grains containing less than 45% gold. In general, silver is the main metal found in native gold (commonly gold particles contain around 10% silver). Gold has its characteristic strong yellow color when it contains less than 10% silver or other metals.

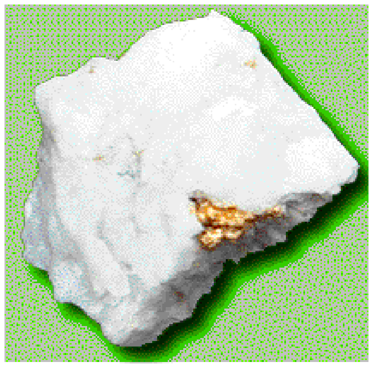

Fig.2.2 - Gold un-liberated from quartz *(photo: Mineral Council of Australia)*

It is very common to find gold associated with sulfides, those shiny metallic minerals that sometimes resemble gold. When gold occurs associated to sulfides, it has a preference for pyrite (FeS_2), followed by arsenopyrite (FeAsS), chalcopyrite ($CuFeS_2$), pyrrhotite (FeS) then other sulfides such as galena (PbS), sphalerite (ZnS), etc. Pyrite chalcopyrite and pyrrhotite are golden colored minerals and sometimes they are known as "fool's gold". Pyrrhotite is magnetic so with a hand magnet it is possible to differentiate it from gold which is not magnetic. Pyrite and chalcopyrite are yellow but harder than gold. A simple way to differentiate these sulfides from gold is to separate some grains, and leave them in vinegar-water solution over night (this works better with oxygenated water—shake the vinegar and water in a jar or bottle for a minute to start the process). In the morning, a dull oxidized layer will appear on surface of the sulfides, but gold will not be oxidized and keeps its brightness.

When gold occurs within sulfides, it is not usually visible. Such tiny "occluded" gold is not easy to extract by gravity concentration, amalgamation, or even by cyanidation. The sulfide must be oxidized (transformed to reddish iron oxide-hydroxide) in order to allow gold to be exposed or liberated. This oxidation can occur by many methods, such as roasting (burning in a bonfire), or mixing with oxygenated water, bleach, etc.

How to find gold deposits

Simple methods can be used to find gold deposits. The particular approach depends on the local geology. For example, soils in tropical environments that have evolved from gold bearing greenstones can become slowly enriched in gold as the bedrock weathers. In the Tapajós region in the Brazilian Amazon, miners systematically pan this type of weathered soil to locate and define the size of deposits. The process is semi-quantitative, and is based on a grid of 200m x 40m. Samples at each intersection of the grid are collected and panned, and visually inspected to determine the amount of gold in the sample. In areas where more gold specks are recovered, the miners establish a finer grid, (for example, a 5m x 5m grid), and attempt to identify the presence of quartz fragments or flaky grains of hematite (an iron mineral which is an indication of pyrite oxidation) using a magnifying lens. Further sampling is undertaken by digging 2 meter deep trenches.

In the Tapajós sampling process, a 10 or 20 L bucket of sampled soil is collected at each intersection of the grid. The material is panned with water, and if the concentrate shows some gold specks, they are counted and examined. If a scale is available, the gold is weighed; but if a scale is not available, the weight of the specks is determined by comparing the grains with pictures of specks of different weights on a plastic card, allowing the miner to make a good estimate of the grade of gold in the sample. It is sometimes also recommended to analyze the samples using the fire-assay method: a 30-g sample is melted in a furnace with borax and lead nitrate allowing all gold in the sample to be captured by the lead forming a nice button which can be visually sized to estimate weight. The shape of the gold specks can indicate if the gold is from a vein, or is recrystallized (i.e., supergenic) - primary gold is usually less round and dendritic (tree-shape). Primary gold also contains more impurities such as copper, silver, etc. than recrystallized gold. The systematic panning method is very inexpensive and allows immediate results. In general, this approach allows miners to detect large gold bearing quartz veins, but often misses small veins less than 1 m. (Information from Mr. Alain Lestra, a French geologist and independent consultant living in the Brazilian Amazon for more than 20 years).

Gold liberation

As a general rule for concentrating minerals we can say that: “to concentrate the mineral of interest we must eliminate mass”. In other words, the mass of the undesirable material, also called “gangue minerals”, must be discarded. Many miners believe that they lose gold when they discard fine fractions of their material. This is true, but the main loss is usually in the coarse fraction of the tailings, because there is often gold that is not liberated in the coarse gangue—if it is not liberated, it cannot be concentrated! The only way to liberate gold from the gangue is by grinding. This concept of “mineral liberation” is very important to communicate to artisanal miners. In order to eliminate the undesirable minerals, miners need to know how (and in which grain size) the gold is "freed" (not attached) from the gangue minerals (e.g. quartz). When the miners grind the ore[2], they intuitively try to reach a grain size in which gold is liberated from the gangue, but they do not know at which size this happens most effectively. If the gold is not liberated, some bad things may happen:

- The concentrate is not enriched with gold (i.e. the mass of gangue is not sufficiently eliminated)
- Gold is lost during the gravity concentration (e.g. sluicing, or centrifuging)
- Mercury cannot trap the gold in the concentrate
- Gold is not exposed to be leached by cyanide

When the gold is "liberated" (freed from the gangue), it can be concentrated nicely. Figures 2.3 and 2.4 show the difference between a ground ore with only a few free gold particles (Fig. 2.3), and an ore with lots of free gold particles (dark particles) (Fig. 2.4).

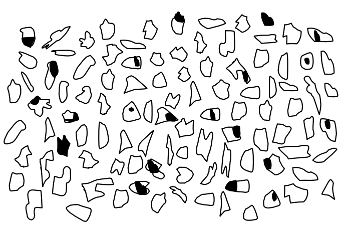

Fig. 2.3 – Example of an ore with **poor** liberation. Gold (dark) is still mostly attached to the gangue (white)

Fig. 2.4 – Example of an ore with **good** liberation. Gold (dark) is mostly freed from the gangue (white)

When gold occurs in water streams or terraces, forming "placer" deposits, it is usually liberated because the transport of the gold particles grinds the minerals and frees gold particles. However, it is also possible to find non-liberated gold particles in placer deposits.

So, it is clear that the first step before grinding and concentrating gold is to determine the best grain size in which most of the gold will be liberated from the gangue. But how do miners do this when they work with varied types of ores? It is important to make a sample of ore that is representative of the ore in the deposit (i.e., a sample that has the same characteristics as most of the ore in

[2] Ore is a rock or a mineral with economic value

the deposit). We can a make a representative sample by collecting pieces of ore from various places in the deposit or vein, crushing them manually in a mortar to pieces finer than 1" (2.5 cm). This material is then spread in a pile and homogenized (mixed vigorously) manually. A pile made of 20 buckets of ore (around 500 kg) is sufficient. Use this pile of ore for all tests in order to better understand the ore. This material is representative of the ore and we call it "head sample". (Unless the ore changes its characteristics a lot (e.g. in some places is weathered, is from the wall rock, or is taken from a different location, etc.), we do not need to test it very often.) Next, take sub-samples from this pile in a very uniform way. Collect 20-liter bucket sub-samples from different parts of the pile. Keep these sub-samples in a safe place with a label **"head sample #___"** and the name of the mine site.

When we desire to establish the degree of liberation of gold, we can do this by sieving a sub-sample (head sample) in different screen sizes and observing the screened fractions with a magnifying lens or under a microscope (Fig. 2.3 and 2.4). Unfortunately, it is often very difficult to find visible gold particles in ground and screened fractions because gold usually occurs in low concentration in most ores - indirect methods must be applied to determine the ideal grain size the ore should be ground to in order to most effectively liberate the gold from the gangue. This can be time consuming, but yields valuable information about the ore we are working. We do not have to do this frequently, only when we change the type of ore being processed. We will need:

- a small ball mill
- a clock
- a water box, 1 or 2 plastic tubs and 1 or 2 buckets
- some sieves (5mm, 2mm, 1mm, 0.5mm, 0.1m; mosquito nets and woman stockings can be used)
- a bathroom scale (up to 200 kg)

Using a small ball mill to investigate gold liberation

A small ball mill can be build to test the liberation. Artisanal miners in Mozambique (Fig. 2.5) make small manual ball mills using a gas cylinder. This can grind 10 to 20 kg of material in one or two hours, depending on the size of the tank. Small ball mills (usually unlined) can also be operated using a motor and connected in-line using a pulley belt (Fig. 2.6). This system of multiple small mills is being used for gold production in Indonesia.

Manual or mechanical small ball mills should operate 40% full to have good performance. Ball mills are loaded with 1 part of ore, 1 part of water and 2 parts of steel balls .

Small balls are best for fine grinding, but big balls help break the larger chunks of ore. Ideally a mixture of small and big ball mill should be used. Always use the same mixture of ball sizes for any tests.

To start the liberation test, the following sequence of tasks is recommended:

- Load the mill with 20 or 40 kg (depending on the size of the mill) of steel balls
- In a bucket, mix 10 or 20 kg of head sample with 10 or 20 kg of water
- Add the mixture into the mill
- Use a little water to wash completely the bucket (gold can stay at the bottom of the bucket)
- Grind (manually or mechanically) for 10 minutes
- Discharge the material into buckets or plastic tubs
- In a water box, concentrate the material by panning or sluicing
- Always collect the tailings (waste) in the water box (and reintroduce into the ball mill for the next 10 minute grinding step)
- Separate the concentrate (with visible gold) and weigh the gold
- Get rid of as much water as possible (try to obtain the same consistency of the mixture head sample + water you had before (see the second bullet, above)
- Load the mill with same amount of balls as before
- Grind for additional 10 minutes
- Repeat the concentration process and re-grind again for additional 10 minutes
- Redo the process until you do not see any more gold in the concentrate. For a given ore, best length of time for grinding would be the total of all 10 minutes grinding steps that you have completed.

If you want to know what the grain size is of the ideal ground product, take a fresh head sample and grind it for the same time you have established (above) and pass the ground product through a series of screens:

- Use as a first screen a 5mm mosquito net, then use a 2mm, 1mm, 0.5mm, 0.1mm (you can use woman stockings for the finer mesh)
- Dry both the material retained in each screen, as well as the material passing through the last screen
- Weigh all screened factions; divide the weight of each fraction by the total weight of the head sample you used; then multiply by 100 to obtain the % of weight retained in each screen
- Note which screen passed 80% of your material--**this is the best size to grind your sample**. Whenever you grind in a different mill, try to reach

the same size. If the ore is the same, this size will give the best liberation in any mill.

Fig. 2.5 - Manual ball mill made of LPG tank (Mozambique)

Fig. 2.6 – A series of small ball mills operating in Indonesia

Basic knowledge for miners

- Gold is deposited in rocks in a number of ways - usually when hot gold-rich fluids cool inside cracks or in zones of reactive bedrock deep inside the earth. This has happened millions of years ago
    - Gold is often found where there are shiny sulfide minerals
        - Pyrite can be distinguished from gold by mixing it with vinegar and water
        - Red rusting pyrite stains in bedrock can be a sign that there might be gold nearby
- Free gold found near rivers comes from bedrock that has been broken up over very long time and usually carried by rainwater to the streams
- Free gold can also be found in crumbled weathered bedrock near where it was deposited
- Gold often has other metals mixed with it - silver is the most common
- The particles of gold in rocks can be both big and small
    - Miners recover more gold when the gold particles are liberated from other minerals
    - Gold particles become liberated by efficient grinding
    - The degree of **liberation** must be tested
    - Poor **liberation** causes the loss of gold in sluices and centrifuges, during amalgamation, and during cyanide leaching

Bibliography

Henley, K.J., 1975. Gold-ore Mineralogy and Its Relation to Metallurgical Treatment. *Minerals Science and Engineering*, v.7, n.4, p.289-312

Mineral Council of Australia. Gold Downunder: http://www.ga.gov.au/education/minerals/goldfact.html

Veiga, M.M., 1989. Technological Characterization of Gold Ores. *Brasil Mineral*, v.72, p.124-136 (in Portuguese)

Veiga, M.M., 1992. Mineralogical aspects. *In*: Aspectos Diversos da Garimpagem de Ouro. Ed. F.A.F. Lins (Editor). Ser. Tecnologia Mineral, n.54, p.15-30. Published by CETEM/CNPq, Rio de Janeiro (in Portuguese).

Chapter 3
Crushing and Grinding

Why crushing and grinding is important

Gold-containing rocks are crushed for several reasons. Crushing reduces the physical size of large rocks, exposing more surface area of rock, thus exposing any gold that may be in the rock and increasing the probability of obtaining the gold from the rock by gravity concentration or by leaching with cyanide. There may be several sizes and shapes of gold grains in the rock--round, flat, coarse or tiny. Because of this, several stages of crushing or grinding can be required. The physical dimensions, the mineralogy of the gold and gangue minerals, and the hardness and internal structure of a rock determine how the rock will break. Rocks are broken by the addition of energy in the form of an impact (hammer, crusher jaw, etc.) which results in smaller particles, plus heat, noise and dust. The crushing or grinding effort is dependent to the following factors:

- rate of ore feed
- feed rock size
- desired product size, and
- hardness of rock

"Comminution" is the technical term used to describe the mechanical disintegration of a rock. This can be done by crushing (coarse) and grinding (fine), or by simply breaking up clumps of soil or clayey materials.

Common rock types in mining have a wide range of crushability (i.e. the ease with which a rock is crushed). The table below shows a number of rock types and their relative crushability. As one can see, rocks with high amounts of quartz are harder than many other rock types, and thus require considerable effort to crush:

Type of Rock	Hardness
Basalt	**Very hard**
Granite	↓
Quartz/quartzite	↓
Copper ore	↓
Iron ore	↓
Sandstone	↓
Limestone	**Soft**

Secondary factors to consider when crushing are the desired size of the crushed material and quantity of material to be crushed ("feed rate"). The desired particle size of determines the number of stages of crushing (primary, secondary and tertiary) and the type of machine to be used. The quantity of material entering the crusher determines the size of the machine selected. The type of crushing or grinding method also impacts the way in which the rock is broken during crushing or grinding. There are four typical stages of comminution:

- Primary crushing – crushing of large rocks fresh from the earth
- Secondary crushing – crushing of rocks after primary crushing
- Tertiary crushing – final sizing of rocks by crushing
- Grinding – grinding of crushed rock to very fine powder

Relatively coarse fragmentation of the rock is accomplished by machines called "crushers", whereas the machines used for fine fragmentation or grinding are called "mills".

Comminution can be achieved in several ways:

Batch comminution: The material is fed all at one time, and the crushing or grinding ceases when the material is discharged. It is not a continuous method. Batch processes are simple and easy to operate, but are not very efficient as the miner has little control on the final particle size. The machine is turned on when the crushing or grinding begins and is turned off when the desired particle size is achieved.

Continuous Comminution: The material is fed and discharged continuously, i.e. the grinding process does not cease. Both "Open" and "Closed" circuits can run continuously. Open circuits discharge all of the ground material to the concentrating device (centrifuge or sluice):

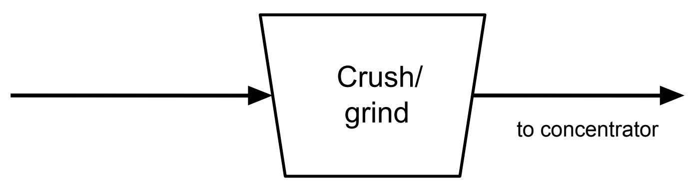

Fig. 3.1 – Open Circuit

Closed circuits use screens or other classifying devices to send coarse particles back to the crusher or mill. All the particles sent to the concentrator are smaller than the screen opening which should be sized to insure maximum liberation of gold particles:

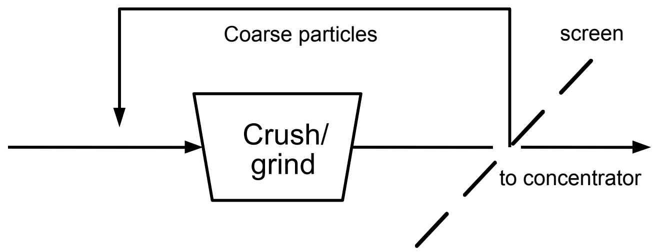

Fig. 3.2 – Closed Circuit

Closed circuit crushing and grinding is the method used by all large mining operations. The advantage of recycling the coarse material retained in the screen is that only the particles of gold that are sufficiently liberated will pass through the screen and be concentrated. This limits over-grinding which can make the gold hard to capture (particles become too small or flat), as well as achieves the best gold liberation size. When no information about the gold liberation grain size is available, miners should test different grinding times using a small ball mill and gravity separation (e.g., a gold pan) to evaluate liberation (see "Using a small ball mill to investigate gold liberation" in Chapter 2, above). Testing for optimum gold liberation will definitely improve gold recovery. In order to reach the best liberation size, comminution equipment must work in closed circuit with classification (e.g., screening) processes. Unfortunately most artisanal gold mining operations conduct their comminution process in open circuit, without any screens.

Comminution is the most costly operation in mineral processing. The type of comminution equipment to be demonstrated to the miners must meet these criteria:

1. Equipment must not be complex (the technical knowledge necessary to operate must be simple)
2. Equipment must be easily accessible (preferably locally manufactured)
3. Equipment must be inexpensive and able to be locally maintained.

Crushing

Different types of equipment are best for each stage of crushing. Crushing typically occurs through the pinching of a rock between two metal plates (jaw, gyratory, or cone) or through the impact of a metal surface on a rock (hammer mill and stamp mills). The following are common types of crushers used in gold mining:

- ***Jaw Crusher***

Jaw crushers operate by means of a moving jaw suspended from an eccentric shaft driven by a diesel or electric motor via a large flywheel. Feed size to a jaw crusher can range from 50 – 300mm; discharge sizes are between 10 – 70mm. Jaw crushers are typically sized by the size of the largest feed particle--if the rocks are large, the crusher must be large. Jaw crushers are very common in artisanal gold mines. A small crusher operating in batches of 5 to 10 tonnes of ore and handling 500 kg/h to reduce it to -1/4" (6.5 mm) is suitable for most artisanal mining operations.

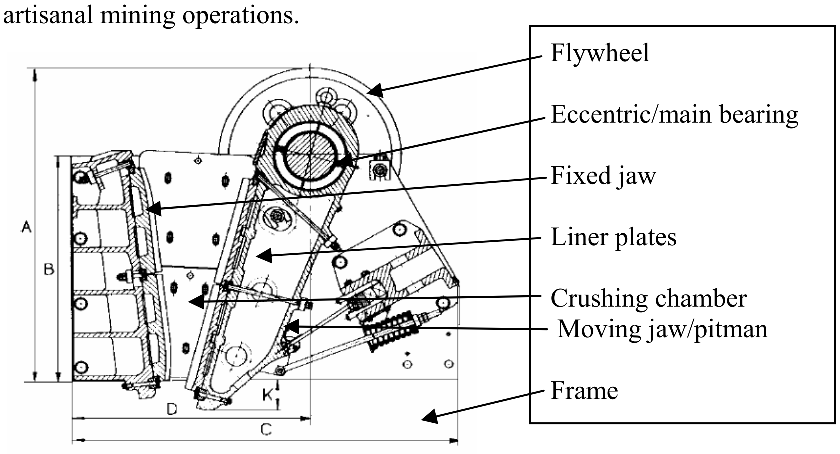

Fig. 3.3 – Parts of a jaw crusher

The energy consumed by a jaw crusher is usually 0.5 kWh/tonne. The maximum feed size for a jaw crusher should be about 85% of the opening gap. The specifications of a small jaw crusher to crush ore from 50 to 9 mm, with maximum capacity of crushing 0.5 tonne/hour is given as follows:

Type of Small Jaw Crusher: 8"x 5" (15 x 7.5 cm)

- Jaw Opening: 15 cm wide x 7.5 cm gap
- Max Feed Size: 2" (50 mm)
- Jaws: Ni-hardened steel
- Jaw Profile: Ribbed
- Crushed product Size: nominal 100% passing –9mm
- Drive V-belt drive, 275 rpm

- Power: 2.2 kW
- Shipping Weight 220kg
- Price (in Zimbabwe): ~ US$ 5000

Fig. 3.4 – Venezuelan miner feeding a small jaw crusher

Fig. 3.5 – A small jaw crusher in Zimbabwe

- ***Gyratory crusher***

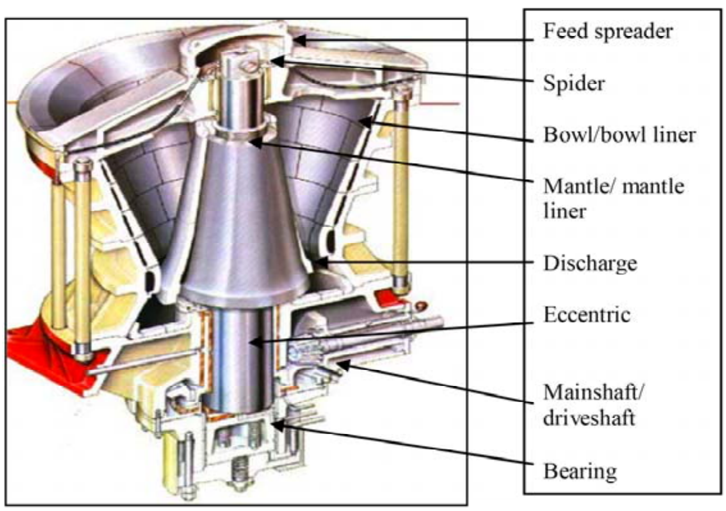

Fig. 3.6 – Parts of a gyratory crusher

Gyratory (and cone) crushers operate by rotating a mantle within a cone shaped bowl, similar to a mortar and pestle. In large-scale operations, coarse material, typically between 500 – 1000mm is introduced from the top into the crushing chamber. The width of the chamber decreases towards the bottom of the crusher and fine material falls through the gap between the mantle and the bowl. Discharge sizes can be 50 – 200mm. The mantle is typically mounted on an eccentric base driven externally by a horizontal shaft. This is an expensive crusher. Most large mining companies use this type of gyratory crusher for feed rates above 100 tonnes per hour of material and when they want to reduce the size of large pieces of rock (as large as 1 meter) to 50 mm in one step.

A variation of a gyratory crusher is the impact crusher. This crusher usually uses rock-to-rock impacts to crush the ore. The most successful machine using this principle is the Barmac, manufactured by Metso (Finland, www.metso.com). The transfer of energy from the spinning rotor to the particles is very efficient, resulting in production of large quantities of fine particles. The percentage of fines produced can be altered by changing the rotor tip speed, chamber configuration, rotor size, cascade ratio or feed gradation. The residence time of particles in the crushing chamber can range from between 5 to 20 seconds. During this time each particle is subjected to hundreds of particle interactions from both coarse and fine particles resulting in cleavage, impact, abrasion and attrition of the particles. The crushing action of the Barmac allows it to liberate minerals, or to preferentially crush gangue without over-crushing the valuable minerals. Barmac has various sizes of crushers including small pilot-plant type of machines that can be useful for artisanal operations, but this crusher is usually best for tertiary crushing and therefore the maximum feed size is usually small (e.g. below 2 cm).

Fig. 3.7 – Barmac impact gyratory crusher

Unfortunately, these crushers are also expensive but there are local versions of this type of mills in artisanal mining regions. An example of an impact crusher developed in Zimbabwe is the Clarson Impact Mill. It has smaller capacity of 2 tonnes/h and may be affordable for artisanal miners (around US$ 6000). This crusher rotates at 3000 rpm with power of 5.5 kW. However, the rapid comminution (from 20 to 1 mm) is obtained at the expense of high abrasion of the equipment walls. Although it probably has a small degree of material-on-material abrasion action, it is very similar to a hammer mill and wears quickly.

- ***Roll Crushers***

Roll crushers are typically used for the crushing of coal and friable rocks such as limestone although they can be used in primary and secondary crushing of hard rocks. This type of crusher is good for sticky material and works by trapping rocks between the teeth of opposed rolls – feed rock is drawn through the rolls like a wringer and discharged through the bottom of the crusher. Rolls rotate at between 60-300 rotation/min and are spring mounted to allow harder rocks and steel to pass through the crusher without breaking the crusher.

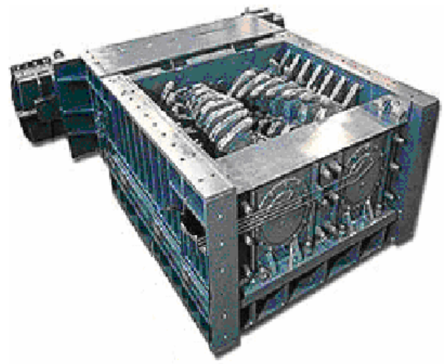

Fig. 3.8 – A Roll Crusher

- ***Hammer Mills***

Hammer mills are actually crushers, not mills since the size generated by the process is usually 0.5 to 1 mm. Hammer mills were devised to work with soft rocks such as limestone, but artisanal miners commonly use them for hard rocks. In a hammer mill, pivoted hammers are mounted on a rotating shaft and crushing is achieved as the rocks break on impact with the hammers and the fixed breaker plates mounted in the mill frame. The speed of the hammer mill can be anywhere from 500 – 1800 rotations/min. Hammer mills thus have little control on particle size and are subject to high wear on harder materials. The discharge of the hammer mills is usually done through a 0.5 to 2 mm manganese steel screen.

The price of a hammer mill usually ranges between US$ 1000 to 10,000 depending on the size and quality for the machine; good hammer mills suitable for small operations can be found in Brazil for about $1200 (not including motor).

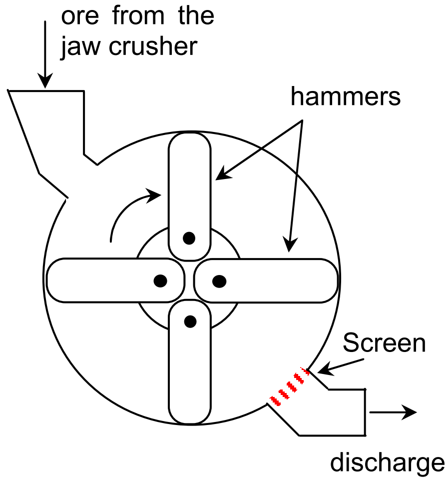

Fig. 3.9 – Parts of a hammer mill

Fig. 3.10 – Miner washing a hammer mill after operation to remove gold stuck inside the mill (Venezuela)

The specifications of a hammer mill with a capacity of 1 tonne/h of hard rock or 6 tonnes/h for soft rocks are given as follows:

- Feed Size: 70mm max
- Product Size: 6mm to < 1mm depending on the discharge screen
- Water: 1500 Liters/hour approx
- Extent of Mechanization: Fully mechanized
- Power: 10-15kW; or small 20 hp diesel motors (e.g., Tobatta, Kubota, or Yanmar as used for irrigation pumps)
- Speed: 900 – 1270 rpm
- Drive: Pulley & V belt
- Construction: internal parts made of manganese steel

In El Callao, Venezuela, a traditional artisanal gold mining site, the ore is wet-ground to below 1 mm by 25 hp hammer mills. Hammer mills have capacity of 0.2 to 0.4 tonnes/hour depending on the hardness of the ore. For soft material, a pair of cast iron hammers (typically US$ 10 - 30) must be changed after grinding 10 tonnes of ore. When milling the relatively soft oxide ores that artisanal miners commonly mine close to the surface, hammers can last for 10 – 20 tonnes. For some very hard ores, hammers are changed after grinding 1.5 - 2 tonnes. Replacement of hammers requires that miners have an electric welding

machine and a supplier of hammers (made of cast iron). Some miners use leaf springs from truck suspensions or pieces of railway rails as hammers.
In South America and China, hammer mills are very popular among artisanal gold miners. One inconvenience is that particles of gold can become retained inside of the mill and at the end of the cycle the mill has to be opened and vigorously cleaned with water.

- ***Stamp mill***

This is another crusher that has the name of "mill". Stamp mills operate simply by the crushing action of the cast-metal stamp heads as they fall onto the ore at the bottom of the mortar box. "Normal" stamp mills have 3 or 5 stamps. The stamps are lifted via the cast iron collars by cams driven by a pulley and flywheel. Feed is typically -50mm, loaded into the top of the mortar box by shovel, and discharge is typically -0.5 to 1mm via a fixed screen on the back of the box. Stamp mills can be operated either dry or wet, and can be either manually, electrically, or diesel driven.

During operation, the base (die) of the stamps becomes deformed and quite often miners have to stop the crushing process to grind off the lips formed on the steel base.

The crushing capacity of a 3-stamp mill is around 0.3 to 0.5 tonnes/h depending on the hardness of the ore. The cleaning of a stamp mill is easy but not quick, and usually involves manually digging out all the material accumulated in the mortar box between the stamp dies. Gold, as a heavy mineral, can be accumulated in the mortar box.

Fig. 3.11 – Three-stamp mill in Zimbabwe discharging crushed material into a centrifuge

Fig. 3.12 – Miner grinding the base of stamps inside a mill

In Zimbabwe, stamp mills are an accepted technology because the entire process is VISIBLE. Miners discharge the crushed product through a 0.5 to 1 mm screen directly into a centrifuge or onto an amalgamating copper plate. Gold liberation at 1 mm particle size is often poor, and is the main reason why Zimbabwean miners often recover less than 30% of the total gold.

Grinding

Grinding is undertaken on already crushed material to achieve adequately fine particle size necessary to liberate the most gold possible. Grinding typically uses some sort of tumbling mill: a round metal barrel driven either manually or mechanically and filled with a grinding media such as steel balls, rods or hard pebbles. Grinding can be undertaken dry or wet. Dry grinding reduces the wear on mill shells, liners and balls, but requires up to 30% more power than wet grinding. Common types of grinding mills are:

Fig. 3.13 – Discharge screen

- ***Chilean-type 'Muller' Mills***

This type of mill combines crushing and grinding. It utilizes two or three wheels running in a circular trough, driven by one of the wheels or by a central boss gear. The mill can either grind batches (where ground ore is taken out periodically and replaced with fresh feed) or operate continuously (for example where a continuous stream of water washes the ground ore out of the mill onto a sluice). The feed size is usually smaller than 10 cm. Some miners in Ecuador crush the ore in a small jaw crusher to 2 to 5 cm and feed this into the Chilean mill. They use a nylon screen (mesh size as small as 0.1 mm) at the discharge of the mill. The mill operates with water (usually a pulp of 20% solids) and the material discharged through the nylon screen goes to sluice boxes lined with mats.

The process is continuous and the output depends on the size of the mill and the grain size of the product. Typically the production is between 0.2 to 0.5 tonne/h for product ground below 0.2 mm. Chilean mills are very efficient, but unfortunately many miners in South America and China add mercury to the mill - the mercury becomes finely pulverized (floured) and is lost with the tailings.

Fig. 3.14 – Chilean mill used by Ecuadorian gold miners

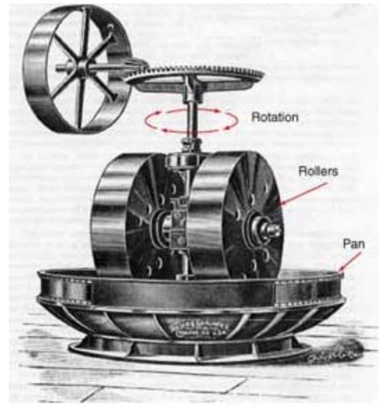

Fig. 3.15 – Chilean mill

- ***Ball mills & rod mills***

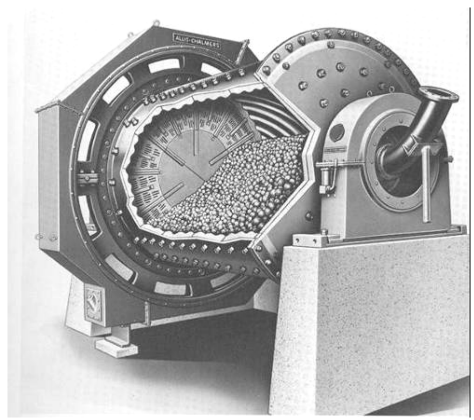

Fig 3.16 – An industrial ball mill

Ball, pebble and rod mills are all cylindrical rotating shells which are mounted on bearings and filled with up to 40% by volume of a grinding medium such as steel balls, rods or hard pebbles. Large models are usually lined with a wear-resistant lining. Mills are typically longer than their diameter, although some ball mills can be shorter in length than diameter. Feed rock size is typically 10-40 mm and discharge sizes can be 0.03 – 0.3 mm. Mills operate at an optimum speed which is typically 70% of the *critical speed* of the mill – the speed at which the contents will stick to the shell of the mill. The critical speed **N** for a mill is calculated based on the diameter **D** (in meters) of the mill: $N = 42.3/D^{0.5}$. For a small ball mill with internal diameter of 90 cm, the critical speed is around 44 rpm. The suggested speed is 70% of the critical speed or 31 rpm.

In order to demonstrate the principles and advantages of a ball mill, a simple unlined steel drum with discharge port on the side of the drum can be used instead of a continuous production ball mill. In Indonesia, artisanal miners use sets of 12 to 48 small unlined batch ball mills (∅48 x 60 cm, 2.5 to 4cm thick walls) to grind primary gold ore. Each mill grinds 40 to 50 kg of material per batch. The grinding time in Indonesia is often too long (3 hours) because miners use excess water and the wrong grinding media (gravels and rods). Similarly, small welded octagonal mills are used in Tanzania but miners do not use water, because after grinding, they have to carry the ground ore in bags to another group of workers who perform the concentration step—dry ore is much easier to carry. Unfortunately, dry grinding is inefficient, takes more time and spreads dust in the air (dust is a hazard to miners). On the other hand, miners do not introduce mercury into dry grinding circuits as they commonly do in wet batch ball mills in Indonesia. With more organization, these Tanzanian miners could improve their milling process. Despite the low production rate of a single small ball mill, using many small batch-ball mills instead of large ones is a good concept for artisanal miners with limited capital. Miners and millers can increase their milling capacity in a step-by-step approach by acquiring one mill after another and connecting them with a belt drive. This is not the best solution in terms of energy consumption, but definitely suits the limited financial capacity of the miners, employs more people and is already a fully accepted concept in many artisanal gold mining regions.

Fig. 3.17 – Series of small belt-driven ball mills in Sulawesi, Indonesia

Fig. 3.18 - Diesel driven octagonal welded dry ball mill in Tanzania

Small mills can be electrically or diesel driven. If expansion is required, a larger mill or more small mills would be necessary. The specifications of an Indonesian small ball mill with are given below:

- Size: ∅0.48 (1.6 ft) x 0.6 m (2ft) long (internal)
- Lining: unlined (25-40 mm thick steel shell and ends)
- Critical Speed: $Nc = 42.3/D^{0.5}$ (in m) = 61 rpm

- Operating Speed: 70 - 75% of critical speed = 45 rpm
- Feed Capacity: 40-50 kg/batch
- Max Feed Size: 12mm
- Water required: for 70% solids at 40kg load = 17 – 18 L
  for 70% solids at 50 kg load = 21 – 22 L
- Product Size: time dependent; typically P80 = 100 mesh (0.150 mm)
- Ball Load: 40% of the mill volume
- Ball Load in kg: 350kg
- ∅ max of ball: 44mm
- Ball Sizes: 50% of 40mm and 50% of 25mm
- Type of Ball: cast or forged steel (0.9 C, 0.85 Mn, 0.2 Si, 0.5 Cr, 0.1 Mo)
- Ball Hardness: 63-65 Rockwell
- Shipping Weight: 280kg
- Extent of Mechanization: partially mechanized; batch manual discharge
- Mode of Operation: batch
- Discharge: lateral door
- Drive: torque arm gearbox and V-Belt
- Installed Power: 2.2 kW

- ***Manual Crushing and Grinding Methods:***

Manual methods of crushing and grinding are important in small scale mining.

Fig. 3.19 – Female miner fine grinding ore with a stone

Fig. 3.20 – Miners in Zimbabwe grinding with mortar and pestle, and screening manually

Sledgehammer

A common method of pre-sizing rocks before grinding in a stamp mill or ball mill is to place oversize rocks (>2") on a large flat rock, inside a Hessian or nylon ring which holds the rocks in place while they are hit with a hammer to produce typically 1 cm rocks. Some miners then use a piece of stone to grind the crushed rocks. In this process, the ground material is screened at 0.5 to 1 mm and the coarse material re-ground.

Mortar & pestle

Crushing and grinding can be achieved in a batch fashion with a mortar and pestle. Pre-sized rocks are placed in a steel bowl with a rounded bottom, or in a short length of wide pipe welded onto a steel plate, and pounded with a steel rod such as an automobile axle.

Fig. 3.21 – Miner in Tanzania using a cloth Hessian ring around the rock to protect his hands when crushing with a hammer

Fig. 3.22 – Miner crushing and grinding with mortar and pestle in Mozambique

In Guinea, West Africa, there are about 300,000 artisanal miners excavating 10m deep shafts and sending ore to the surface with ropes and buckets. The ore is pounded by women in mortars with pestles made of wood. The efficiency of this grinding process is very low and does not promote good liberation of the gold. The concentration by panning in "calabaces" (no mercury is added) recovers less than 5% of the total gold.

Manual stamp mill (crushing)

Fig. 3.23 – Hand stamp mill made in Zimbabwe. One and two stamp models are available.

Hand stamp mills such as the ones made in Bulawayo, Zimbabwe (Matabeleland Engineering), are useful for grinding small quantities of -50 mm ore to 0.5 -1 mm. The hand-operated mill is a simple construction of one or two stamps and a camshaft supported on a heavy timber frame.

A small one-stamp mill, the "Katanka", was developed in Zimbabwe by the company Small Mining Supplies to be a portable crusher that can be engine-driven. The mill frame is made of flanged pipe construction rather than wooden beams. The discharge screen size is adjusted easily by changing the mesh in the discharge splash box. Typical product size is below 0.6-0.8 mm.

Fig. 3.24 – One-stamp Katanka mill made in Zimbabwe

Manual ball mill (fine grinding)

Small ball mills can be made from a simple steel shell such as a gas cylinder or steam pipe, supported on wooden trestles or forked timbers by shafts and a hand crank welded to the ends of the cylinder. In Mozambique, the port used to load and discharge the ore is held in place with rubber straps cut from tire inner tubes.

Fig. 3.25 - Small manual ball mill used in Mozambique

Fig. 3.26 – Loading steel balls into a manual ball mill

"Quimbalete", "Maray", "See-Saw" or "Rocker" crusher/mills

"Quimbaletes" or rocker mills have been used extensively in Latin America for crushing and grinding. Quimbaletes can be made of solid stone or scrap steel, and can found in many sizes: Larger rockers (approximately 300 kg, but sometimes as heavy as 2000 kg) generally accomplish coarser grinding, and smaller ones (perhaps only 50 kg) can be used wet for fine grinding. Stone quimbaletes (granite blocks) are sometimes rocked by standing from side-to-side on a wooden plank attached to the top, or by pushing on a lever arm. Steel quimbaletes are made of a sheet metal box mounted on a shallowly curved 1 cm plate, and rocked on top of a flat steel base. The box is filled with concrete or stones, and rocked by a handle attached to the end. Quimbaletes represent a significant improvement over hand-operated mortar and pestle mills which grind only about 20 kg per man/day to <0.5mm. A large quimbalete can crush 45 to 90 kg per man/hour. Depending on quimbalete design and length of milling, can grind to 100% less than 0.1 mm. Stone quimbaletes can be an affordable option where the cost of steel and welding is prohibitive.

Fig. 3.27 - Quimbalete filled with stones on steel plate *(photo M. Prieste)r*

Fig. 3.28 Granite quimbalete *(photo M. Priester)*

Fig. 3.29 – Quimbalete operated by foot *(photo A.J. Gunson)*

Basic knowledge for miners

- Rocks containing gold are crushed and ground to free or "liberate" the gold particles so that they can be concentrated and extracted
- Hardness and brittleness determine how difficult it is crush and grind the rocks.
- Crushing and grinding can be done in **separate batches**, or **continuously**
- It is best to use a "closed circuit" to grind rocks
    - Closed circuits use a screen to separate the largest particles and re-grind them with the fresh ore feed

  - The screen size in a close circuit is determined by testing the best liberation size (see chapter 2)
- Jaw crushers are used to break up ore in preparation for grinding in ball mills
- Hammer mills are relatively low-cost crushing/grinding machines that can break up ore to about 1 to 0.5mm
- Stamp mills are more costly than hammer mills; they can break up ore to about the same size as hammer mills
- Chilean mills can grind more finely (to less than 0.2 mm) than hammer or stamp mills but miners should never introduce mercury into them; the mercury flours and gold is lost
- Ball mills can accomplish the finest grinding
  - Care has to be taken not to over-grind the ore – mineral particles can become too small (forming a mud) that it is difficult to disperse the slurry and separate gold particles.
  - Small batch ball mills can be powered in series by a single engine - this is commonly done in Indonesia
  - Low cost, hand-driven small ball mills can be made from LPG containers
  - Miners sometimes introduce mercury into small ball mills - this is **bad** because the mercury is floured which leads to loss of fine gold with mercury
- Manual quimbaletes or "rocker mills" can be made cheaply from large stone boulders or steel boxes; these hand operated rocker mill can grind to less than 0.1 mm

<u>Bibliography:</u>

Chemical Engineers Handbook, 6th Edition, Chapter 8 – Size Reduction and Size Enlargement, R.H. Perry, McGraw Hill 1984

McIntosh Engineering, 2005. Crushers and rockbreakers. http://www.mcintoshengineering.com/Hard%20Rock%20Handbook/Rules%20of%20Thumb/crushers_and_rockbreakers.htm

Mississippi State University, Dept of Geosciences, 2003. http://www.msstate.edu/dept/geosciences/CT/TIG/WEBSITES/LOCAL/Summer2003/Dawson_Dara/d

Nordberg 'Red Book' Reference Manual, Second Edition, Rexnord Process Machinery Division, USA, 1983

Chapter 4
Gravity Concentration

Introduction

Gravity concentration is a process to concentrate the mineral of interest (in this case gold) using the difference of specific gravity of gold and gangue minerals. The specific gravity of gold is 19.5 and the specific gravity of quartz (the common gangue mineral associated with gold) is 2.65 (i.e., gravity concentration works because gold is heavy, and quartz is light). Often gravity separation methods are confused with size classification because large particles of light minerals can behave like a small particle of a heavy mineral. The most effective gravity separation processes occur when applied to ore particles of about the same size. The most important factor for a successful gravity separation is liberation of the gold particles from the gangue minerals. It is not easy to establish the degree of liberation of low-grade minerals such as gold. Classical microscopy of screened fractions to establish mineral liberation is unreliable with gold ores. The most recommended method to establish the optimum gold liberation size is grinding for different times (or grain size distributions) and applying gravity concentration to the ground products. This is a classical and important procedure to recommend any type of gravity concentration process. Because most artisanal miners do not classify (screen) the crushed/ground material (i.e. they work in open circuit), their chances to improve gold recovery are very limited.

The main advantages of gravity concentrators over gold cyanidation are:

- relatively simple pieces of equipment (low capital and operating costs)
- little or no reagent required
- works equally well with relatively coarse particles and fine grained materials

Calculating recovery and concentrate grade

There are two main variables of high importance in mineral processing: recovery and concentrate grade. They are always “enemies”, i.e. when you have high gold recovery, the gold grade of the concentrate is low. This is easy to understand. If you are concentrating a ore with 10 grams of gold per tonne of ore and you have a concentrate with a large weight, the recovery is likely high, but you probably the grade is close to 10 g Au/tonne…in other words you did not concentrate too much gold. In opposite, if you have almost pure gold in your concentrate you lost lots of gold in the process and the recovery might be low. Then the trick is to find a process and a condition (time, equipment, etc.)

in which the gold recovery is good and the grade of the conctrate is also acceptable.

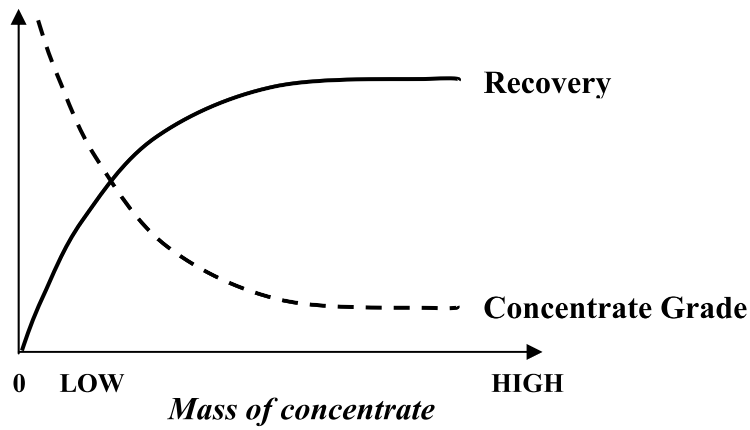

Fig. 4.1 – Gold recovery and concentrate grade

Observe Fig. 4.1 which is a hypothetical example of a gold ore. When the mass of concentrate is HIGH, the gold recovery is HIGH but the concentrate grade is LOW. Miners want high recover and a concentrate with almost pure gold.. Of course this is the ideal situation but hard to be met. Where is the best point in this curve? There is not a clear answer for this. Some miners prefer to discharge the concentrate from the sluice box or centrifuge more frequently to have high recovery but the grade of the concentrate is low and then they have to spend more time in panning and amalgamating a large amount of concentrate. Other miners prefer to run their sluice boxes for long time (e.g. 7 days) to have a very rich concentrate but their recovery is usually low.

The grade of the concentrate is determined by chemical analysis. This is not quite easy and available in many artisanal mining areas. The analysis can be done by "fire-assay" in which a sample of 30 grams of the concentrate is melted at high temperature with lead, borax and other chemicals. Other analytical procedure is the digestion of 5 to 10 grams of concentrate with "aqua regia" followed by precipitation of gold from the solution or extraction of gold with kerosene. This is followed by the use of an atomic absorption spectrometer to read the concentration of gold in the solution.

The gold recovery can be calculated when we know the total gold grade of the ore being processed (Au_t), the mass of the material being processed (M_t) and the mass of gold produced (M_p).

$$\text{Au Recovery (\%)} = \frac{M_p}{Au_t \times M_t} \times 100$$

The gold grade of the ore being processed is obtained analyzing a representative sample of the ore (pulveriuzed) by “fire-assay” or aqua-regia” process.

For example, if a miner processed 12 tonnes of ore/h for 8 hours, with a grade of 10 g Au/tonne and at the end of the day he put in his pocket (after amalgamation and retorting) a doré of 300 grams, his gold recovery was:

Au_t = 10 g Au/tonne (or ppm)
M_t = 12 tonnes/h x 8 hours = 96 tonnes
M_p = 300 g

$$\text{Au Recovery (\%)} = \frac{300}{10 \times 96} \times 100 = 31.3\ \%$$

In a Gravity operation, the best way to determined the total mass of ore being processed is collecting a sample from the tailings (in this case we consider that the mass of the concentrate is very small compared with the tailings). The following procedure is suggested:

- use a bucket and collect ALL the flow of slurry coming out of the equipment (sluice or centrifuge or table, or any other equipment)
- fill the bucket and ask somebody to take note of the time needed to fill the bucket (this is usually a few seconds…repeat 3 times to see if the time measurement is OK)
- leave the material resting for awhile
- siphon off the water avoiding taking the solids
- dry the solids and weight

Then the % of solids in the flow can also be measured:

- use the bucket and sample again the slurry coming from the sluice box; now you don’t need to collect all the flow.
- mix the pulp and transfer it to a 2 L PET Coca-Cola bottle
- divide the bottle in 10 parts
- leave the material resting and next read how much material settled down

- read the amount of material settled…this will be the approximately the % of solids in the flow.

This is an approximation since the % of solids in a pulp is the weight of solids divided by the weight of solids + weight of water. You can also have this % accurately measured if you dry and weight the solids settled in the bottle.

The % solids in a sluice box cannot be higher than 30% otherwise the flow will be too thick and the gold concentration will not be effective. The % solids must be reduced when the material has too much clay.

Sluices

Sluices are inclined, flat-bottomed troughs that are lined on the bottom with a trapping mechanism that can capture particles of gold and other heavy minerals. They can be used either for alluvial or for primary ore (sluices are sometimes called "strakes" or "blanket tables"). Ore is mixed with water and the pulp poured down the trough. Sluice designs have utilized readily available materials for thousands of years, such as animal furs as trapping mechanisms--in the ancient Greek myths, the Argonaut hero Jason recovered the "golden fleece", a sheepskin sluice lining, by killing the dragon that guarded it.

Sluices work on the principal that heavy particles tend to sink to the bottom of a stream of flowing water while the lighter particles tend to be carried downstream and discharged off the end of the sluice. Sluices are used in various sizes, from small hand-fed sluices to large sluices found on dredges or fed by trucks, front-end loaders or bulldozers, which can process as much as $150 m^3$ of alluvial ore per hour. Much like in the past, today's hand-fed sluices are usually 1 to 2 meters long, 30 to 50 cm wide, with walls 10 to 30 cm high. Sluices are usually inclined at a 5 to 15 degree angle. Many miners working alluvial deposits today use large sluices when sufficient water and operating capital is available. In monitor-gravel pump systems, slurry is pumped through 7.5-15 cm hoses onto 1-1.5 m wide by roughly 5 meter long sluices, such as those used in Guyana, Indonesia and Brazil.

Used correctly, sluices are efficient devices to separate gold from gangue. While sluices are not necessarily more efficient than panning, they do allow miners to increase the amount of ore they process, thus boosting their income considerably. Unfortunately, the resulting increase in the volume of ore processed can put large amounts of silt into streams, damaging regional water supplies and thus harming people, animals and aquatic life. Sluices can cause other environmental problems as well--those lined with mercury coated copper plates are especially destructive because the slurry solids scratch the mercury from the copper plate and carry it downstream, poisoning fish and people.

Fig. 4.2 - Hand fed sluice in South Africa

Fig. 4.3 - Monitor pump fed sluice in Indonesia. Note the turbulent flow which limits recovery of fine gold

Good sluice design

Even though sluices have been used throughout the world for thousands of years, they are often not designed or operated correctly. Limited knowledge of the basic operating principles, lack of capital and access to more efficient modern lining carpets greatly reduces gold recovery, especially recovery of fine gold.

Particles suspended in a slurry stream settle when the intensity of the turbulence cannot support them. A well-designed sluice insures that the maximum amount gold can settle near the bottom of the slurry stream where it can be caught by trapping mechanisms such as carpets or riffles. Trapping mechanisms shelter gold particles from being lifted back into the current by turbulent forces, holding the gold from being washed off the end of the sluice.

Gravity causes gold to settle in water faster than silica and other gangue minerals. The rate of settling depends on particle density, size and shape: Large, dense, spherical grains settle quickly, whereas small, less dense and flatter particles settle much more slowly. Coarser grained low-density particles can settle at the same rates as finer high-density particles. In sluices where turbulence is low, the difference in settling rate between heavy and light particles tends to separate the slurry into loosely stratified zones. As the slurry stream flows down a sluice, the densest and largest particles accumulate in a zone close to the bottom where they can become trapped within the lining carpet's pile or weave and sheltered from the current, while the smaller, lighter particles tend to stay in suspension near the top of the stream and be carried off the end of the sluice.

The rate of flow influences how gold and gangue particles in the feed stream settle to the bottom of the sluice, and how they become re-suspended. Flow velocities are controlled by the amount of feed pulp, and by the sluice box's inclination, width, and length. At low flow velocities, the densest and largest particles settle to the bottom, while the less dense and smaller particles remain suspended in the feed stream. On the bottom of the sluice, sediments in the surface layer move slowly down the sluice by rolling and sliding. Increased flow velocities can cause these sediments to be lifted and suspended or bounced downstream: High flow velocities cause turbulent currents that, if strong enough, can fully re-suspend the bottom bed load and carry it all downstream.

For efficient operation, the slurry flow velocity must be adjusted fit both the range of gold particle sizes in the feed, as well as the trapping mechanism used. Flow should be fast enough to insure that the trapping spaces created by the riffles or carpet liner are not filled and blocked with gangue (i.e., the carpet must be kept from "sanding up"), yet slow enough to allow as much fine gold as possible to settle to the bottom where it can be trapped.

Increasing the angle of the sluice causes the flow velocity to increase; increasing the slurry depth by narrowing the width (or by increasing the input) also causes the flow velocity to increase; lengthening the sluice also increases the flow velocity as the slurry moves down the sluice because the fluid accelerates with distance. For a given feed rate and sluice width, the optimum flow velocity is empirically determined by incrementally increasing the angle of inclination until the trapping mechanism is clear of silica and other light gangue minerals (or the other way round, reducing the angle of inclination until the sluice starts sanding out, and increasing it again slightly).

The flow rate should be constant. The highly variable, discontinuous feed rates in hand-fed sluices are not efficient because the bottom carpet quickly becomes clogged with gangue, blocking the trapping spaces. In hand-fed sluices, water is poured onto the sluice one bucket at a time, but even at the peak-flow of each bucket pour, the velocity is usually too low to lift much of the

Fig. 4.4 - Stream contaminated with silt in Mozambique

gangue and keep the trapping mechanism open. Even though some gold particles can become entrained within the surface sediments as they roll and slide down the sluice, the trapping efficiency of these surface sediments is much lower than that of a carpet with exposed fibers. Continuous gravity flow from a diesel barrel filled with water is better than pouring one bucket of water at a time into hand-fed sluices.

Gold ores typically contain a mixture of coarse and fine-grained gold particles. Because fine gold settles much more slowly than course gold, it is often best to use multiple stage sluices—capture the coarse gold using riffles, coarse expanded metal or/and vinyl loop carpets in a relatively steeply inclined first stage (faster flow velocity); then screen the coarse material off by using an inclined grizzly screen at the end of the first sluice, and feed the passing fine material (plus the water) onto a more shallow angled, perhaps wider sluice, where the remaining fine gold is recovered on a more tightly woven or pile carpet. This second sluice can be oriented either perpendicular to, or underneath the first sluice in a zigzag configuration. Differently angled zigzag sluices allow variable flow velocities, while reducing acceleration of the slurry stream by shortening the length of the bed. The feed box for zigzag sluices usually has to be higher than straight sluices, so they work best when the feed can be pumped to the sluice, and when the discharge can be in the opposite direction as the feed. Zigzag sluices are used often in large alluvial mining operations.

Fig. 4.5 - Feed box for hand fed sluice: mixing ore with water

The American company Keene Engineering offers a large variety of riffled sluice boxes made of aluminum with rubber ribbed matting and vinyl carpets. The A52 Keene 10”x 51” (25 x 129 cm) may be an interesting alternative to demonstrate to ASM. The cost in the USA of this sluice is around US$ 100. This small portable sluice (weighing 5kg) has the

Fig. 4.7 – Ground ore from a Chilean pan feeding alternating sluice boxes with carpet (Ecuador)

capacity of processing up to 5 tonnes/h of ore. Keene sluices were very popular in Africa some years ago. A copy of the Keene sluice was widely promoted in Zimbabwe as the Bambazonke. The company also provides pumps (8 to 20 centimeters) and a large variety of accessories.

Fig. 4.6 - Clogged trapping mechanism (blanket) of hand-fed sluice

Feed preparation

The ore should first be screened so that the particle size is as uniform as possible and the coarse barren material is eliminated. Under ideal conditions, the feed should not be coarser than the largest possible gold particle. Large rocks on the sluice create eddies and turbulence that keeps the fine gold in suspension; the high flow velocities required to move rocks off the sluice also leads to loss of gold. In alluvial sluices, a “grizzly” (inclined parallel bars spaced about 1-2.5 cm apart) can be used to screen the feed and make sure larger rocks are kept out of the sluice. Grizzlies also remove clumps of clay that can roll down the sluice bed, sticking to gold particles and carrying them into the tailings.

Do not over-grind primary ore. Grinding too much can make smaller and flatter gold grains that tend to stay in suspension and ultimately be washed off the end of the sluice. Gold particles are very difficult to be concentrated when the material is a slurry of fine-grinding minerals. The same happens when the ore is rich in clayminerals. This forms a muddy-viscous pulp that must be adequately dispersed with caustic soda or dispersants to create conditions for gold to be concentrated by gravity processes. The more fine particles in the ore, the less % of solids must be used in the concentration process.

The ideal feed contains between 5 to 15% solids. A high percentage of solids makes the slurry too viscous - dense particles are buoyed upwards by less dense particles, limiting the ability to the slurry to stratify according to density. If very little water is available, and the gold is not too fine, coarse gangue particles can carefully be raked out of the sluice.

Fig. 4.8 - Pump-fed zigzag sluice in Suriname

Fig. 4.9 - Cleaning up Hessian carpets using a series of buckets

Sluice design and construction

Miners should design sluices to accommodate the anticipated feed rate by adjusting the width (increasing width decreases depth and flow velocity). Note that adjusting the width strongly influences the flow velocity - width is considered by some researchers to be the best control of flow velocity. Flow rates can be fine-tuned by adjusting the slope. When possible, miners should design sluice features (e.g., angle, width, etc.) so that they can be changed to insure optimum recovery. Wide sluices need to have carefully designed feed boxes to insure even slurry distribution over the whole width of the sluice.

Flow accelerates with distance, making it harder for the trapping mechanism to capture small gold particles. Research has shown that 90% of gold is recovered in the first 1/3rd of the sluice, 9% in the 2nd 1/3rd, and only 1% in the last 1/3rd. Most gold is caught in the first 0.5 meter of the sluice, so keep the sluice length short (less than 2 m for hand-fed sluices). Zigzag configurations break flow velocity and help to increase recovery; three 2m zigzag sluices are usually better than one single 6m sluice.

The optimal slope is usually between 10 and 15 degrees, but can be as low as 5 degrees for fine grained primary feed. In Ecuador, miners use a 5-8 degree cement sluice box lined with carpets. They discharge the concentrate in the carpet every hour. As the sluice is not steep and the discharge is very frequent, they have a good gold recovery (>50%) but low grade in the concentrate. The mass of material to be amalgamated is large and then they have to reduce the mass panning.

Use multiple stage sluices to capture coarse and fine gold in different passes. Capture the coarse gold first, then the fine gold. The turbulence from faster flows needed to capture coarse gold in riffles can be calmed by placing a short smooth section (a "slick plate") before the next stage.

Clean-up time is a critical activity. Trapping mechanisms should be easily removable and cleaned. Complex assemblies reduce the likelihood of cleaning. Trapping efficiency can be monitored by checking sluice tailings constantly by panning. Clean-up time can be as often as once an hour to prevent blocking of the carpet, especially for primary ore with high sulfide content. To enable continuous operation, parallel sluices should be installed (one sluice in operation, one in cleanup and preparation). To improve recovery and prevent theft, the top sections of alluvial sluices should be washed at least once per day.

Secondary sluices can be used to re-concentrate the concentrate recovered by the primary sluice, therefore reducing the mass of material to be amalgamated. Secondary sluice tailings should be recycled to the primary sluice.

Trapping mechanisms

Bed linings should be firmly fixed to the bottom of the sluice, especially when not backed, to prevent captured gold from migrating down the sluice underneath the lining and being lost off the end of the sluice.

Riffles

a) Cross riffles made from railroad rails, angle iron, wood or split bamboo are often used to trap gold particles >1mm. The simplest riffles are stones, but these can cause turbulence likely to cause gold loss. Carpet and/or expanded metal should be used underneath the riffles.

b) Rudimentary riffles do not necessarily improve recovery--turbulence can break up stratification, and cause the loss of fine gold. While catching some of the coarse gold, riffles often only leave the impression that recoveries have improved.

c) Riffles protect the carpet lining from wear and keep it firmly on the bed of the sluice.

d) Ore with a range of coarse particle sizes may need to utilize several kinds of riffles (e.g., large and small expanded metal riffles).

e) Select riffle size and spacing, then select the flow rate that keeps the sheltering spaces behind the riffles clear of sand.

f) 25 mm angle iron riffles are commonly used with 4.0-6.5 cm gaps, canted uphill at about 15 degrees. There should be very little sand between the riffles. If there is too much sand, the flow is either too slow, or the riffles are too high.

g) Expanded metal grating (see picture, below) forms shallow riffles which cause a local turbulence that keeps the sand moving downstream while providing effective shelter for gold grains less than 0.1 mm. Wider sluices need a heaver gauge metal to hold the liner flat.

h) When the ore contains some magnetite, Cleangold® (see below) sluices can form a magnetite bed that can trap fine gold.

Fig. 4.10 – Expanded metal and cross riffles in a Keene sluice

Carpets

a) Type of carpet lining is usually determined by what is available.

b) Fibrous or hairy fabrics like sacking, sisal, blankets, or old carpets have hairs that can trap fine gold particles and prevent them from being lifted back up into the current by turbulence. Animal hides are usually not a good option, because they tend to fowl.

c) In general, the best carpets have open fibrous structures that let gold particles settle deeply in the lining.

d) If rubber backed carpets are not available, use a tighter weave cloth backing underneath the carpet to prevent loss of gold.

e) Wash carpets in a series of buckets, in barrels cut lengthwise into troughs, or in tubs.

It is important to demonstrate different types of sisal fabrics and carpets. The best carpet used in ASM operations is the 3M Nomad Dirt Scraper Matting, especially the type 6050 (medium traffic with backing) which consists of a coiled vinyl structure; type 8100 (an un-backed version) can also be used. Nomad is usually recommended for relatively coarse gold, but can also trap fine gold efficiently. The price of Nomad carpets in ASM sites can reach up to US$ 150/m²; alternately, a Nomad type vinyl loop carpet is available from manufacturers in China for a fraction of this price. The Brazilian company Sommer (subsidiary of the German company Tarkett Sommer) sells 2 types of carpets widely used by Brazilian ASM: "Multiouro Tariscado" (which is good for gold of medium sized rice grains) and "Multiouro Liso" (which is good for -0.15 mm gold). These carpets can cost around US$ 10 to 15/m². None of these carpets are easily accessible to ASM in Africa. Sisal fabrics however, can cost as little as US$ 3/m², and are available in most African countries; depending on the type, they can be used for coarse, medium and fine gold recovery. It is a matter of trying different types. Raffia mats have been used in Zimbabwe for fine gold concentration. This definitely must be further investigated and collaborative tests can be done with the miners to establish the ideal type of sisal cloth.

Another interesting sluice liner is the one manufactured by **Cleangold®,** a company based in Lincoln City, Oregon. The Cleangold® sluice uses polymeric magnetic sheets similar to the material used to make magnetic advertisements, with the magnetic poles aligned perpendicular to the direction of the slurry flow, glued to the bottom of a simple aluminum sluice box.

Magnetite, a mineral commonly found in gold-ore deposits, is held by the magnetic sheeting, and forms a fine-grained corduroy-like trapping mechanism on the sluice floor. These inserts can be available in any size, but they are relatively expensive. For example, Cleangold® can manufacture a 60 x 50 cm insert for around US$ 165 (in USA). Gold becomes trapped in a magnetite layer which can be easily scrapped and washed into a pan. A high grade of gold concentrate is obtained. In many cases the use of mercury to amalgamate the concentrate is not necessary. In one test comparing the Cleangold® sluice with a centrifugal concentrator, the sluice obtained slightly better gold recoveries than the centrifuge. In a recent field test in Venezuela conducted by UNIDO, tailings from hammer mills and Cu-amalgamating plates were passed without regrinding through a 60 cm long Cleangold® sluice box. About 11% of gold in the tailings was recovered and the concentrate analyzed 2850 ppm Au. The Cleangold sluice can also take advantage of the fine pieces of steel released from hammer and ball mills. They are also concentrated on the magnetic sluice and play the role of magnetite.

MINTEK (South Africa) has devised interesting sluice boxes (strakes) with rubber mat glued to it. Black ribbed vinyl mats are also useful to recover gold; they are easy to clean and cost in USA about US $15/m².

Fig. 4.11 – Cleangold magnetic sluice

Optimal slurry flow velocity

Different trapping mechanisms require different flow velocities. Adjust the width and/or slope to control flow velocity to optimize the performance of the various riffles and carpets used. Coarse gold recovery needs faster flow velocity (narrower and/or steeper sections); finer gold recovery requires slower speeds (broader and/or less steep sections).
Keep feed rate and pulp density constant. Increasing the flow can increase turbulence and make it more difficult for gold particles, especially the fine gold grains which tend to stay in suspension, to contact and be trapped at the bottom of the sluice. Slowing or stopping the flow fills the trapping mechanism with gangue. Avoid turbulent flow, especially when trying to capture fine gold. Higher flow velocities can be necessary to keep the gangue from clogging riffles and carpets, but high speed tends to push fine gold off the end of the sluice. Lower flow velocities can yield higher recovery (fine gold is recovered in addition to the coarse gold), but if too slow, can lead to clogging of the trapping mechanism.

Distribute the flow evenly over the sluice bottom by making sure the sluice bottom is flat—avoid twisting and sagging.

When water supply is short, use narrower sluices to insure adequate flow velocity to keep trapping mechanism clear.

Assess the efficiency of recovery by panning the tailings, or by passing them over a short test-sluice.

Centrifugal concentrators

Centrifugal concentrators were originally developed to improve gold recovery from alluvial sands. Since about 1990, they have been used increasingly for hard rock mines, which is now the largest area of application. Centrifugal concentrators consist of a vertical rotation bowl with a series of concentric rings that trap the gold. A centrifugal force is applied on the ore particles, in such a way that this force is 60 (in the case of Knelson) to 300 (in the case of Falcon) times higher than the gravitational force. The rotor is accelerated and feed slurry is introduced to the concentrating cone through a stationary feed tube. Upon reaching the deflector pad at the bottom of the cone, the slurry is driven outward to the cone wall by the centrifugal acceleration. As slurry flows up the cone wall, the solids fill each ring to capacity creating the concentrating bed. The tailings product overflows the bowl and the gold becomes trapped in the rings. Some centrifuges have a smooth wall at the bottom of the bowl where stratification takes place. The high density gold is concentrated at the wall forcing and displacing lower density particles away from the wall. Compaction of the bed in the rings can be prevented by introducing pressurized fluidization water from behind the rings. This helps the high-density gold particles displace the lower density gangue particles causing the gold grade to increase in the concentrating rings with time. After a period of time, the feed is stopped and the rotor is shut off. The concentrate is flushed from the cone into the concentrate launder and can be upgraded further by panning.

The two main manufacturers of centrifugal concentrators are: Knelson and Falcon, both from British Columbia, Canada. Both concentrators have a ribbed rotating cone into which the pulp of 20 to 40% solids is fed and the concentrate is accumulated in the riffles. Compaction of the concentrate layer is avoided by injection of water in counter flow. This water fluidizes the concentrate bed and allows fine gold particles to penetrate into the concentrate layer. The main problems of these centrifuges in ASM operations are:

- high cost
- lack of skilled operators
- lack of clean water and controlled pressure for counter flow

Fig. 4.12 – Centrifuges operating in Brazil

For hard rock deposits, the ore must be ground before feeding to the centrifuge. The feed should also be screened to below about 1 mm to remove coarse material, which can be ground further and fed back to the separator. These centrifuges recover between 15% and 60% of the gold, depending on the mineralogy of the ore. In large scale mines the tailings are usually processed by cyanide leaching.

There are many models of centrifugal concentrators with capacity up to 100 tonnes of ore/h. For a small-scale production, a centrifuge with 1-2 tonnes/h capacity is more than enough. This uses a motor with 1.5 hp and 80-140 liters/min of water.

Many other types of centrifuge are available in artisanal mining sites. In Brazil there are at least 4 manufacturers of cheap centrifuges. The bowls of these machines are not made of polyethylene like the ones of Knelson concentrator but of carbon steel. In Poconé, Brazil, these cheap centrifuges work for 8 hours with nominal capacity of 24 tonnes/h resulting in a concentration ratio of 1000 to 1 or higher. It is common to observe concentrates with more than 1000 g/t of gold. The volume of concentrates is fixed, limited by the volume of the riffles so the weight of the concentrate recovered each cycle is almost constant.
The "ABJ Bowl," in effect is a copy of the Knudsen concentrator out of California, is extensively used in Zimbabwe. The conic centrifuge does not have counter-flow water. The centrifuge has 3 vertical pieces of steel that promotes turbulence of the slurry flowing up the riffles on the bowl, facilitating the ability of the gold to replace other less dense minerals trapped in the riffles. When the concentrate bed in the riffles is thus "scratched," sites on the bed are opened for gold concentration. About 30 to 33 kg of concentrate are obtained during a given run. The main specifications of the ABJ centrifuge used by artisanal miners in Zimbabwe are:

- Diameter of the bowl: ∅0.78 m
- Operation: unfluidized centrifuge, ribbed cone
- Cone Material: butyl rubber
- Operating Speed: 102 rpm
- Feed Capacity: up to 3 tonnes/h in slurry at 30% solids
- Feed Size: -4mm max
- Shipping Weight: 130kg
- Extent of Mechanization: partially mechanized; batch discharge of concentrates
- Mode of Operation: batch
- Discharge: from bottom
- Drive Bevel gear and V-Belt
- Installed Power: 0.7 kW
- Price: about US$ 2000

Fig. 4.13 – ABJ centrifuge operating in Zimbabwe

Fig. 4.14 – Rubber cone with ribs (ABJ centrifuge)

The company Small Mining Supplies from Zimbabwe recently introduced a new centrifuge called GoldKacha Concentrator. The specifications of this centrifuge are:

- High capacity – 3-4 tonnes/hour
- Feed size -3mm
- No fluidization water
- No drive belts
- Replaceable polyurethane cone
- Slurry distributor
- Low power requirement: 0.5 kW
- Weight 108 kg
- Cost approximately $US 2200, but variable depending on currency fluctuations

Fig. 4.15 -- Small Mining Supplies (Harare) new centrifuge, the “GoldKacha”

One of the main problems observed in Zimbabwe ASM operations is the use of mercury in the ABJ concentrators. Mercury flours in the process, and it is lost to the tailings together with fine gold. Very little has been done to change this bad practice.

Panning

Panning is the most ancient form of gravity concentration. Pictures of gold pans appear on Egyptian monuments as old as 2900 BC. The circular or back-and-forth shaking of ore and water in a pan causes the ore to stratify--the heavy minerals settle to the bottom of the pan while the lighter gangue can be washed off the top.

Panning is the basic means of recovering gold from alluvial and high-grade primary ore. In Zimbabwe, for example, miners rarely use the stamp milling plants for their high-grade reef ores. They rely on pounding this ore with mortar and pestle and use pans for concentration. They later wash these panning concentrates through a clay/sand sluice lined with blanket or rubber matting. Assays of these tailings are always high, suggesting that either gold liberation is poor, or panning efficiency is low. Primary crushing uses a 4-pound hammer to produce affordable sizes for grinding in a mortar using a steel bar pestle. The ground up material is then classified through a sieve to collect the fine undersize material. In most cases in Zimbabwe, the coarser oversize is thrown away and not reground for better liberation. All the undersize is then panned and the gold recovered. A magnet can be used to remove the black magnetite. The magnet is applied to the bottom side of the pan and moved in a circular motion with the pan slightly tilted. Thos rich gold concentrate does not need amalgamation, as it can be smelted directly.

Different kinds of gold pans

While artisanal miners are usually expert panners and are able to achieve incredible results, even with the most rudimentary pans, they are sometimes unaware of the advantages of the range of shapes used by their fellow miners around the world.

Panners commonly use gourds, kitchen bowls or cooking pans to pan for gold. They also use specially designed gold pans made of wood, metal and plastic. Gold pans are usually round, but can sometimes be rectangular, as in Vietnam. Wooden pans have the advantage of having a slightly rough surface than can hold the gold a bit, but steel pans can be roughened by rusting with acid (or lemon juice), and new plastic pans can be given a “tooth” by rubbing with sand. Wooden pans also have the advantage of buoyancy, making it easier to support a pan full of ore in water. Pans can be cut from steel sheeting and riveted, or pounded into shape from steel oil or cyanide drum tops using auto-body repair techniques. Steel and aluminum pans are sometimes mass-produced by metal “spinning” processes. Cast aluminum pans are also available in some places.

In North America, flat bottom pans have been used for over 150 years to capture coarse gold. Typically these types of pans are made of steel, with sides about 35 degrees from horizontal. Today these pans are also formed of plastic and have 2 or 3 small riffle-like ridges circling the sides.

Fig. 4.16 - Miners can capture fine gold even in a very worn out pans (Tanzania)

Fig. 4.17 - Aluminum kitchen bowl used as a gold pan (Sudan)

Fig. 4.18 - Using a gourd ("calabace") as a gold pan (Guinea)

Fig. 4.19 - Wooden bateas (Lao PDR)

Fig. 4.20 - Riveted shallow batea made of sheet metal (Brazil)

Fig. 4.21 - North American plastic pan with riffles in the side (Mozambique)

Fig. 4.22 - Using a steel batea (Brazil)

Fig. 4.22 - Small rubber coated cone-shaped batea for testing ore (Peru)

Fig. 4.24 - Steep-walled plastic kitchen bowl (Mozambique)

Fig. 4.25 - Hand carved wooden bowl and gourds (Sudan)

In Brazil, Indonesia and elsewhere, 150 to 155° conical "bateas" capture coarse gold relatively quickly, and are also good to capture fine gold. In Peru, miners use small 15 cm diameter bateas coated with rubber to evaluate recovery by testing sluice tailings. In Africa, miners often use steep-walled plastic pans, but these are less efficient than bateas. Sudanese panners use hand-carve ellipsoidal wooden bowls and gourds.

Fig. 4.26 – Child in Lao PDR panning gold with a wooden batea

Basic knowledge for miners

- Gold pans, sluices and centrifuges are all methods of "gravity concentration"
- Gravity concentration works because gold settles faster than other minerals (e.g., sand) in water
- Gravity concentration works best when the particles in the feed are close to the same size—screen the ore before concentrating, and re-grind the oversize
- Using mercury in sluices and centrifuges does not improve recovery—indeed, gold is often lost along with the mercury. These practices release much mercury to the environment and should be banned in all countries.
- Panning
    - Panning is an efficient and very low cost method of gravity concentration—unfortunately, miners can only process small amounts of ore in a day.
    - There are many shapes and sizes of gold pans that are used by miners in the world

- Sluices
    - Sluices are as efficient as panning, but a miner can process much more ore per day with a sluice
    - Sluices work best when the water/slurry is fed at a constant rate
        - Use an old diesel drum to feed the water at a constant rate
    - Miners should experiment with different kinds of carpets and riffles
    - Control the slurry flow velocity by adjusting the slope angle to be just steeper than the angle where the sand clogs the carpet
        - Keep the sand out of the spaces in the carpet fibers in order to trap the gold
    - Adjust the sluice width and slurry depth to fit the feed rate, kind of ore and grain size, the slurry density and trapping mechanism (e.g., about 1 cm depth is good for one meter wide Nomad carpet sluices at stamp mills grinding quartz ore in Zimbabwe)
    - Most gold is captured in the first 1/3rd of the sluice
    - Use short sections of sluice (consider using a zigzag configuration if possible) to limit acceleration of slurry
        - If the slurry flowing over a sluice is deep, the pulp can speed up too much and lead to loss of gold; shallow slurry (e.g., 1 cm deep on a Nomad carpet) does not accelerate as much as deep slurry
    - Use different trapping mechanisms and/or slope angles to capture coarse and fine gold
    - Copper amalgamation plates are a form of sluice that should be banned in all countries
- Centrifuges
    - Centrifuges (e.g. Knudsen type-ABJ, GoldKacha) can be simple and relatively inexpensive; these centrifuges recover about the same amount of gold as a copper amalgamating plate
    - More sophisticated centrifuges (Knelson and Falcon) are more expensive and require a clean constant water supply to operate, however these centrifuges can recover more gold than other forms of gravity concentration equipment
    - Putting mercury in centrifuges leads to the loss of fine gold with the floured mercury

Chapter 5
Gold Amalgamation

Mercury, a brief history

Mercury has been used for more than 3500 years. Samples of mercury were discovered in ancient Egyptian tombs that date to 1500 or 1600 BC. The Romans used elemental Hg as an amalgam to separate gold from other materials and as an amalgam to coat gold onto copper.

The chemical symbol of mercury, Hg, comes from the Greek name "Hydrargyrum" (liquid silver), and the name Mercury was given by medieval alchemists after the fleet-footed Greek god. In 1533, Paracelsus wrote a book about occupational diseases in which he described Hg poisoning of miners in detail. Although Paracelsus was intrigued with Hg, he considered it a metal that was deficient in its coagulation ability. He believed that all metals were liquid Hg up to the midpoint of the coagulation process. Consequently, he expended much unsuccessful effort trying to coagulate metallic mercury to convert it into gold.

Historically, inorganic Hg compounds have been used extensively as an antiseptic, disinfectant, purgative, and counterirritant in human and veterinary medicine. Various Hg compounds were developed to aid in the control of bacteria, fungi and other pests. Paracelsus introduced probably the most unusual medicinal use for Hg. He dissolved Hg in oil of vitriol (sulphuric acid) and distilled the mixture with Spiritus vini (alcohol) as a cure for syphilis. This use of Hg persisted until the 1930s. Many of these applications have been gradually replaced by other compounds.

The extraction of gold by amalgamation was widespread until the end of the first millennium. In the Americas, mercury was introduced in the 16^{th} century to amalgamate Mexican gold and silver. The Spanish authorities encouraged mercury ore prospecting in order to supply the Californian mines. In 1849, during the American gold rush, small mercury deposits were exploited. At this time, mercury was widely used by American miners in their pans. The amalgamation process was widely used by Canadian miners from the 1860s until the1890s as observed in the reports of the Minister of Mines. Mercury was used in sluice boxes or in copper plates. Archives from British Columbia, Canada, report the use of 11 kg of Hg/day/sluice by miners in the Cariboo goldfields. Currently, amalgamation practices in North America are restricted to small operations, but the mercury contamination left by the gold rushes is still noticeable. For example, between 1860-1895: 6,350 tonnes of mercury were lost in the Carson River, Nevada, USA. More than 12,000 tonnes of mercury were lost by the gold miners to the water streams in California and Nevada, USA. A serious disease called "mercurialism" (intoxication by mercury vapor) was a common illness among the cinnabar (mercury sulfide ore) miners and gold panners in North America.

Mercury uses and properties

In nature, mercury forms many minerals, but the most common is called "cinnabar" (HgS) which has been mined in Spain, Kyrgyzstan, Algeria and China to produce metallic mercury for batteries, chlorine factories, fluorescent lamps, electric switches, dental amalgams, etc.. Currently, countries such as Finland, Peru, USA, Russia, Canada, Chile, etc. produce mercury as a by-product from other types of mines (e.g. gold, copper and silver). Mercury is also recycled from electric switches, batteries and lamps and re-sold to the market. The annual world mercury production by mines and recycling is between 3000 and 4000 tonnes.

Annual use of Hg in products in 2004 was comprised mostly of dental amalgams (270 t), electrical switches and relays (150 t), measuring/control equipment (160 t), energy-efficient lighting (110 t), and disposable batteries (estimated at 600 t). Mercury is also still used in chlor-alkali (chlorine and caustic soda) production (possibly 700 t in 2004, but declining every year) and as a catalyst for the production of plastics, especially in China, India, and Russia (as high as 600 t) (see Swain et al, 2006 paper).

Artisanal gold miners consume something between 800 and 1000 tonnes of metallic mercury annually. The majority of this mercury is lost to the environment. Most mercury used by artisanal miners comes from developed countries and enter the developing countries to be used in electronic or chemical industries or by dentists. The artisanal miners usually acquire mercury from legal sources such as dental-material suppliers, but they use mercury in a careless way contaminating themselves, families, neighbors and the environment. Despite the huge use of mercury to extract gold in the past, in many countries mercury is no longer allowed to be used in gold mining.

Metallic mercury is a heavy metal with specific gravity of 13.5, is liquid at ambient temperature, and has its boiling point at 357 °C (i.e. above this temperature it becomes vapor). Metallic mercury has a low vapor pressure which means that even at ambient temperature, mercury also evaporates. Mercury vapors are very toxic, so it is important to cover mercury with a centimeter of water inside closed containers (the water prevents the mercury from evaporating).

Amalgam formation is thought by some authors to be a formation of alloys between mercury and metals. Others believe that amalgamation may be an adhesion process or an interpenetration of the two elements. Mercury forms amalgams with all metals except iron and platinum. Gold, in particular, can combine with mercury forming a wide range of compounds. The three main amalgams are: $AuHg_2$, Au_2Hg and Au_3Hg. The amount of mercury in the amalgams formed by the artisanal gold miners depends on how strongly the miners squeeze off the excess mercury using a piece of canvas. Usually manually squeezed amalgam contains 60 to 70% gold. When the amalgam is filtered with a centrifuge, it can contain up to 80% gold.

Forming gold amalgam

Amalgamation is efficient for liberated or partially liberated gold, and for particles coarser than 200 mesh (0.074 mm). Coarse nuggets do not need to be amalgamated as they are visible and miners usually collect them manually in order to sell at a higher price than for amalgamated gold. There are many methods to amalgamate gold. Typical amalgamation methods used by artisanal miners are listed as follows:

- Whole ore amalgamation in a *continuous process*: Hg is mixed with the whole ore in pump boxes, is introduced in sluices during gravity concentration, is added to the grinding circuit, or the whole ore is amalgamated using copper plates.
- Amalgamation of gravity concentrates only in a *discontinuous process*: mercury is mixed with concentrates in blenders, pans or drums; separation of amalgam from heavy minerals is necessary.

WHOLE ORE AMALGAMATION IN A CONTINUOUS PROCESS is a bad practice. Feed flows continuously from the grinding circuit into the amalgamation equipment where the contact of the ore with a bed or bath of mercury takes place. Continuous methods do not use amalgam-ore separation after amalgamation. Some miners use reagents (such as cyanide) into the amalgamation system to clean gold surfaces and to reduce the “flouring effect” where mercury loses its coalescence (i.e., its capacity to hold together) and forms lots of minuscule droplets. Unfortunately both mercury and gold are lost in solution by the action of strong reagents. Continuous amalgamation causes high environmental pollution, high contamination of the miners and significant mercury and gold losses. Amalgamation processes which should be prohibited and which are still used by artisanal miners in various countries include:

AMALGAMATION IN GRINDING MILLS is an insane process that mixes all of the ore to be ground with mercury in ball or rod mills. This leads to considerable loss of gold, and to extreme loss of mercury. For example, miners in North Sulawesi, Indonesia, introduce mercury into ball mills to grind the ore but they recover only 50% to 60% of the mercury. Lots of droplets of mercury adhere to the gangue and are carried away into the tailings. Some of these minuscule droplets of mercury also carry gold to the tailings. The mercury losses in these cases are huge.

COPPER PLATES are stationary copper sheets covered with mercury, inclined at about 15-20° slope (copper plates are a form of sluice where mercury is used as the trapping mechanism instead of riffles or carpets). The amalgamation takes place when the gold particles in the 10 to 20% ore pulp contacts the mercury coated plate surface. The velocity of flow has to be sufficiently low so that the precious metal particles gold can sink to the plate surface and yet high enough that other mineral constituents of the concentrate do not remain on the plate. The efficiency of the process depends on the operator's ability, but usually is low due to the short time of ore-mercury contact because the plates are usually only 0.8 m to 1.5 meters in length. Abrasion of the pulp of ore with the copper-mercury surface releases mercury droplets which are carried away with the tailings. Amalgam is removed by scraping, periodically interrupting the process. When scrapping the surface of the copper-mercury plates, miners are exposed to high levels of mercury vapor and become contaminated. In Zimbabwe, miners loose even more mercury to the tailings when they scrub the plate with sand after scraping the amalgam in an effort to clean the plate and get any residual gold. Gold is also lost when the pulp is too thick or when the copper-mercury amalgam on the surface of the plates becomes oxidized (forms yellow spots). Some miners use sodium cyanide to remove the oxidation spots. They do not have any idea how dangerous is to handle cyanide in a pH close to neutral. This can form HCN (a gas) which is fatal in low doses.

AMALGAMATING POTS follow the same principle as plates but the ore pulp sinks in a bath of mercury. Gold is retained in the mercury and the mineral portion floats to be discharged. The mercury bath can also be continuously pumped out from the system to be filtered (400 mesh = 0.044 mm screen) where the amalgam is collected.

MULLER PAN consists of three heavy concrete or steel wheels that rotate in a strong circular trough filled with mercury. The ore is ground and the amalgamation occurs at the same time. Unfortunately, mercury pulverizes (flouring effect) and it is lost. This process is popular in South America and China. The pollution caused by this process is well reported.

MERCURY in SLUICES is a very inefficient method still used by some artisanal gold miners--sluice boxes built with riffles are loaded with mercury. When the pulp with gold flows through the sluice, the riffles trap the gold and the amalgam is formed simultaneously. This is a very inefficient and polluting process. The contact time is very short and large portions of mercury are lost. Some miners believe that gold recovery can be improved by using Hg in the riffles. This is NOT TRUE. Tailings from sluices boxes operating with mercury are very rich in gold as well as mercury. Sluice boxes are excellent for gold concentration but should not be used to amalgamate gold.

A better approach is to AMALGAMATE CONCENTRATES in a DISCONTINUOUS PROCESS. Batches of gold-rich gravity concentrates are amalgamated, and the amalgam is subsequently separated from the excess mercury. **Because only relatively small amounts of concentrates are amalgamated, this is much more efficient and safer than continuous processes**. This kind of discontinuous process can recover over 90% of the gold as observed in many operations. The amalgamation time should not be too short (e.g., 15 minutes) or two long (e.g., 2 hours). Long mixing of the mercury with the concentrate increases the possibility of the "flouring effect". Batch or discontinuous amalgamation can be very efficient and can minimize mercury losses when properly done. Mercury losses of less than 0.5% are not difficult to achieve.

Fig. 5.1 – Miner discharging an amalgamation drum on a sluice box

The most common discontinuous amalgamation process uses an AMALGAMATION DRUM. This consists of a small (20-kg) steel or plastic drum that receives batches of gravity concentrate and mercury: a ratio of 1 part of Hg to 100 parts of concentrate has proven effective. The amount of water in the drum should not be excessive--about 50% water and 50% concentrate provide good mixture. A few grams of soda or detergent can be added to the drum to clean natural fats and greases from the gold surface (use less than 1g/kg of concentrate). The drums can be rotated manually, or by using a small electric motor. Keep residence time below 1 hour to avoid flouring of the mercury. It is not necessary to use grinding media such as steel balls inside the drum--three or four large rubber balls are sufficient to mix the concentrate with the mercury as this improves the contact between mercury and the free (liberated) gold particles without flouring the mercury; a chain can also be used to improve the mixing. After amalgamation, the concentrate is discharged from the drum and the gangue is separated from the amalgam and excess Hg (usually by panning). Elutriators or spirals can also be used (see elutriator below).

Fig. 5.2 – Amalgamation drums on mechanical rolls

Some miners use HIGH SPEED BLENDERS to reduce the amalgamation time. This process actually pulverizes mercury and reduces its ability to amalgamate gold particles. Blenders should not be used in amalgamation because the agitation is too vigorous.

Fig. 5.3 – Miner introducing concentrate into a high speed blender--this is very inefficient because the high speed flours the mercury

PANNING is used frequently for amalgamation. Instead of using a drum most artisanal miners prefer to amalgamate by manually by mixing in a pan, but unfortunately this method does not always provide enough contact with the gravity concentrate to promote good recovery. Very often this operation is conducted at the river margins, leading to mercury contamination of streams. Pan amalgamation should be done only water boxes or in pools excavated a good distance away from the watercourses, allowing recovery of all tailings which contain residual mercury. Amalgamation tailings often contain residual gold which could provide a livelihood to individuals who properly and safely empty the tailings boxes and ponds and extract the gold.

Improving amalgamation

The main factors that limit efficient amalgamation are:

1. Poor liberation - the gold surface is not exposed
2. The gold surface is dirty
3. The mercury is not "activated" and it is not catching the gold

Even if a particle of gold is not completely liberated from the gangue minerals, it is possible to concentrate it. If some gold is "occluded" (i.e. hidden) in a particle of another mineral, this can make the particle heavy enough to be concentrated in a gravity process (e.g. sluicing). In this case, the concentrate needs to be further ground prior to amalgamation to expose the gold and enable trapping by the mercury. The way to identify occluded gold is by chemical analysis (by a chemical lab) of gold in the amalgamation tailings. The way to collect a sample of tailing is as follows.

- When the sluice or other concentration process is running, collect a cup (about 0.25 L) of the pulp of the tailing every 15 minutes (or less) and toss it into a bucket.
- After collecting about 5-10 liters of pulp, wait for the solids to settle in the bucket and siphon or pour the water out.
- Spread the wet tailings (which look like a paste) on a plastic tarp and let them dry in the sun.
- When dry, break up the chunks of tailings in a mortar with a pestle; bring this material back to the tarp.
- Mix the powder vigorously on the tarp to homogenize it, and make a pile.
- Collect about 1 kg of the powder from each side of the pile a spoonful at a time, and put it in a plastic bag. Close the plastic bag and write a label with the name of the sample and date; send it to a lab.
- If a chemical lab is definitely impossible to find, grind the tailings sample in the mortar and pan it to see if there is any visible gold.

If the tailing analysis indicates gold grades above 20 mg/kg or 20 ppm, or if there is visible gold in the pan, this is an indication that either the amalgamation has not been properly performed or that the gold particles were not exposed (i.e., liberated) to the mercury for amalgamation. If in the panning process some droplets of mercury are visible, this is an indication that the amalgamation process has been too long, or that the mercury introduced into the drum was "sick". The solution is to reduce the amalgamation time (keep the time around 30-40 minutes), and to use "activated" sodium-amalgam instead of pure mercury in the amalgamation process (see details below on how to activate mercury with a radio or 9 volt or 12 volt car battery).

Fig. 5.4 – Miner activating mercury using a radio battery; the process takes about 10 - 20 minutes

Sometimes the surface of gold is covered with organic matter, oil or iron oxides (red earthy minerals). A good way to get rid of this is by using a bit (1g/kg of concentrate) of caustic soda or non-foaming detergent. A vigorous agitation of the concentrate with a little water (30% water) before the amalgamation can also remove any earthy minerals adhered to the gold surface. Then adjust the water content up to 50%, add mercury into the drum and perform the amalgamation as described above.

When the mercury is "sick" it does not amalgamate gold efficiently because the mercury is "oxidized". In order to find out if the mercury is "sick", introduce a shiny copper wire into the mercury and check if the wire comes out amalgamated. If not, the mercury is "sick". Sodium or zinc amalgams have better properties to amalgamate gold than pure mercury. Dr. Freddy Pantoja from Colombia developed a process to make sodium-amalgam to amalgamate gold from gravity concentrates. He puts the metallic mercury into a plastic cup with water and 10% (or a table spoon) of

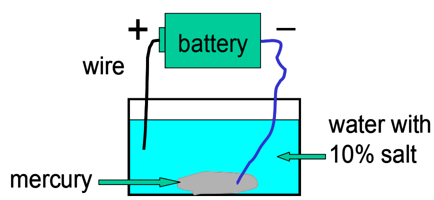

Fig. 5.5 – Pantoja's process to activate mercury (forming sodium-amalgam)

sodium chloride (salt table). Then the mercury is connected with a wire to the negative pole of a radio or a 9 volt (preferably) or a 12 volt car battery and another wire connects the positive pole to the saline solution. After 10 to 20 minutes, the sodium-mercury amalgam is formed. Test again with the shiny copper wire to see if it is amalgamated. This "activated" mercury must be immediately used as it looses its strength within about one hour.

Amalgam-heavy minerals separation

After amalgamation, the amalgam has to be cleaned of heavy minerals using gravity separation methods. The main methods are as follows:

PANNING is the most used process. The material from the drum is manually panned. The ability of the panner determines the quality of separation. Usually this process is performed in a water box or in an excavated pool, which provides an opportunity to collect and store the mercury-contaminated residues thus protecting watercourses.

Fig. 5.6 - Miner separating the amalgam from the heavy minerals by panning in a water box

SPIRAL PANS are tilted plates, 0.5 to 2m in diameter, with spiral riffles on the surface which move the Hg from the discharge port into the centre of the wheel where it is collected for recovery. Water jets crossing the wheel diameter wash the gangue minerals downwards and they are discharged at the edge.

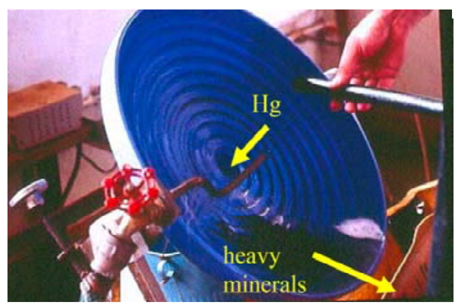

Fig. 5.7 – Spiral to separate amalgam from heavy minerals

ELUTRIATION is performed using a vertical tube made of glass, plastic or steel that receives a water inflow at the bottom that carries the heavy minerals and gangue upwards to overflow while the mercury and amalgam sink to the bottom. Sometimes it is difficult to adjust the water speed inside the tube by opening and closing a valve (tap), but clear Plexiglas tubes allow the operator to see and better control the speed of water and thus achieve a good separation of the mercury and amalgam from the heavy minerals. Some amalgamation drum manufacturers in Zimbabwe (e.g., ABJ) discharge the material from the drum into a short steel elutriator; the overflow from the elutriator then flows onto a copper-mercury plate. Unfortunately, these elutriators are often not deep enough, making it difficult to control the water speed, and the copper-mercury plate does not retain the fine droplets of mercury formed in the amalgamation drum. A longer elutriator would more efficiently separate the excess mercury and amalgam from the heavy minerals.

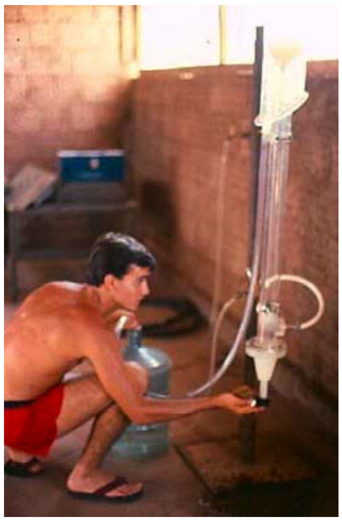

Fig. 5.8 -- Elutriator made of Plexiglass allows operator to better control the process

Fig. 5.9 – ABJ amalgamation barrel with short elutriator (copper plate not shown)

Separating excess mercury from amalgam

Not all the mercury added to the amalgamation process combines with gold and forms amalgam. The excess mercury must be removed and can be reused. The most common system used by miners is to squeeze off the excess mercury through a piece of fabric. As gold amalgam is solid, it does not pass through the fabric. Squeezing with bare hands is dangerous because mercury can penetrate the skin and attach to the fat in human cells, so rubber gloves should be used. That said, contamination of workers through their hands is usually a minor problem compared to Hg entering the body as vapor. Even at low temperatures, Hg vapors are released into the atmosphere so precautions like storing mercury under a 1 cm layer of water, using retorts when burning amalgam, etc., are very important.

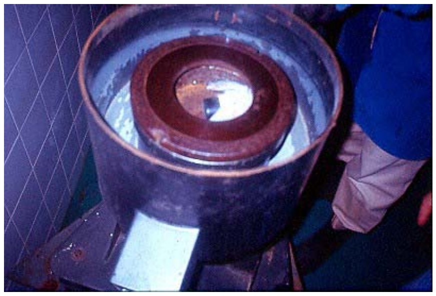

Fig. 5.10 – Centrifuge used to “filter” excess mercury from amalgams; Knudsen type centrifuges can also be used.

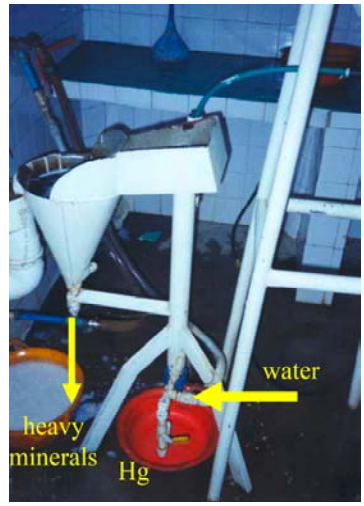

Fig. 5.11 – Elutriator made of steel tubes; heavy minerals go up and are discharged; mercury and amalgam discharged at bottom

A creative way to remove excess Hg from amalgam without using the hand squeezing process was developed by Mr. Carlesi in his private Amalgamation Center in Venezuela. The amalgam with excess mercury is transferred to a cup made of steel, porcelain or PVC, covered with a piece of fabric, and placed in a centrifuge (the same type used to concentrate gold). Running the centrifuge for 1 or 2 minutes removes the excess mercury for reuse. The resulting amalgam has less than 20% Hg. This mechanical procedure eliminates the contact of mercury with the miners’ hands and increases the amount of gold in the resulting amalgam.

Hg

It is also possible to improvise a centrifuge by using two PVC tubes forming two cups connected to each other with a piece of fabric in the middle. The cups are strongly joined together with clamps and the assembly is attached to a horizontally oriented bicycle wheel. After rotating for couple minutes, the excess mercury is forced through the fabric the second cup.

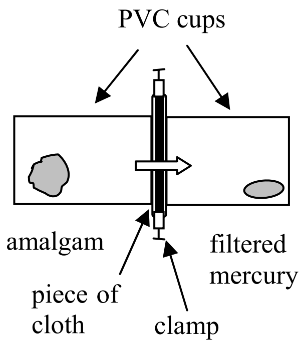

Fig 5.12 –PVC cup system for bicycle wheel centrifuge

Fig. 5.13 – Mercury filter made of PVC cups attached to a bicycle wheel centrifuge

Hotspots

Amalgamation tailings are sometimes recycled to the primary gravity circuit even though gold recovery from these tailings is very low. Unfortunately the mercury in these amalgamation tailings (sometimes 1000 g/t) is dispersed to tailing ponds or waste piles from which the mercury can eventually reach watercourses. These tailings form sites with high concentration of mercury. These are known as "hotspots" of pollution. Mercury can be oxidized and mobilized from these sites to be methylated and rapidly accumulated in the aquatic biota.

When amalgam-heavy mineral separation is conducted at the creek margins by manual panning, the mineral portion with residual mercury overflows to the watercourses also creating "hot spots".

Most miners sometimes store amalgamation tailings for reprocessing when good quality ore is not available. If the miners simply reuse the same circuit as they used the first time, reprocessing these tailings will only recover only a little more gold (<10%). A separate process must be applied to recover more gold--the grinding process must be better. This is because the gold in the tailings is usually associated with the coarse fractions and it is not liberated from the gangue. The only way to increase liberation is to re-grind the tailings to a finer grain size, using for example, a ball mill. Mercury contaminated tailings must never be treated with cyanide since this will solubilize mercury and transform it in a more toxic form, mercury cyanide.

Some measures to have less residual mercury in the amalgamation tailings are:

- improve amalgamation using activated mercury (sodium-amalgam), as described above
- improve mercury-heavy mineral separation (for example with a careful panning or by using a good elutriator or spiral) as described above
- use of special silver-mercury plates to clean tailings

The use of special silver-mercury plates manufactured by two Brazilian companies (Goldtech and Rio-Sul) has been tested in many parts of Brazil and Venezuela to clean-up mercury-contaminated tailings. The silver plates are costly (around US$ 200/plate) but they remove very efficiently the residual mercury from the amalgamation tailings. When a zigzag configuration of 4 small (40x30 cm) plates was tested in Venezuela, the amount of mercury in the tailings from copper-mercury plates was reduced from 60 mg/kg Hg to less than 3 mg/kg.

Mercury recovery by retorting

In some countries, artisanal miners use nitric acid (30%) to dissolve the mercury in the amalgam, rather than heating the amalgam. This is a dangerous and expensive procedure. In addition, it is very difficult to precipitate all of the mercury from the nitric solution. Mercury precipitation is usually done by introducing pieces of metal such as aluminum, copper or zinc in the solution. The remaining nitric solution cannot be discarded because it is extremely corrosive and still contains residual mercury.

The most common process to separate mercury from gold is the decomposition (i.e., “roasting” or “burning”) of the amalgam by heating above 360°C. Most Hg compounds evaporate at temperatures above 460°C; gold must reach almost 3000°C to evaporate. When heated, mercury becomes volatile leaving the gold behind in solid state. Unfortunately this operation is usually conducted in open pans using a blowtorch or a bonfire as the heat source. Very often women burn mercury at home in their kitchens. Children are the main victims of this lack of understanding of mercury vapor inhalation causes mercury intoxication—mercury vapors are invisible. Very few miners are aware of the dangers of mercury vapors or use retorts to condense mercury. With retorts, mercury condensation is usually higher than 95%, and condensed mercury can easily be reused. Substantial reduction in air pollution is obtained and the exposure of miners and neighbors to harmful mercury vapor is significantly reduced.

The mercury vapor released by miners when they burn amalgam in open pans is transported a short distance in the air where it condenses and falls back to the ground. Ultimately this precipitated mercury can be transformed into methylmercury in aquatic environments—methylmercury easily bioaccumulates in the fish species people like to eat. The main problem is the exposure of workers and their families and neighbors to Hg vapor. In Central Kalimantan, Indonesia, amalgam is burned in open pans everywhere, including kitchens and restaurants. A similar situation has been observed in the Mekong River in Lao PDR, where a large audience of women and children observed the "fascinating" color transformation when amalgam is burned and gold is obtained. In many African countries, amalgams are burned in small tins put into bonfires. Miners remove the *doré* (retorted gold) from the fire as soon as the surface of the amalgam becomes yellow. Usually the burning time is too short and the temperature is too low to vaporize all the Hg, so gold *doré* usually contains as much as 20% Hg. This residual mercury is released in gold buyers' and jewelry makers' shops located in urban areas, poisoning workers and their neighbors. A solution is to use air blowers or "mvuto" bellows (see below) to increase the temperature of the bonfire so that burning in retorts is hot enough to vaporize all the mercury.

Mercury vapor is extremely toxic. There are a large variety of retorts that can recover mercury and eliminate vapor inhalation by miners. Some retorts are made with stainless steel while others use inexpensive cast iron. There is also a variety of homemade retorts made with water pipes (used for plumbing) or with simple kitchen bowls. Mercury losses during retorting are usually less than 5%, but this depends on the type of connections or clamps used in the retorts, and on the way the retort is operated.

It is important to understand why miners do not use retorts. Engineers tend to look for the efficiency of the retorting process, but in many cases this is not the most important concern of miners when considering changing to cleaner technologies. The arguments against retorts are site-specific and sometimes fraught with misconception. However, in some cases there are good reasons why retorts are not being used and these must be analyzed carefully. Some of the most common arguments used by ASM for not using retorts are:

Arguments	Reasons	Possible solution
it takes time (miners become vulnerable to bandits attack when retorting)	low temperature	air blower in bonfire; blowtorch; avoid crucible made of ceramic or clay
it needs practice to operate	heating process must be uniform when using blowtorch	training
gold is lost during retorting	Amalgam isn't visible in iron retorts, creating the perception that gold is lost	glass retorts demonstrate that gold is not evaporated with Hg or trapped inside retorts
gold sticks in the retort crucible	sometimes gold adheres to crucible bottom	• crucible must be filled with soot, or baby powder or clay • avoid overheating
Hg loses coalescence after it is condensed from retorts	condensed Hg disintegrates into fine droplets	salt and radio battery to re-activate Hg
gold becomes brown	unknown; probably due to a superficial reaction with iron	• not well studied; • use stainless steel or enameled crucibles; • remelt, or hammer gold *doré*

All these factors must be taken into consideration when recommending the most appropriate type of retort for a specific mining region. In some cases, gold buyers use the miner's negative perceptions of retorts to lower the purchase price—an example of this is when miners sell brown retorted gold. Ways to avoid obtaining brown gold have not been well studied yet, but some solutions being adopted elsewhere include:

- the use of oxidizing conditions
- the use stainless steel or enamel crucibles
- re-melting the gold
- hammering the gold *doré*

The first option has been adopted by the Gama Project in Peru. A cooperative built a large fume-hood where the artisanal miners can burn their own amalgam in their open pans (as they traditionally do) with a blowtorch. The vapors are extracted by a fume hood and Hg is retained in condensers and filters. The efficiency of this process is around 85%. This raises an important point: cultural aspects must be carefully examined before suggesting any type of solution for ASM. Even a crude method of retorting, such as "baking" the amalgam in the scooped-out cavity of a potato, is better than nothing. This has been described in the "Gold Panner's Manual", a booklet for North American weekend prospectors. Readers are advised not to eat the potato after processing!

Classical retorts

There are many different types of retorts being commercialized by different companies around the world. The best retorts are those made of low cost, local and easily accessible materials and which are easy to demonstrate. Durability can be a factor, but as long as the retorts are cheap and accessible, this becomes less relevant for miners. Some retorts condense the evaporated mercury using water to cool the condensation pipe, and others use only air. Both methods are efficient, but air condensers are cheaper and more practical. A well-designed retort able to be manufactured by local mechanical shops is the one designed by CETEM (Center of Mineral Technology in Brazil). This retort can be made of either SAE 1020 steel or stainless steel. The latter is better as gold does not stick to the crucible after retorting.

Another good retort is the one recommended in Indonesia by the German institution GTZ. It is made of stainless steel and is water-cooled by natural convection through a cup and jacket surrounding the condensation tube. Clamps hold the crucible to the retort body.

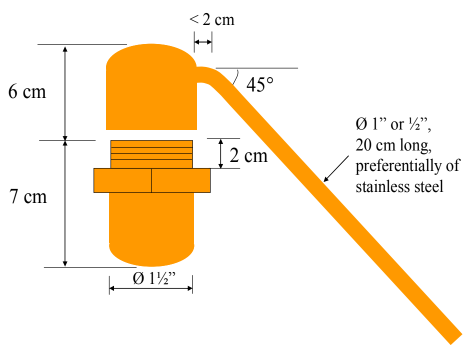

Fig. 5.14 – Design of a retort suggested by CETEM (Brazil)

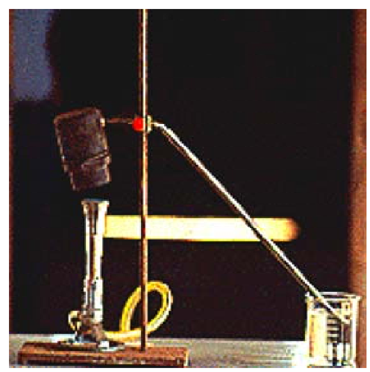

Fig. 5.15 – CETEM retort operating

In El Callao, Venezuela, a site with more than hundred years of artisanal gold mining, UNIDO promoted a contest among the manufacturers to invent a retort. A creative type was manufactured by a local shop using ordinary steel with only the crucible made of stainless steel (the crucible was a small stainless steel sauce bowl acquired in a local supermarket for US$ 1). The bowl was thin, allowing fast increase in temperature, and because it was cheap, it could be easily replaced. The main advantage is the ability to quickly produce a yellow retorted gold. The cooling pipe extends into a glass of water at the back of the stand.

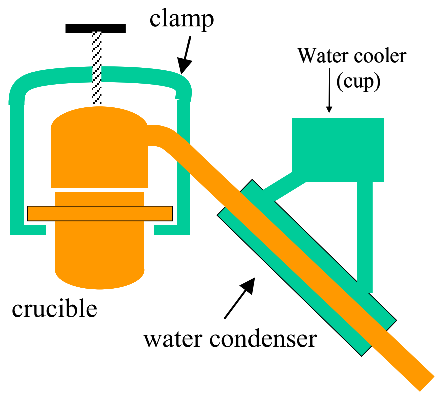

Fig. 5.16 – Components of the GTZ retort

Fig. 5.17 – Retort manufactured in Indonesia by GTZ

Fig. 5.18 – Venezuelan retort; a low cost stainless steel crucible bowl fits into the opening.

Fig. 5.19 – Venezuelan retort in operation (extra stainless steel crucible shown at left).

Operating retorts

One of the main objections expressed by miners who do not use retorts is the difficulty of operating a retort. A suggested sequence for good retorting is as follows:

- When using a retort for the first time, burn the entire retort (inside and outside) and cool it down; this will remove oil and zinc (when using galvanized steel). Actually, it is not recommended to introduce a piece of amalgam the first time you use a new retort.
- For the first use, put nothing inside, then in a second test use just mercury, and in a third time use it with the real amalgam.
- Cover the interior of the crucible with a fine layer of clay or soot (black fume) using a reducing torch and cool it down.
- Place the amalgam inside the crucible (some miners wrap it in paper).
- Immerse the tip of the cooling tube into a glass of water.
- Heat the entire body of the retort at low temperature for 5 to 15 min (**do not heat the cooling tube**).
- You will see air bubbles coming out in the water glass at the end of the cooling tube.
- Increase temperature and distribute the heat evenly over the retort body.
- Tap the cooling tube to release Hg which may be stuck inside the pipe.
- Increase temperature and concentrate flame at the crucible bottom.
- When no more mercury is coming out (perhaps after 15-20 min), **REMOVE THE WATER GLASS** …AND **THEN TURN OFF THE FIRE.**
- Cool the retort in water before opening. **Do not open warm retorts**.

One of the main sources of mercury contamination of retort operators is when miners open the retorts while they are still warm. Mercury vapor escapes and contaminates the operators.

It is common to see formation of a gray powder, likely mercury oxide, on the condensed mercury. This can be separated by washing with water. Even when using a good retort, some mercury may remain in the gold *doré*.

THE FIRST STEP TO STOP THE RETORTING PROCESS IS TO **REMOVE THE WATER GLASS** at the tip of the cooling tube. A serious problem can result when the condenser starts to cool. A vacuum forms in the retort drawing in water. This can EXPLODE the retort. To avoid this problem, before shutting-off the torch, remove end of the condenser tube immersed in water, wrapping it with a wet towel to capture any residual mercury fumes. Let the retort cool slowly. The total cycle time for effective retorting varies from 15 to 30 minutes depending on the intensity of the fire. All retorting must be done outdoors, or in a properly designed, well-ventilated fume hood.

Home-made retorts

There are many types of retorts that can be made by the miners which do not need a mechanical shop to manufacture. A very popular design is the RHYP retort devised by Dr. Raphael Hypolito from University of Sao Paulo, Brazil. It can be made with ordinary steel water plumbing connections. Black ungalvanized pipes are best because mercury sticks to the zinc galvanizing coating on water pipes, but if necessary galvanized pipes can be burned to remove the zinc (see below). An end plug into which the amalgam is placed serves as the distillation chamber; the plug can thread directly into the 90° elbow, or connected via a very short threaded nipple. The size of the retort can vary from 2 to 20 cm. An iron tube is connected to the elbow bend by a thread, bushing, or by welding. The condensation tube should be at least 50 cm long and should curve downwards to permit good condensation of gaseous mercury without any coolant. For better performance, this retort can be surrounded by a charcoal bed in order to heat it as a whole, reducing mercury leakage. A hole in the ground or an iron bucket with charcoal or wood can be used. About an hour after the fire is ignited, all the mercury should be retorted off.

Whether working in a charcoal bed or in a bonfire, it is important to increase the temperature of the fire using an air blower or bellows. This definitely reduces the retorting time to less than 30 min., but it is important to wait for the retort to cool down completely before open it.

When using galvanized pipes and water connections for the first time, miners MUST burn off the zinc layer before starting the retorting process, otherwise the evaporated mercury will form a zinc-amalgam and stick inside the retort. It is important to be very careful when burning off the zinc layer of the galvanized pipes since **zinc vapor is very toxic**. One way to remove the zinc layer is to leave the pipes and connections burning in a hot bonfire away from the public.

The British NGO, Intermediate Technology Development Group (ITDG) has been promoting the RHYP retorts in many African countries. Knowing that a good retorting process also needs a trained operator, they alert the miners: "*Do not worry if, the first time you use the retort, only a small part of the expected amount of mercury is recovered. Most of the mercury is normally trapped in the retort, and will be recovered in second and subsequent uses.*"

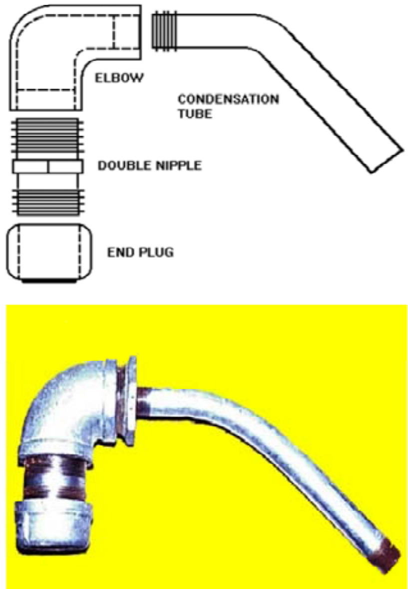

Fig. 5.20 – Scheme to build a RHYP retort

Fig. 5.21 – Indonesian version of the RHYP retort with a 2" crucible

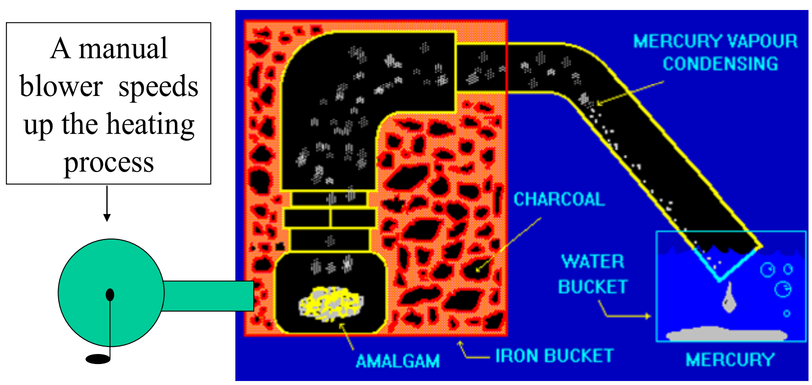

Fig. 5.22 – The RHYP retorts work faster when an air blower increases the temperature of the charcoal bed

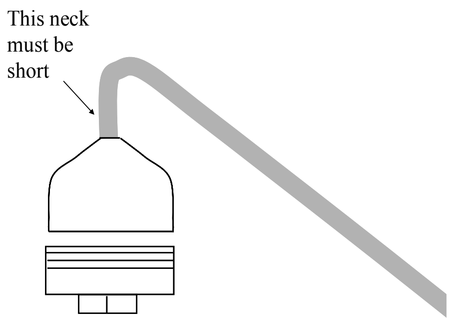

Fig. 5.23 – Different models of the RHYP retort have been devised. It is important to build a “short neck” retort to avoid Hg returning to the crucible

Fig. 5.24 - Miner showing retorted gold (*doré*) in the crucible (a hollow pipe end cap) of a RHYP retort

Homemade retorts can also be made of tins and bowls. The Chinese two-bucket retort consists of a metallic bucket and a bowl filled with water. A larger bucket covers the first bucket that contains the amalgam. The PNG "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 elements and Hg vapors condense on the cover bucket walls.

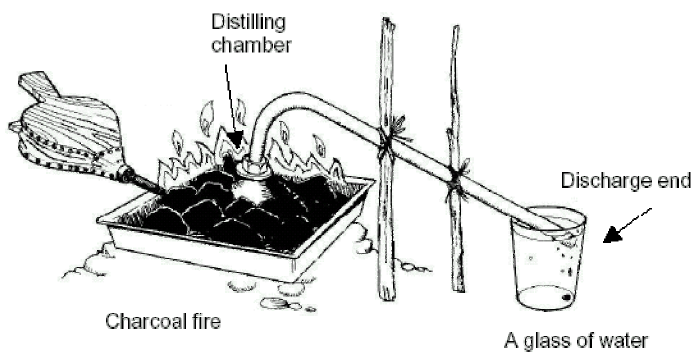

Fig. 5.25 – Version of the RHYP retort devised by ITDG

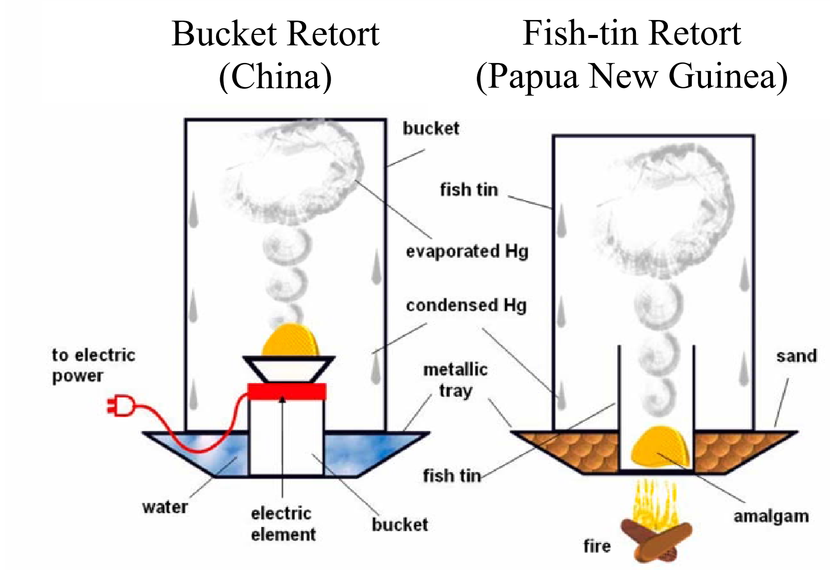

Fig. 5.26 – Home-made retorts used in China and Papua New Guinea

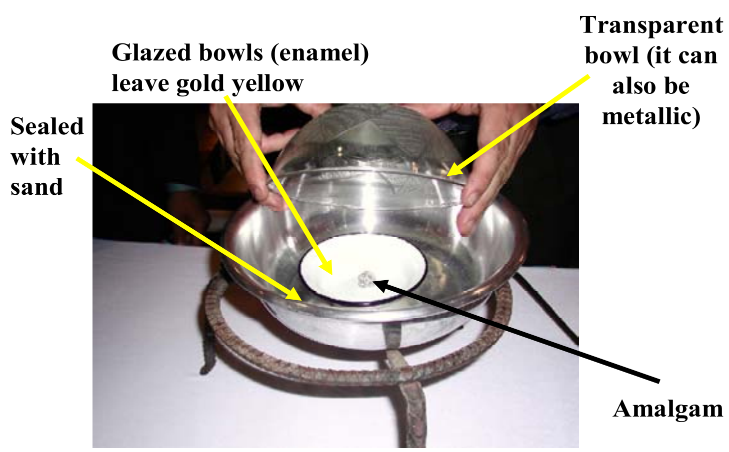

Fig. 5.27 – Kitchen-bowl retort made in Laos. Use damp sand to make a good seal—keep the sand damp while heating

A variation of these types of retort is the **kitchen-bowl retort**. Those retorts can be made with metallic and glass bowls found in local markets in artisanal mining areas. The main parts are:

1. a large steel or enameled bowl (with a hole cut at the bottom)
2. a small stainless steel or enameled bowl to hold the amalgam (it fits into the hole made in the large metallic bowl)
3. a glass bowl to be used as a cover (Glass bowls are good for demonstrations to miners because they can see the process, but they aren't necessary for day-to-day use. Stainless steel or enamel bowls work just as well)
4. a metallic support to hold the bowls (this can be replaced with 3 stones)

The hole cut into the bottom of the metallic kitchen bowl allows direct contact of the small bowl with the amalgam with the fire. This is not absolutely necessary but it speeds up the retorting time. It is recommended to have this little bowl made of stainless steel or enameled steel. This results in a yellow *doré* (retorted gold) which is less likely to stick to the bottom of the small bowl. In Mozambique, miners use a stainless steel ashtray as crucible to receive the amalgam.

In the kitchen-bowl retort, the amalgam placed in the small bowl is heated by a bonfire, a kerosene stove or a blowtorch (propane or butane). Mercury evaporates and condenses on the walls of the glass cover, dripping onto the sand. The sand must be kept slightly wet to make a seal that prevents loss of mercury vapor. During the retorting process it is recommended to have a bucket with water beside the operator so that when the sand becomes dry, the operator should drip some water on the sand (remember that dripping water on a hot glass bowl can cause it to break). A wet towel can also be used to cool the glass cover. It is important to use a glass cover at least at the first operations to show the miners that the retort works, i.e. amalgam color changes from grey to yellow. After some time using the glass cover, miners will realize that it takes more than 20 min to cool down the glass cover, even when using a wet towel because glass keeps the heat longer than steel. Once miners understand the process, a metal bowl (not aluminum which amalgamates with mercury!) can be used as a cover (like the PNG fish-tin retort). Miners will appreciate this because the steel cover cools down very fast, is cheaper than a glass bowl, and impossible to break. After retorting, the sand can be panned and mercury droplets recovered.

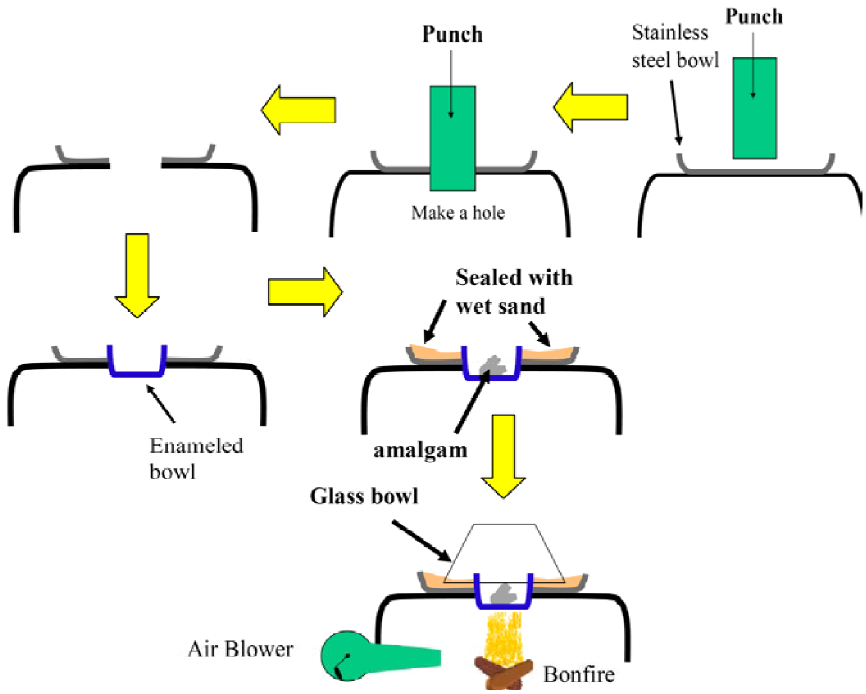

Fig. 5.28 – How to make a kitchen-bowl retort

Fig. 5.29 – Ecuadorian miner using the kitchen-bowl retort with a torch

Fig. 5.30 – Zimbabwean miners using the kitchen-bowl retort on a bonfire

Fig. 5.31 – Kitchen-bowl retort on a bonfire in Zimbabwe (using a "mvuto" blower).

Fig. 5.32 – Stainless steel ashtray used as crucible in the kitchen-bowl retort

Another creative home-made retort is the one made by the artisanal gold miners in Jacobina, Bahia State, Brazil. They use two stainless steel cups with different diameters placed inside of each other. The amalgam is placed between these two cups and a propane torch burns it from the top. The evaporated mercury condenses at the wall of the second cup and drips in a metallic bowl with water.

Fig. 5.33 – Kitchen-bowl retort using a metallic bowl instead a glass bowl as cover and a kerosene stove for heating; a metallic cover cools down faster than glass

Fig. 5.34 – Miner in Lao PDR: recovering mercury from a glass bowl retort using cotton

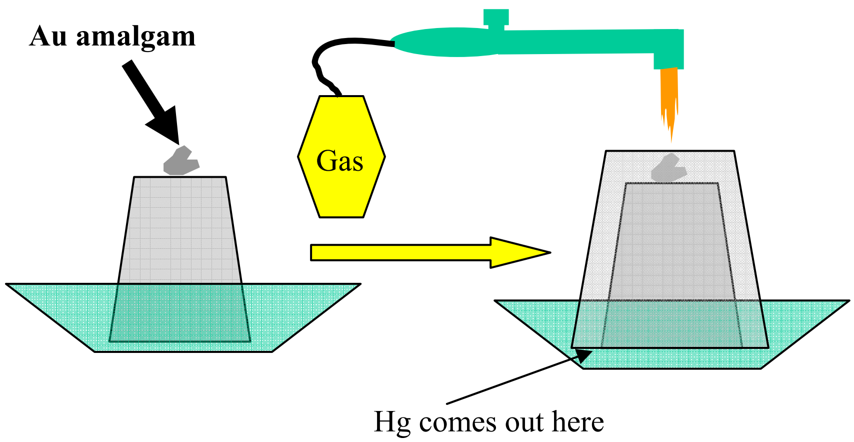

Fig. 5.35 – Two-cup retort made by miners in Jacobina, Brazil

How to reduce the retorting time

One of the main complaints from miners regarding the use of retorts is the long retorting time. When the retort is made with a thick steel and when the amalgam is burned on a bonfire or charcoal bed, the retorting time can be as long as one hour. Retorting is a crucial step since the miners are vulnerable to bandit attacks.

Miners have been using a variety of measures to increase the temperature of the bonfires or the blowtorches to speed up the retorting process. For bonfires, the main procedure used is a manual or electric air blower. Blacksmiths have used blowers that blow air through a bed of charcoal for centuries. These blowers are popular in Africa among the steel workers. In Zimbabwe, miners and steelworkers use a homemade air blower called “mvuto”. A “mvuto” (Shona for “bellows”) is a very efficient blower made from a plastic flour bag attached to a length of steel pipe. Mvutos made of animal skins have been used for many hundreds of years in Africa. Today, miners use a thick plastic bag (use a 10 or 20 kg flour bag) from bakeries and a piece of steel pipe (inside diameter about 3.5 cm, 80 to 100 cm in length). The bottom corner of the bag is cut to fit the pipe which is inserted through the hole and tied with string or rubber bands. The end of the pipe is placed in a bonfire. A large rock (10 x 15 x 15 cm) placed inside the bag holds the mvuto in place. The tricky part is the mvuto operation. Miners open the plastic bag just a bit with both hands to capture the air, and close it immediately while pushing downward to force the captured air through the pipe to the fire. Experiments in Zimbabwe using kitchen-bowl and water-pipe retorts with mvutos have shown excellent results and the retorting time is 10 to 15 minutes because the mvuto makes the bonfire very hot.

In Indonesia miners use a mixture of gasoline and air pumped through bellows by foot to a blowtorch. The temperature reached by this simple process is enough to melt gold (1064 °C).

Other methods, such as impregnation of the charcoal with diesel, have also been used by miners to increase the temperature of the bonfire.

Another option to increase the retorting temperature has been used by artisanal gold miners in Manica, Mozambique. The RHYP retort is placed on top of a kerosene cooking stove. The retorting time in a bonfire there is usually 30 minutes but this was reduced to 10 minutes with the stove.

Fig. 5.36 - Indonesian miners burning amalgam using a foot pump-gasoline-air torch

Fig. 5.37 - Sudanese miner using a hand-operated air blower to heat a kitchen-bowl retort

Fig. 5.38 - Miner closing an RHYP pipe retort in Mozambique. Note that the pipe plug crucible is threaded directly into the elbow.

Fig. 5.39 - Heating an RHYP pipe retort with a kerosene stove.

Fig. 5.40 – Operating a "mvuto" that blows air into a bonfire with a kitchen-bowl retort (Zimbabwe)

Fig. 5.41 – Making a "mvuto": a steel pipe is inserted through a hole in the corner of a plastic bag and tied with string

Recycling mercury

Recycled mercury or Hg recovered by retorting often does not have the same amalgamating properties as new mercury or activated mercury (sodium-amalgam) because a thin layer of "oxidation" has been formed, probably due to absorbed oxygen on the surface of the mercury. In this condition, Hg forms thousands of droplets (i.e. it flours) and loses its amalgamation capacity. Facing this problem, many miners simply throw away the mercury recovered from retorts. The most efficient way to reactivate the surface of Hg is by using an ultrasonic bath such those used by dentists, causing Hg droplets to coalesce in seconds (~US$200-400). Battery operated-ultrasonic denture cleaners can be more affordable (e.g. the "allSonix" costs Euro 30, but make sure that the unit is truly "ultrasonic" as some cheap models are not real ultrasonic cleaners, even though they are sold as such). A much less expensive method involves the electrolytic activation ("Freddy Pantoja") method that has been described above using a solution of 10% table salt and a simple flashlight battery to clean the mercury surface. To agglomerate the mercury droplets, put them in a plastic or glass cup (don't use metallic cups). Add water and a spoon of table salt (to make a 10% NaCl solution) to the mercury. Connect the negative pole of a radio or 9V or battery to the mercury and the positive pole to the solution. The droplets coalesce together in 1 to 3 minutes. Alternatively, some authors suggest the use of potassium permanganate to re-coalesce mercury.

A process to immobilize the contaminated water effluent (e.g., using lateritic material or activated charcoal with iodide) should accompany all activation methods. Even if the amount of effluent being discharged is small, some soluble Hg can easily be transformed into methylmercury after being released into the aquatic environment.

Melting gold

When the amalgam is retorted, a gold *doré* is obtained. This is then re-melted to rid it of the impurities. Gold melts at 1054 °C. Melting occurs in village gold and jewelry shops, at home or at the mine site. In fact, the *doré* still contains mercury. Even when it is well retorted, *doré still* contains at least 2% of Hg, which is released when gold is melted. When gold is obtained by burning amalgams in bonfires, as usual in African countries, it can contain up to 20% Hg. In gold shops, the melting operation is usually carried out by gold buyers under the miner's supervision. Mercury levels in the air in the interior of these shops are very high and contaminate the workers. Fume hoods used to extract vapors are usually rudimentary, consisting only of a fan, which blows the Hg vapors out into the urban atmosphere. Exposure of innocent people living near gold shops to Hg vapor creates an extremely serious hazard. The video documentary "The Price of Gold" produced by the BBC in 1993 profiled the case of severe mercurialism in a 60 year-old neighbor living in an apartment above a gold shop in the Amazon for period of 10 years. This individual suffered from extreme muscle tremors and his neurological functions were dramatically reduced. He had to be cared for like a child by his daughter. Similarly, a local gold dealer in the town of Kereng-Pangi, Kalimantan, Indonesia buys about 3 kg of gold daily from about 10,000 artisanal miners who extract gold from alluvial ore. When he melts the gold in the shop, Hg contaminated vapors are carried by the wind straight to a nearby elementary school. Assuming that the gold bullion contains 5% residual Hg, this shop alone releases approximately 55 kg of Hg annually.

When melting retorted gold, a gold shop should use condensers and filters. The company Apliquim developed and installed in Brazil a special fume hood comprising a metallic condenser and a filter at the end of the duct. The filter is made of activated charcoal impregnated with a solution of potassium iodide (10-30%). The filter must be changed every year and the used filter must be buried in a safe place and covered and compacted with red soil. An air cleaner used by some gold shops in Brazil consists of a concrete water box with a chicane made of concrete or steel inside. The mercury-contaminated air passes through the water filled chicane and through a chimney which contains a carbon filter. The filter is similar to those used above stoves in domestic kitchens but impregnated with potassium iodide solution. Activated charcoal is readily available in some artisanal mining areas where it is used to recover gold in cyanidation circuits.

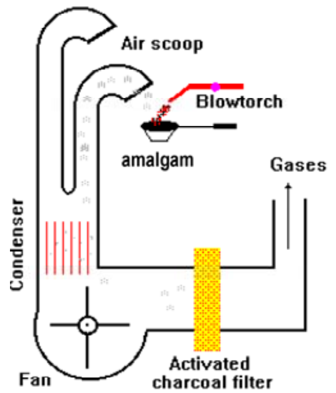

Fig. 5.42 – Scheme of a fume-hood with condenser and filter made by Apliquim in Brazil

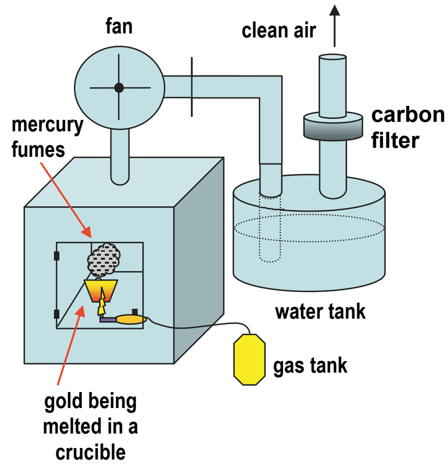

Fig. 5.43 –System to clean air from the fume hood. Placing the blower after the carbon filter creates negative pressure that can prevent leakage

The Ratio of Mercury Lost to Gold Produced (Hg_{lost}:$Au_{produced}$)

In general, the amalgamation method controls the levels of mercury loss. The ratio of Hg_{lost}:$Au_{produced}$ has been used as a parameter to quantify Hg losses or releases to the environment. Using this ratio, it is possible to establish improvements in the amalgamation process measuring the amount of gold produced and the amount of mercury lost monthly. One of the common and confusing issues in reporting this ratio is that some people report just the Hg_{used}:$Au_{produced}$ ratio, which does not necessarily reflect the amount of Hg lost. Some miners report the amount of mercury they introduce ("used") in the amalgamation process (e.g. manual or drums) but they do not report how much mercury they recovered when they squeezed the excess mercury after the amalgamation. Most Hg is recovered when the excess Hg is squeezed off with a piece of cloth. This Hg is recycled. The ratio of Hg_{lost}:$Au_{produced}$ varies from one operation to another and, when very little gold is produced in an operation, the ratio provides a false impression that a high amount of Hg is lost. It is clear that the calculation of the mercury lost should be made regionally based on the monthly production of several operations. Therefore, processing plants that recover little or no gold should not be considered in the calculation.

In general, the ratio Hg_{lost}:$Au_{produced}$ is between 1 and 3 when miners amalgamate the whole ore in a copper plate and do not use retorts. When the whole ore is ground in a ball mill with mercury this ratio can be as high as 100, as observed in Indonesia. When miners only amalgamate concentrates and do not use retorts, this ratio is around 1. When concentrates are amalgamated and retorts are used this ratio is very low (below 1:1). However, it is important to collect information from various miners throughout a region to establish this ratio, as some miners produce more gold or amalgamate more efficiently than others.

Amalgamation centers

An example of an effective and creative solution has been applied in Venezuela, where Amalgamation Centers were constructed to increase gold recovery and reduce Hg releases. Miners bring their gravity concentrates to private or state-owned centers to be amalgamated, retorted and melted by trained operators. Of course, this is a site-specific measure because transporting hundreds of kilograms of gold concentrates through the jungle can present a problem for miners.

In many mining sites in Africa and Asia, miners conduct the amalgamation step within their villages or near watercourses. In many cases the entire process is carried out inside the miners' houses in front of the kids. An amalgamation center does not need to have the characteristics of centers in Venezuela with an operator doing everything, but if possible, the location should be a place as far from populated areas as possible. These centers can house common facilities to amalgamate concentrates with drums, pan the heavy minerals in a water box, use an elutriator, as well as retort and melt gold. All amalgamation tailings should be safely stored in the center. A center is also a good way to organize the miners. A Miners' Association or Cooperative can own all pieces of equipment in the amalgamation center and charge a monthly rate for their use. Centers can also be used to transfer technology to the miners and discuss common problems. The minimum requirement for an "amalgamation center" is a well-ventilated shelter. Shelters enclosed on 3 sides are not adequately ventilated, and amalgam burners working inside can be exposed to large amounts of mercury vapors, even when using retorts.

Huts and latrines can also be built to make the site comfortable for those waiting for their turn to amalgamate their concentrate, thus increasing the likelihood that the center will be used.

Effects of mercury vapor exposure

Metallic Hg is slightly volatile at room temperatures and its vapors are invisible. At higher temperatures, even more vapor is released. Metallic mercury is not absorbed efficiently by the skin or alimentary tract, but vapors are readily absorbed through the lungs. Cases of poisoning from mercury vapors are considered a serious occupational hazard that can be prevented by proper precautions.

Inhalation of Hg vapor is most significant for miners and gold shop workers who are directly involved in handling and burning metallic Hg; but Hg vapor can also affect surrounding communities indirectly. Mercury vapor is absorbed through the alveolar membrane of the lungs, then complexes in the blood and tissues, before reacting with biologically important sites--Kidneys are the most affected organs in exposures of moderate duration to considerable levels, while the brain is the dominant receptor in long-term exposure to moderate levels. Since mercury vapor poisoning affects liver and kidneys, high Hg levels in the urine can indicate undue exposure to Hg vapor. Total mercury elimination through urine can take a number of years, so Hg levels in urine should not be expected to correlate with neurological findings once exposure has stopped.

Normal mercury levels in the air in areas remote from industry are about 0.002–0.004 $\mu g/m^3$, and in urban areas about 0.01 $\mu g/m^3$. The mercury vapor limit for public exposure is 1.0 $\mu g/m^3$. When burning amalgam in open air, miners can be exposed to Hg levels around 60,000 $\mu g/m^3$. Acute Hg poisoning, which can be fatal or can cause permanent damage to the nervous system, has resulted from inhalation of 1,200 to 8,500 $\mu g/m^3$ of Hg vapor.

In Mozambique, using the kitchen-bowl retorts, mercury in air was measured with a LUMEX portable Hg-atomic spectrometer. At 1 meter from the kitchen-bowl retort levels in the air were 3 $\mu g\ Hg/m^3$. Mercury at the miners' nose decreased to 0.4 $\mu g/m^3$. The World Health Organization (WHO) guideline for worker's exposure is 25 $\mu g\ Hg/m^3$ (TWA - time weighted average to which workers may be exposed for 8 hours per day without risk). A person exposed to about 40 $\mu g/m^3$ of Hg in air should show levels of Hg in urine around 50 $\mu g/g$ creatinine. This is the maximum mercury concentration in urine recommended by the WHO.

Miners who frequently burn amalgam in open pans show Hg levels in urine above 20 µg/L. The WHO – World Health Organization considers 4 µg/L as a normal Hg level in urine. When reporting results of mercury in urine as µg/L only, we cannot know how diluted is this urine and it is difficult to compare results from one individual to another. Some researchers analyze the first urine in the morning, which is the most concentrated one, but this is also not very accurate. The analysis of creatinine in urine determines how diluted the urine is, so there is no need to sample the first urine in the morning if creatinine is measured.

Mercury levels in the urine of new workers should be lower than those of workers with a longer duration of exposure. In persons not occupationally exposed to mercury, urine levels rarely exceed 5 µg Hg/g creatinine. In Europe, mercury in urine above 5 µg Hg/g creatinine is considered an "alert value", and above 20 µg/g creatinine an "action level" i.e. the worker should be removed immediately from the source of pollution. In El Callao, Venezuela, where miners amalgamate the whole ore using Cu-plates and burn amalgams in shovels very close to their noses so that they can carefully observe the burning process, about 15% of the workers have shown levels ranging from 1221 to 3260 µg Hg/g creatinine.

Short-term exposure to high Hg levels causes clinical symptoms that mainly involve the respiratory tract (e.g. coughing, pain in the chest). Acute exposure has caused delirium, hallucinations and suicidal tendency as well as erethism (exaggerated emotional response), excessive shyness, insomnia, and in some cases, muscular tremors. The latter symptom is associated with long-term exposure to high levels of Hg vapor. Long-term, low-level Hg vapor exposure has been characterized by less pronounced symptoms of fatigue, irritability, loss of memory, vivid dreams and depression. The common manifestations of chronic exposure to excessive levels of Hg vapor are metallic taste and gum diseases such as gingivitis, and ulcers.

Some miners believe that using dust masks or a piece of fabric over their nose and mouth protects them from mercury vapor. Dust masks filter only a very small percentage of Hg vapor and are not appropriate. Proper fitting silicone rubber respirators with special cartridges for Hg vapor are much better than dust masks, but even these do not filter 100% of the mercury in the air, and they become less effective over time. Therefore these respirators should not replace the use of retorts and proper ventilation. The accumulation of Hg on mask cartridges is rapid and can actually increase a worker's exposure when the mask is used repeatedly, so mercury filtering cartridges are recommended with a restricted number of uses--some mercury filtering cartridges have a built in "end of service life indicator" (see www.northsafety.com).

Basic knowledge for miners

- Mercury as been used to amalgamate gold for over 2000 years. It has been used as an antiseptic and disinfectant, but today mercury is mostly used in batteries, chlorine factories, fluorescent lamps, electric switches, and dental amalgams
- Mercury is 4 times heaver than quartz sand (pure gold is 7 times heaver than quartz)
- Mercury is liquid at room temperature: it boils and fully evaporates at 357 °C
- Mercury vapors are very toxic, so it is important to cover it with a centimeter of water inside closed containers because even at room temperature, mercury evaporates.
- ASM amalgam contain 50-60% Au
    - If pressed or centrifuged, amalgam can contain up to 80% gold
    - Mercury amalgamates with all metals except iron and platinum
    - Mercury can efficiently amalgamate both liberated and partially liberated gold
    - Mercury efficiently captures gold particles coarser than 0.074 mm
- Whole ore amalgamation is extremely polluting and intoxicates miners/millers
    - Hg and gold are carried away into tailings
    - Hg can flour or get scratched from copper plate
    - Ball mills with mercury inside in Indonesia loose over 50-60% of the Hg
- Hg in riffles DOES NOT increase recovery
- Tailings from whole ore amalgamation contain lots of gold
- Miners must be careful using cyanide to keep Hg from loosing coalescence or to remove yellow oxidized spots on copper plates because **DEADLY** HCN gas can form at neutral pH
- Amalgamating concentrates only requires much less mercury to catch the gold
    - 90% recovery observed in practice
    - Mercury losses can be as low as 0.5% when properly done

  - Mix for at least 15 minutes, but never longer than 2 hours (to avoid flouring)
  - Use a few grams of soda or soap to clean natural fats or grease (1g/kg concentrate).
- Use 1 part Hg to 100 parts water in amalgamation barrels; use 50% water and 50% concentrate
  - Agitate slowly for less than one hour to minimize flouring
- Amalgamate away from water courses. Use water boxes, or amalgamation ponds, and carefully dispose of tailings
- One of the main causes of inefficient amalgamation is inadequate liberation where the gold surface is not exposed to contact the mercury; alternately the gold surface can be dirty, or the mercury is not sufficiently activated (the surface of the mercury is oxidized).
- Mercury can be cleaned or "activated" by putting it in salty water and connecting a radio or car battery: the positive wire to the water and the negative wire to the mercury for about 10-20 minutes. Use this mercury within 1 hour.
- Excess mercury can be removed from amalgam by centrifuges or presses
- The best way miners can protect themselves from mercury vapor is to use retorts.
  - Retorts capture over 95% of the vapor which condenses for later reuse
- Remove the condensing tube from the water before the removing from the heat to avoid sucking water into the crucible and exploding the retort
- When using retorts use a torch, or a campfire with a blower to speed up the retorting
  - Simple blowers like the Zimbabwe "mvuto" can make campfires very hot
  - Insufficient heat leaves more than 20% of the mercury in the gold
    - This mercury poisons people in cities who live near gold buyers and refiners

Bibliography

D'Itri, P.A. and D'Itri, F.M., 1977. Mercury Contamination: a Human Tragedy. New York, John Wiley. 311p.

Farid, L.H.; Lins, F.F.; Gonçalves, M.M., 1992. Amalgamation. *In*: Aspectos Diversos da Garimpagem de Ouro. Ed. F.A.F. Lins (Editor). Ser. Tecnologia Mineral, n.54, p.53-66. Published by CETEM/CNPq, Rio de Janeiro (in Portuguese).

Swain, E; Jakus, P.; Rice, G.; Lupi, F.; Maxson, P., Pacyna, J.; Penn, A., Siegel, S.; Veiga, M., 2006. Socioeconomic Consequences of Mercury Use and Pollution. Submitted to AMBIO. 40p.

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

UNEP, 2002. Global Mercury Assessment. UNEP Chemicals, Geneva, 270 p. http://www.chem.unep.ch/mercury/Report/Final%20report/final-assessment-report-25nov02.pdf

Veiga, M.M. and Baker, R., 2004. Protocols for Environmental and Health Assessment of Mercury Released by Artisanal and Small-scale Gold Miners. Published by GEF/UNDP/UNIDO Global Mercury Project. Vienna, ISBN 92-1-106429-5, 294p.

Veiga, M.M. and Meech, J.A., 1995. A Brief History of Amalgamation Practices in the Americas. Proc. 16th Brazilian Symp. on Ore Processing and Hydrometallurgy. vol 1, p.581-594. Rio de Janeiro, Sept. 17-22, 1995. http://mining.ubc.ca/files/papers/JMeech/briefhi2.htm

Chapter 6
Cyanide Leaching of Gold

Introduction

Cyanide leaching has been the main industrial process used to extract gold from ores since it was invented in 1887. However, the use of cyanide has been controversial due to its potential toxic effects on workers and the environment. There have been several accidents involving cyanide spills during transport or the accidental release of cyanide contaminated tailings, that have resulted in killing of fish, birds and other animals. Despite this, there are very few cases of people being poisoned from the use of cyanide for mining gold. The potential for such accidents demands that gold miners use cyanide in a safe and environmentally responsible manner. The advantages of cyanide leaching are:

- Only a relatively small amount of cyanide is needed to recover gold, usually less one kg of cyanide per tonne of rock.
- Cyanide is very selective leaching gold and only minor amounts of other minerals in the ore.
- Cyanide leaches coarse and very fine gold as well as gold that is attached to the rock.
- The process is quick; tank leaching normally takes less than one day.
- Cyanide remaining in the waste (tailings) product can be destroyed to minimize the environmental impact.
- Cyanide degrades naturally in the environment, primarily from exposure to the sun's ultraviolet light, to less toxic forms and ultimately to nontoxic carbon dioxide and nitrates.
- If used responsibly, the risk of cyanide poisoning can be minimized.
- Cyanide does not accumulate in animals or plant life.

Disadvantages of cyanide leaching are:

- Cyanide is highly toxic, and at high concentrations it will kill fish, birds and mammals (including humans).
- Cyanide reacts with mercury to produce soluble chemical compounds that are easily transported with water, thereby spreading mercury contamination to large areas.
- When cyanide reacts with mercury, it converts the mercury to a form in which it more easily enters the food chain and becomes more harmful.

Large-scale mining operations employ a number a safety measures to control and monitor the leaching process and manage waste. The challenge is for small-scale miners to achieve this same level of control and monitoring without the use of sophisticated and expensive equipment. Some basic technical skills are required to successfully and safely operate a cyanide leach process.

This chapter will describe:

- The toxicity of cyanide
- How cyanide is used to leach gold
- The operation of cyanide processes including heap, vat and tank leaching
- The interferences to the process
- How gold is recovered from the leach solution,
- How to manage cyanide in a responsible manner.

There is limited focus on chemistry with no description of cyanide species – the term cyanide refers to free and/or weak acid dissociable cyanide. An important outcome will be to show why mercury should not be used prior to cyanide leaching. It is important to understand that in addition to the health and environmental impacts, using mercury to treat the ore before cyanide leaching will lower the amount of gold that is recovered.

Toxicity of cyanide

Free cyanide is very toxic and is readily absorbed through inhalation, ingestion or skin contact and is distributed throughout the body via blood. It induces tissue anoxia so that oxygen cannot be utilized and death results from the depression of the central nervous system.

Fig. 6.1 - Fish kill from cyanide tailings that spilled into the Tisa River, Romania, 2000.

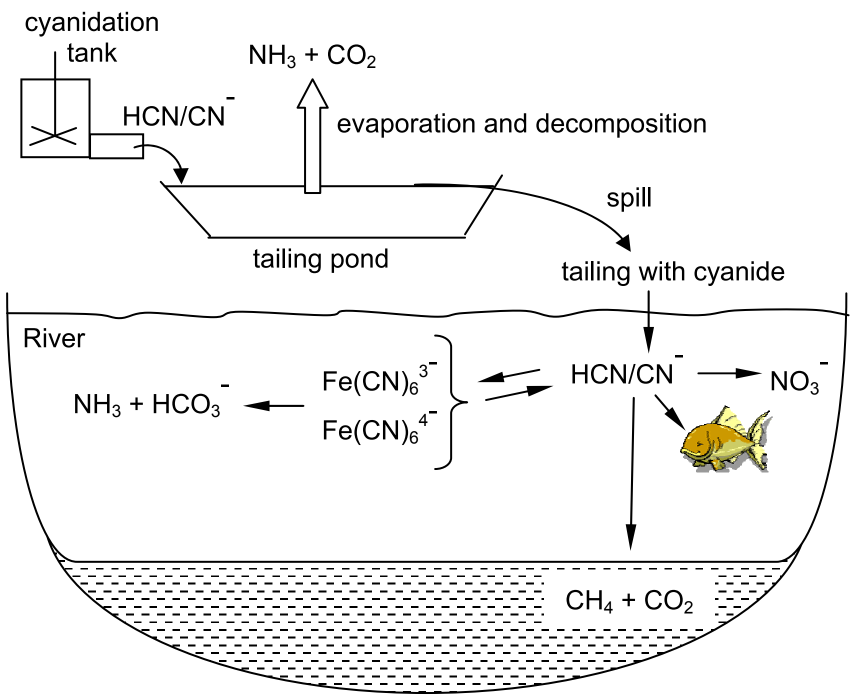

Fig. 6.2 - Simplistic schematic showing the cyanide cycle in the environment.

In solution, about 3 to 5 mg of cyanide/kg body weight is lethal, which is a very small amount. In respiratory exposure to hydrocyanic acid (HCN-gas), death occurs at 0.1 to 0.3 g/m³. Fish are the most cyanide-sensitive group of aquatic organisms. Free cyanide concentration between 0.05 and 0.2 mg/L (about one small drop of cyanide per liter) is fatal to fish.

The greatest source of cyanide exposure to humans and some animals is cyanogenic food plants and forage crops, not mining operations. If managed properly, risk of contamination of plants from cyanide is very low. Cyanide does not cause mutations or cancer. There is no indication that cyanide is biomagnified in food web.

Cyanide breaks down by oxidizing in air and as a result of exposure to sunlight. Degradation of cyanide forms less toxic or non-toxic compounds. Free cyanide seldom remains biologically available in soils and sediments because of natural degradation processes. It complexes with metals, is metabolized by various microorganisms and is lost to the atmosphere where it breaks down. In the presence of air, cyanide salts in the soil are microbiologically degraded. At depth in a waste pile or at the bottom of a tailings pond, there is very little oxygen present. Under these conditions, the cyanide breaks downs to release gaseous nitrogen compounds that are non-toxic and enter the atmosphere.

Cyanide leaching

Leaching of gold from ore using cyanide involves a series of steps. After crushing and/or grinding, cyanide is used to leach the gold from the rock, dissolving it into the water. The water containing the gold is called the "pregnant solution". The next step is to recover the gold from solution, which is usually achieved using activated carbon or zinc. Next the carbon or zinc is processed to produce gold bullion.

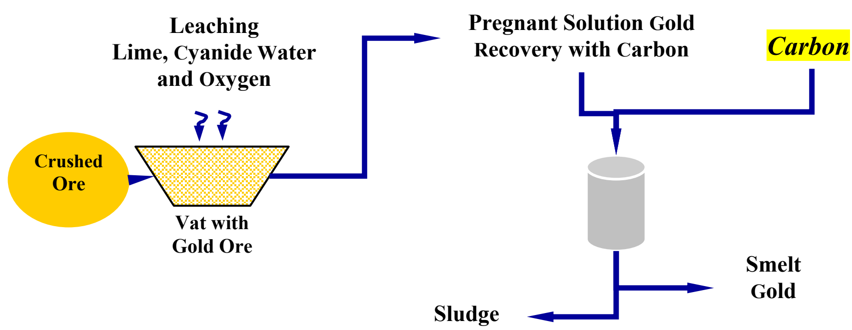

Fig. 6.3 - Steps in cyanide leaching process (Whitehouse et al., 2005)

To leach gold, there are four components required: water, cyanide, air (oxygen) and alkalinity (high pH). If one of these components is missing, the process will not work. Under the correct conditions, cyanide will dissolve the gold from the rock leaving it in the water. While there is usually enough oxygen in the water, an alkaline such as lime must be added along with the cyanide. Cyanide leaching of gold is described by the following chemical reaction, which shows that oxygen is needed.

$$4Au + 8NaCN + O_2 + 2H_2O \Rightarrow 4NaAu(CN)_2 + 4NaOH$$

Prior to adding the cyanide, lime or another alkaline must be added to the rock. At low pH, cyanide is unstable and cyanide gas will evolve, which if inhaled by the miners is toxic. If too much lime is added, it will slow down the leaching process. Therefore enough lime must be added to increase the pH to between 10 and 11 where cyanide is stable in water and the gold leaching reaction occurs quickly. Typically one to two kg of lime is required per tonne of ore. The exact amount of lime that is required will depend on the properties of the ore and can be checked by measuring the pH of the pregnant solution using litmus paper. If the pH is less than 10, more lime should be added and if it is greater than 11 less lime is required. If lime is not available, the pH can also be adjusted using soda ash or caustic soda.

The cyanide is purchased as either a powder or in pellets. For heap or vat leaching, the cyanide should be added to the pH adjusted process water and for tank leaching it should be added directly to the tank. Typically from 0.5 to 1 kg of the cyanide is needed per tonne of rock or about 0.5 to 1 liter of cyanide powder per cubic meter of rock. For heap and vat leaching, the feed solution will contain 0.1 grams of cyanide per liter. For tank leaching there should be between 0.1 and 0.5 grams of cyanide per liter. The cyanide will react with the gold so that the concentration of cyanide in the pregnant solution will be lowered to between 0.01 and 0.05 grams of cyanide per liter.

The concentration of cyanide in the water can be measured by titration with silver nitrate using potassium iodide as an indicator. This is a simple procedure that can be very helpful to small-scale miners and will be described in the section on monitoring and control.

Interferences to cyanide leaching

Although cyanide selectively leaches gold, it can react with copper, iron, silver and mercury. When these metals react with cyanide, they consume it, meaning there is less cyanide available for leaching the gold.

Ores with copper minerals such as malachite and azurite cause the largest problems because the copper in these minerals reacts quickly with cyanide. Native silver, electrum and other silver minerals will also leach in cyanide. When silver is present, it will be recovered with the zinc or carbon processes and can be separated as a by-product.

Although most iron minerals do not dissolved at high pH, and therefore do not cause a problem, pyrrhotite (iron sulfide mineral) does react with air, which releases iron. The problem can be avoided by mixing the pH adjusted slurry for a few hours so that it can react with air – this process is called pre-aeration. The

iron that is released precipitates quickly into a form that does not interfere with cyanidation. After this time period, the cyanide can be added to the tank.
Some gold ores contain natural forms of carbon, such as graphite or decomposed organic material that adsorb the gold in the same manner as activated carbon – this natural carbon robs the gold from the pregnant solution. In this case, the recommended process is leaching the gold in an agitated tank and adding activated carbon pellets directly to the tank – this process is call carbon in leach. The activated carbon is coarser than the ore and can be recovered using a screen. Kerosene and oils will also interfere with cyanide leaching by coating the gold and the activated carbon preventing leaching and gold adsorption, respectively.

In gold ores, mercury can be present in the mineral cinnabar, but there is usually very little natural metallic mercury. The cinnabar leaches slowly and so does not cause a significant problem. However, many small-scale miners amalgamate the ore with mercury on copper plates or in amalgamation drums before cyanide leaching. After amalgamation on copper plates, the ore will contain between 50 and 100 ppm (g/tonne) of mercury and after amalgamation in a drum, mercury is commonly between 200 and 500 ppm. This residual mercury will react with the cyanide so that it is not available to leach gold and will lower the amount of gold recovered.

In some countries, miners crush, concentrate and amalgamate their ore in a central processing facility operated by millers. In exchange for use of the facility, the miller receives the amalgamation tailings, which are then leached with cyanide. Both the miners and the millers would get more gold if they eliminated the use of mercury and made other arrangements to share the gold extracted only by cyanidation.

Industrial practices

There are three main types of processes that use cyanide to recover gold: heap leaching, vat leaching and agitated tank leaching.

Heap leaching – For heap leaching, the rock is crushed and mixed with lime prior to placing over an impermeable base composed of clay, asphalt or tarpaulin. In general crushing the ore to smaller particle sizes will increase the overall gold extraction, although this is not always the case. Typically ore is crushed to below 10 cm for heap leaching. Mixing with lime not only provides alkalinity, it also helps to agglomerate the fines to ensure good flow of cyanide solution. If the ore contains excessive amounts of fines, they should be removed by screening and treated separately. The pH adjusted cyanide leach solution (pH 10.5 with 0.1 grams cyanide per liter) is applied to the top of the heap using hoses or a sprinkling system for even distribution across the heap. The base should be contoured so that the pregnant solution flows to a collection pipe or impermeable lined ditch. A layer of crushed rock above the base will help to ensure flow of the leach solution. Gold can be recovered from the clear solution using either zinc precipitation or carbon adsorption. This process typically requires from three weeks to two month to leach the gold and the gold extraction ranges from 35% to 65%.

A variation of heap leaching, sometimes referred to as percolation leaching, is conducted in large open tanks. In this case, the bed of ore should not be too deep as oxygen may become depleted, preventing the cyanide leaching reaction.

Vat leaching- In vat leaching, the crushed ore (finer than 5 cm) is mixed and lime and is added to an impermeable vat. The pH adjusted cyanide solution (pH 10-11 with 0.1 grams cyanide per liter) is added to the vat, flooding the rock. At the end of this period, the leach solution is collected from a drainage pipe. The gold is recovered from the clear solution using either zinc or carbon. The leaching time ranges from 3 to 7 days and the gold extraction ranges from 45% to 70%. After leaching, the vat must be emptied so that fresh ore can be added for the next leach.


Fig. 6.4 - Vat leach at a milling center in Zimbabwe

Agitated tank leaching – For tank leaching, the ore must be finely ground to below 0.15 mm. The ore is added to a tank with water at about 40 to 50% solids (weight of ore divided by weight of ore plus weight of water). The pH is increased to between 10 and 11 by adding lime and then the cyanide is added at a concentration of between 0.1 and 0.5 grams cyanide per liter. Agitation must be strong enough to prevent particles from settling to the bottom of the tank. Agitation can be achieved by mixing with an impeller. In another method, compressed air is supplied to the bottom of the tank for agitation – this is referred to as a ”Pachuca”. Agitation helps to keep air in the process to allow the cyanide leaching to occur. The tanks can range in size from small barrels to very large tanks. The gold can be recovered from the pregnant solution using either carbon or zinc. The average leaching time to dissolve the gold is one day (24 hours) and gold extraction is often greater than 90%.

Fig. 6.5 – Tanks of gold cyanidation in North Sulawesi, Indonesia

Process selection - When coarse gold is present, large-scale mines will often recover this gold first using gravity concentration as coarse gold dissolves very slowly in cyanide solutions. While the overall gold recovery may not be improved, this practice can lower the cost of the downstream cyanide leaching process, which will require less cyanide and will leach faster. For artisanal mining, the immediate recovery of a high-grade gravity concentrate may benefit the miners by providing cash flow as payment for gold recovered from cyanide leaching will be delayed.

In general, gold recoveries are highest from agitated tank leaching (typically greater than 90%) and lower for vat leaching (45 to 70%) and heap leaching (35 to 65%). However, agitated tank leach requires the highest level of technology and heap leaching requires the lowest. Therefore, the best process for small-scale miners will depend a number of factors including the nature of the ore, the availability of process equipment and the skill levels of the miners.

Monitoring and control - The main differences between large-scale gold mines and artisanal small-scale gold mines are the monitoring and control. Is the pH high enough? Is there enough cyanide or too much? When has all of the gold been leached? Can we get more gold by grinding the ore particles smaller?

The pH is simple to control by using litmus paper and should be between 10 and 11. For tank leaching, the pH should be adjusted with lime to the target pH before adding cyanide. For vat and heap leaching, enough lime should be mixed with the rock so that the pH of the pregnant solution is in the current range. If the pH is below 10, more lime should be added and if it is greater than 11 less lime is needed.

The cyanide concentration should be added at 0.1 to 0.5 grams per liter. The cyanide will react with the gold so that when gold leaching is finished, the concentration will be between 0.01 to 0.05 grams per liter. The cyanide concentration can be measured using a titration procedure. A simple method involves collecting 25 mL of clear solution and adding 3 drops of potassium iodide. A solution of silver nitrate (8.67 g silver nitrate per liter) is added one drop at a time. When the solution becomes milky, the volume of silver nitrate solution that was added is recorded and the concentration of cyanide is calculated using the equation:

Cyanide grams per liter = 0.20 x milliliters of silver nitrate solution

As an example, the leach solution for a percolation leach was collected and 25 ml was added to a flask. After adding the potassium iodide, silver nitrate solution was added. The solution became milky when 5 ml of the silver nitrate solution was added. The concentration of cyanide in solution is therefore 0.2 x 5 ml, which equals 1 gram cyanide per liter.

This measurement can be used to control the process. Some ores require more cyanide because the cyanide reacts with other metals in the ore. If the cyanide concentration of the pregnant solution is less than 0.005 gram per liter, more cyanide should be added at the start of the process. If the cyanide concentration is above 0.01 gram per liter, less cyanide is needed to leach the gold. Such practices can optimize the amount of cyanide added for maximum gold recovery while preventing the use of excess cyanide, which decreases the amount of cyanide that needs to be purchased and the reduces the potential environmental impact.

To determine when the gold is finished leaching, it is helpful to measure the concentration of gold in solution at time intervals. Small-scale miners generally do not have sophisticated analytical equipment needed for this measurement. For heap or percolation leaching, there is a simple technique that can be used. Fine zinc powder in a sock can be placed in the flow of the pregnant solution. After a few hours, if the zinc has turned black or brown.

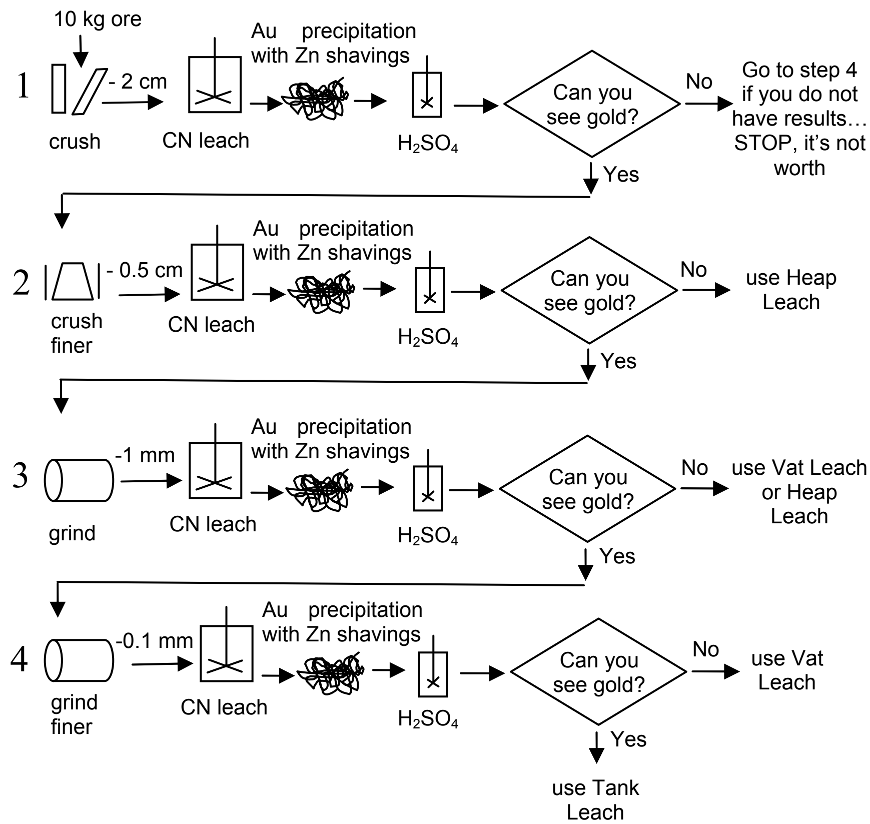

Fig. 6.6. - Schematic showing procedure to find best crush/grind size.

To determine how much crushing and grinding gives the best gold recovery, a series of tests should be conducted. For some ores, the gold recovery changes by only a small amount when crushing finer, while for other ores the gold recovery can be improved greatly. Once the relationship between gold recovery and crush size is known, the crush size can be selected and used for all the ores in the area since the geology is usually similar. To determine the relationship, a sample of the ore should be crushed to below 2 cm and then leached in a drum. After leaching, the gold should be recovered using zinc dust. The rock should be crushed finer to below 0.5 cm and then re-leached with cyanide again using zinc dust to recover the gold. This process should be repeated for particle sizes below 1 mm and 0.1 mm. In all steps it is suggested to leach the zinc with sulphuric acid after the gold precipitation. This will make gold visible.

Recovering gold from the pregnant solution

After the gold is leached, it is recovered from the water (called the pregnant solution) using one of two processes: zinc precipitation or carbon adsorption.

Zinc precipitation - In the zinc precipitation process (called the Merrill Crowe process), the gold cements onto fine zinc powder removing all of the gold from the pregnant solution and forming a zinc-gold powder that can be smelted to recover the gold. For this process to work, it is important to remove all particles from the pregnant solution using a filter. The filter can be made of cloth or a layer of clay overlying the cloth. If the solution is not clear, the fine particles will interfere with the cementing processing and lower the recovery of the gold. Next the air must be removed from the leach solution in vacuum cylinders. If air is not removed, the zinc can become coated and prevent the gold from cementing. The gold loaded zinc dust is then filtered to remove the solution, which can be recycled to the leaching process. Sulfuric acid will dissolve the zinc leaving a gold residue. This product is upgraded further by smelting.

While large-scale gold miners have specialized equipment to filter the pregnant solution and then remove air, these processes can be difficult reproduce for small-scale miners. However, simpler but less efficient zinc precipitation process can be used. In one process, the pregnant solution is forced up a through a series of PVC columns containing zinc wool or shavings. For the process, six 10 cm diameter by 20 cm columns are filled with zinc wool. The columns are connected in series with the overflow from one column flowing to the base of the next. As the gold adsorbs, the zinc becomes black. Once all the zinc has turned black, the zinc is smelted or sold to a gold dealer.

As described in the previous section, if mercury was present in the ore, it will be dissolved by cyanide. During zinc precipitation, the mercury will coat the zinc and prevent gold from adsorbing. Therefore, less gold will be recovered. Since the next step is to smelt the gold loaded zinc, any mercury attached to the zinc will be burned exposing the miners to toxic mercury vapor.

If silver is present, it also will be recovered with the gold. If a lot of silver is in the ore, it may be preferred to recover the silver as a separate product. One process involves washing the gold loaded zinc with nitric acid, which will dissolve the silver to form silver nitrate. The residue is smelted to recover the gold. Salt is added to the silver nitrate solution, which precipitates silver chloride onto steel-wool. The silver chloride is then washed from the steel-wool and smelted.

Fig. 6.7 - PVC Columns used for gold precipitation with zinc shavings

Fig. 6.8 – Zinc shavings are leached with sulphuric acid and gold is left behind.

The zinc can be purchased as a powder, as shavings or as wool. Finer zinc wool will have more surface area and will load more gold.

Carbon adsorption - Activated carbon can be purchased or produced by burning natural materials such as coconut, fruit pits and other woody materials under controlled conditions. The most common type of activated carbon is made from coconut shells. The carbon is purchased in pellets that are typically 1-2 mm in size. Coconut carbon can adsorb as much as 10-15 g of gold per kg of carbon, although loadings of 2 to 5 g of gold per kg are more practical.

Fig. 6.9 - Recovery of gold loaded carbon using a screen.

Carbon can be used to treat clear solutions or it can be used directly in the leach tanks. Carbon in columns are used to treat the clear pregnant solution. The pregnant solution is forced up through a series of columns that contain the carbon. Enough columns should be in place so that the pregnant solution is in contact with the carbon for between 4 and 6 hours. The amount of gold adsorbed to the carbon can be maximized by using a series of columns (4 or 5). After a period of time (2 or 3 days), the 1st column is removed form the series and processed to recover the gold (called stripping). A new column with fresh carbon is added to the end of the series. The process can also be conducted in batches by flooding the carbon and letting stand for 4 to 6 hours before draining the solution. Fresh solution can then be added and the process repeated several times (5 or 6) before the carbon is ready for stripping.

One advantage of carbon is that it can be added directly to a leach tank (called carbon in leach) or mixed with the slurry following leaching (called carbon in pulp). The carbon can be placed in socks that hang into the tank or it can be added directly to the tank and then recovered by passing the slurry across a screen to recover the coarse carbon pellets from the finely ground ore particles.

When using carbon, mercury causes problems with the recovery of gold. The mercury will also attach to the carbon, coating the surface of the carbon and preventing gold from attaching. This will result in less gold adsorbed onto the carbon and in a lower gold recovery.

Stripping – Once the carbon is loaded with gold, the carbon needs to be processed to separate the gold. Some small-scale miners will burn the gold loaded carbon and then smelt the residue. However, this process produces a large volume of slag and can be difficult to control. If mercury is present, burning will produce toxic mercury vapor that will be inhaled by the miners.

Rather than burning the carbon, a better practice is to strip the gold from the carbon and then use zinc precipitation or electro-winning to produce a high-grade product that can be smelted. In the stripping process, the carbon is added to a tank containing a hot (80 to 90 ^{o}C) cyanide solution (2 g cyanide per liter) with a high pH (10 g caustic soda per liter). Enough solution should be added to the tank to immerse all of the carbon. The carbon is left in the tank and the temperature maintained for two to three days before draining the solution from the carbon. The addition of 10% to 20% alcohol (ethanol) can speed up the process, lowering the stripping time to about 12 hours. **Alcohol should not be added when the material has residual mercury**. The solution now contains a high concentration of gold that can be recovered by zinc precipitation or electro-winning. The carbon can be treated and recycled to the leaching process. Recycling the carbon is an important cost advantage of this process.

The following are the steps to strip 5 kg of carbon. Based on a loading of 4 g gold per kg carbon, this is enough carbon to adsorb 20 g of gold. The stripping should be conducted in a steel tank (preferably stainless steel). The volume of 5 kg of carbon plus the stripping solution will be less than 10 liters, but a slightly larger tank size of perhaps 15 liters is recommended.

- Prepare 5 liters of strip solution by adding 2 g cyanide per liter and 10 g caustic soda per liter in a container such as a plastic bucket
- Add carbon to the 15 liter metal tank
- Add 5 liters of strip solution to the tank
- Cover tank with a lid with a vent pipe
- Heat tank to just below boiling (80 to 90 ^{o}C) over a bonfire or some other source of heat
- Maintain temperature for at least two days
- Drain solution from the carbon – this could be done from a drainage pipe with a valve near the base of the tank.
- Treat strip solution using zinc or electro-winning as described below

The stripping time can be lowered to about 12 hours by adding alcohol. In this case between 10% and 20% alcohol should be added to the strip solution before adding it to the tank.

Treating strip solution – The gold needs to be recovered from the strip solution so that it can be smelted using either zinc precipitation or electro-winning.

Fig. 6.10 - Pouring of smelt product into water to obtain fine droplets of gold before extracting silver

Zinc precipitation is the simpler of the two processes. Immediately after draining the hot strip solution, zinc wool or shaving is added to the solution. Since the solution is hot, it is not necessary to remove fine particles or remove air. The gold will cement quickly, leaving a zinc residue that can be washed with acid (sulphuric or nitric) to dissolve zinc and then smelted. If mercury is present it will attach to the zinc wool and interfere with the cementing of the gold. Smelting zinc should be avoided, because it produces zinc gas which is toxic.

For the electro-winning process, the gold solution is added to a cell using a current of 12 Volts and 60 amps causing the gold to attach to the steel-wool. The gold is then washed from the steel-wool, which can then be re-used. If mercury is present, electro-winning will evolve mercury vapor that will be inhaled by the miners.

Carbon recycling – After stripping the carbon from the gold it can now be recycled to cyanide leaching to recover more gold. Before recycling, it should be screened at about 1 mm. The carbon coarser than 1 mm can be recycled, but the carbon finer than 1 mm should not be re-used. To make sure that the carbon remains fresh (effective for gold recovery), after recycling 5 times, it should be re-activated. There are two steps involved. The 1st step is to wash with hot hydrochloric acid (85 ^oC) to dissolve any carbonates and metals that may have accumulated. The 2nd step is to roast the carbon at about 700 ^oC. These steps will ensure that the carbon remains effective at adsorbing the gold.

Smelting Gold- To upgrade the gold that has been recovered by zinc, the zinc residue is washed with sulfuric acid to dissolve the zinc (gold is not dissolved) and then smelted. For smelting, borax and siliceous fluxing agents are added and the mixture is melted at 1200 ^oC. After allowing the melted gold to settle, the melt is cooled until it becomes solid and the slag knocked of the gold using a hammer. When refining is required, the melted gold is poured into water to make fine droplets before leaching it with nitric acid to dissolve silver. This makes the silver removal faster.

Cyanide leaching involves a good technical understanding of the process, expensive chemicals and specialized equipment. For small-scale miners, carbon adsorption is simpler and will usually recover more gold than zinc precipitation. Since the miners already have cyanide, the miners will also have the capability to strip the carbon. The strip solution can be treated by zinc precipitation. This process is simpler and requires less specialized equipment than electro-winning and may therefore be preferred. The best process will depend on a number of factors including the minerals in the ore, the technical skill level of the miners and the availability of chemicals and equipment.

Fig. 6.11 - Tailings pond from cyanide leach

Cyanide management

Best practices are recommendations to minimize health and environmental impact, while maintaining high gold recoveries and lowering costs. Best practices principles for the operation of gold cyanide leach processes are:

- Establish procedures for the safe storage and handling of cyanide.

- Use the minimum amount of cyanide needed to extract the gold.
- Dispose of cyanide in a manner that minimizes the environmental impact.
- Monitor operations, discharges and the environment to detect and deal with cyanide escape, and impacts of release.
- Promote recycling and effective disposal of remaining cyanide

Cyanide is purchased as either pellets or as a powder, which is relatively stable unless it comes into contact with water and particularly acids, which produces poisonous cyanide gas. Important things to consider:

- Cyanide should be stored in a well-ventilated area, kept away from acids, water, corrosives and explosives.
- The storage area should be fenced and locked to prevent accidental access.
- When preparing leach solutions, the miners are at risk of exposure.
- Workers should be alerted when cyanide is present and smoking, eating and drinking should not be allowed.
- Plastic gloves should be worn to avoid contact between skin and cyanide.
- Mixing of solutions should be conducted in a ventilated area and cyanide should only be added after the pH is adjusted to above 10.

Adding excess cyanide does not increase the amount of gold recovered and therefore it only represents an extra cost. Cyanide levels in the tailings water and pregnant solution should be measured. If concentrations exceed 0.01 grams per liter, less cyanide should be added to the process.

For heap leach and vat leach operations, it is important not to lose the leach solution through leaks as it contains the gold. Therefore it is important to have a waterproof barrier at the bottom of the heap or vat. When the gold is finished leaching, the material in the heap or vat should be rinsed with water and the water should be collected in a watertight pond. This water will contain cyanide and a small amount of gold. Recycling this water for the heap or vat leach, will save on the amount of lime required, the amount of cyanide required and returns the residual gold to the process where it can be recovered.

The waste from tank leaching is normally deposited to a tailings pond, which should have a waterproof barrier at its base. The waterproof base will prevent the loss of water contaminated with cyanide to streams. If the leach is discharged to a stream there is a risk that it will kill fish, contaminate wells, poison drinking water and possibly kill people. The pond should be shallow to take advantage of the natural cyanide destruction resulting from exposure to sunlight. Water from the tailings pond should be recycled for processing. Any cyanide remaining will help to leach more gold.

The areas around heaps, vats or tailings ponds should be fenced and warning signs should be posted to prevent accidental access. Fences will keep out animals such as livestock that would be poisoned by drinking the water. Fencing will also reduce access to children and other people who may mistakenly approach these facilities.

Basic knowledge for miners

- Some basic technical skills are required to successfully and safely operate a cyanide leach process.
  - The process needs to be controlled and there are relatively simple tests to do this (e.g., pH paper, blackening of zinc strips in sock, etc.)
- Under the correct conditions, cyanide will dissolve the gold from the rock leaving it in the water.
  - To leach gold, there are four components required:
    - **water, cyanide, air (oxygen)** and **alkalinity (high pH).**
    - If one of these components is missing, the process will not work.
- While there is usually enough oxygen in the water, an alkaline such as lime must be added along with the cyanide
- There are three main types of processes that use cyanide to recover gold
  - heap leaching, vat leaching and agitated tank leaching.
- After the gold is leached, it is recovered from the water (called the pregnant solution) using one of two processes: zinc precipitation or carbon adsorption.
- Only a relatively small amount of cyanide is needed to recover gold, usually less one kg of cyanide per tonne of rock
- Cyanide leaches coarse and very fine gold as well as gold that is attached to the rock
- The process is quick; tank leaching normally takes less than one day
- Adding excess cyanide does not increase the amount of gold recovered
- Although cyanide selectively leaches gold, it can also react with copper, iron, silver and mercury. When these metals react with cyanide, they consume it, meaning there is less cyanide available for leaching the gold
  - Some ores require more cyanide because the cyanide reacts with other metals in the ore

  - Ores with copper minerals such as malachite and azurite cause the largest problems because the copper in these minerals reacts quickly with cyanide
- Free cyanide is very toxic and is readily absorbed through inhalation, ingestion or skin contact and is distributed throughout the body via blood. Cyanide stops cells from absorbing oxygen, so death results from the depression of the central nervous system
- Cyanide is highly toxic, and at high concentrations it will kill fish, birds and mammals (including humans).
  - If used responsibly, the risk of cyanide poisoning can be minimized
- Again, if the leach is discharged to a stream there is a risk that it will kill fish, contaminate wells, poison drinking water and possibly kill people.
- Cyanide reacts with mercury to produce soluble chemical compounds that are easily transported with water, thereby spreading mercury contamination to large areas
- When cyanide reacts with mercury, it converts the mercury to a form in which it more easily enters the food chain and becomes more harmful
- Cyanide remaining in the waste (tailings) product can be destroyed to minimize the environmental impact
  - Exposure to the sun's ultraviolet light, coverts cyanide to less toxic forms and ultimately to nontoxic carbon dioxide and nitrates. Cyanide does not accumulate in animals or plant life
- It is important to contain cyanide waste in a sealed pond—recycling the cyanide containing water is good for the environment and helps leach more gold.

Bibliography

Best Practice Environmental Management in Mining: Cyanide Management Published by Environment Australia and Distributed by the Australian Minerals & Energy Environment Foundation 1998.

House, I., Marsden, J.O., Chemistry of Gold Extraction, 1992

Priester, M., Hentschel, T., Small-Scale Gold-Mining, Friedr. Vieweg & Sohn Verlagsgesellschaft mbH, 1992.

Whitehouse, A., Mulyana, A, Hutabarat, I., 2005. Alternatives to Mercury Amalgamation to Recover Gold, US Department of Interior, Office of Surface Mining

Chapter 7
Environmental Effects of Mercury

How mercury contaminates the environment

When gold miners use mercury to amalgamate gold they should be aware that they can easily contaminate themselves, their families, and their neighbors, as well as people living far way from their worksites. The way the contamination takes place depends on how the miners do their work. For example, if the whole ore is amalgamated and discharged without adequate settling ponds, or if mercury contaminated materials are dumped directly from a raft into the river, mercury will be carried downstream and dispersed over a very wide area where it can transform into methylmercury in the sediments at the bottom of the rivers, lakes or streams. Methylmercury is easily absorbed by worms, snails and insects and becomes highly concentrated in fish, especially the piscivorous species (fish that eat other fish). Eating fish contaminated by mercury from ASM activities can pose a great health risk to people living downstream of mining areas. Likewise, mercury vapor emitted from open pan amalgam burning is dispersed in the air. Most of the vapor settles onto the ground and can contaminate soils up to two kilometers downwind from burning. Some vapor however travels long distances and comes down with rain. If the miners amalgamate concentrates in pools, mercury tends to be concentrated within a relatively small area, forming a local "hotspot", i.e. a site with high concentration of mercury-contaminated material.

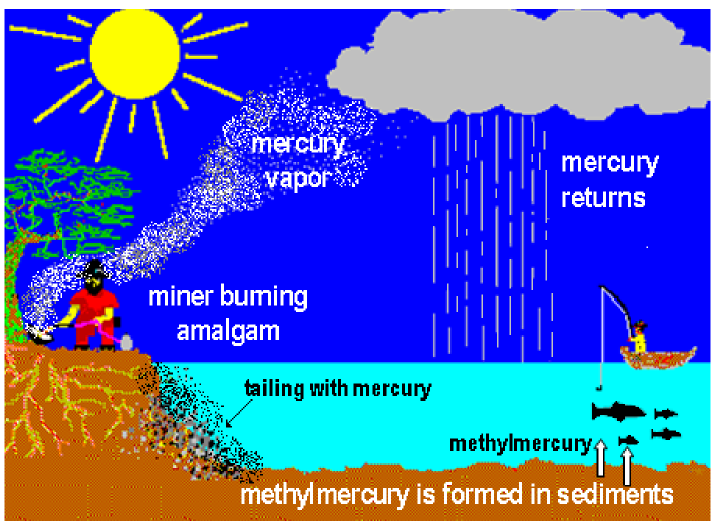

Fig.7.1 – Mercury emitted by miners can be transformed into methylmercury to be accumulated in fish

Environmental mercury contamination can be caused by present-day mining, or by historic and abandoned mining sites that continue to emit mercury to the air or water for many years after mining has ceased. It is difficult to obtain reliable, quantitative data about how much mercury is released from active artisanal gold mining sites because miners do not freely provide information about the amount of mercury they use. At abandoned sites, determining the extent and magnitude of mercury contamination is even more difficult.

Analyses of water, sediments and soils surrounding mining sites can provide only estimates of the amount of mercury released. In order to obtain reliable figures about the amount gold produced or the amount of mercury lost, it is necessary to build a trust relationship with miners to guarantee access to their mining and processing sites. Gaining trust takes time, but without it, it is very difficult to understand how much mercury is used and lost at each unit of operation. Ultimately, remediation of mercury contaminated sites may be necessary to prevent further exposure of human populations, and to ensure that mercury does not continue to be released into the environment and eventually become methylated.

Protect your environment

Mercury released during amalgamation in ponds or next to rivers, and especially during burning of amalgam, contaminates the soil and water of the local environment. This mercury continues to evaporate from soils around amalgamation areas and will continue to contaminate the air that is breathed by miners and their families. Mercury lost during amalgamation and during burning can be washed into ponds and streams. Mercury deposited in water can be transformed into methylmercury which builds up in fish. While the fish themselves are not affected, frequent consumers of fish downstream from artisanal gold mining areas can become mercury intoxicated--it is irresponsible to contaminate an environment and subject non-miners and innocent people to mercury contamination.

When amalgam is burned, mercury vapor is carried by the air to very distant places. Likewise, when mercury is used with copper plates (and other forms of whole ore amalgamation) the sand and silt flowing over the plates scours mercury from the plate and carries it in the river to regions far from the mines. **Microscopic droplets of mercury become attached to fine, muddy sediment particles which travel easily downstream, far away from mining areas**. Even if amalgamation is conducted in enclosed ponds, elemental mercury adhered to small sediment particles can be washed into regional stream systems during rainy periods. Mercury attached to the fine particles of sediment can travel kilometers and part of it is oxidized. In a slow-moving area of the stream, the particles sink and find reducing conditions (rich in organic matter) at the bottom of the river. Then, through a biological process, bacteria can produce methylmercury. The methylmercury formed does not stay in the water and it is quickly taken by organisms and it goes up into the food chain to become concentrated in fish, especially the carnivorous species. The more sediment particles introduced to the water, the more that mercury is transported to other places downstream. (Note that metallic mercury is not soluble and does not stay in the water. There is no health risk from drinking clear or filtered water from streams. However, because mercury can be attached to the fine sediment particles, it is not advisable to drink dirty water.)

People must not eat fish that have been grown in amalgamation ponds or near streams that might receive mercury contaminated water. Amalgamation should only occur in ponds that are dedicated for this purpose; similarly, fish should only be grown in special dedicated ponds. Water that has been contaminated with mercury or that has been used for amalgamation must NEVER be used for cooking, bathing or drinking.

It is important that forests around mining areas are protected and are not cut down. These “buffer zones” allow the sediments to settle locally, preventing the transport of mercury attached to fine muddy particles from reaching streams or lakes where it can be transformed into harmful methylmercury. Similarly, it is also critical that residual mercury contained in amalgamation ponds does not reach open aquatic systems; efforts should be made to site amalgamation ponds in safe places, protected from flooding during rainy seasons. Hg-contaminated tailings should be disposed in cement-lined ponds. Where cement-lined ponds are not available, a “harm reduction approach” may be necessary--in some situations it may be sufficient to contain amalgamation tailings in covered 1m-deep holes lined with plastic and compacted red earth (the iron oxide in red earth easily attaches to elemental mercury, holding it in place).

Basic knowledge for miners

- Miners should be aware that mercury amalgamation can contaminate
  - miners themselves
  - their families
  - their communities
  - people living a long distance away
  - the environment
- Burning amalgams in open pans can cause significant mercury soil contamination up to 2 km away

  - Mercury vapor can travel even greater distance and fall down with the rain
- Amalgamation in pools or ponds tends to keep mercury contamination in a relatively small places or "hotspots"
- Dumping amalgamation tailings into rivers carries the mercury far away
  - Mercury in these streams transforms into methylmercury through chemical and biological reactions in the river sediments
  - Methylmercury builds up worms and bugs that in turn are eaten by fish - in general, this mercury doesn't make the fish look sick
  - People downstream from ASM areas who eat these apparently healthy (but poisonous) fish can become very poisoned by methylmercury
- Contaminated soils and tailings release Hg long after mining has ceased
  - This poses a long-term hazard to miners and local communities
- Metallic mercury is not soluble in water and quickly settles to the bottom.
- Mercury does not stay in solution in water
- Mercury stays attached to small suspended particles
  - Water that is filtered, or is clear generally contains only very low amounts of mercury
  - Dirty water has silt particles that can hold tiny mercury particles in suspension
  - Do not drink unfiltered/unclear water in ASM areas
- Never use copper amalgamation plates
  - Sand in slurry scours the mercury from the plate and carries it with the tailings
  - Mercury lost from copper plate amalgamation attaches to tiny pieces of sediment/silt and can be carried far away.
  - Cyanidation circuits make the mercury more easily methylated
- Never put mercury in centrifuges or ball mills
  - This pulverizes mercury which is lost with tailings
  - Pulverized mercury does not amalgamate gold
- Never discharge amalgamation tailings into water courses
  - Mercury-contaminated tailings can be carried to long distances
  - Residual mercury in amalgamation tailings can be transformed into methylmercury
- Always make amalgamation distant from streams, rivers or lake
- Do not dump amalgamation tailings (contaminated with Hg) into water streams.
- Methylmercury can build up in fish

        - Do not eat fish that have been farmed in active or abandoned amalgamation ponds
- Don’t cut forests around mining areas because the soil in these forests can help keep the mercury from entering the streams
- Dispose amalgamation tailings in cement lined ponds
    - If necessary dispose amalgamation tailings in pits dug in red clay soils (iron rich laterites)—these soils contain iron oxides and clays that hold mercury in place
        - Dig pits at least 1 meter deep; line pit with red clay soil and plastic sheeting; cover it with red clay soil

Chapter 8
Health Consequences of Mercury Exposure

Mercury in the environment

Mercury is a naturally occurring element that is present in low concentrations in all living things. Elemental mercury is a heavy, silvery liquid that has had many industrial purposes, and is used in thermometers, switches, fluorescent lights, and to manufacture caustic soda. Humans have also known how to use mercury to amalgamate gold for at least 2,000 years.

Mercury is the only metal that is present as a liquid at room temperature. It also has the lowest boiling point of all metals, which is why it evaporates or "burns" easily. Mercury vapor is colorless and has no odor and is extremely toxic. Mercury is also very "sticky". When evaporated, particles of mercury easily stick to surrounding furniture, walls, skin and clothing. Clothing worn during burning can continue to emit high concentrations of mercury for many hours and can contaminate other areas, including the air your family may breathe.

Natural processes, especially volcanic activity and natural forest fires, release about 1/3 of the global annual contribution of mercury to the atmosphere. Human activities, especially burning of coal and using gas in vehicles and in generating stations, contribute more mercury to the atmosphere than the mercury that comes from nature. Mercury released by small-scale mining activities around the world is a very significant source of atmospheric mercury and must be reduced. Mercury used in gold extraction is often discharged along with mine tailings and during burning of amalgams. Mercury released during burning of amalgams can seriously contaminate local environments including homes, neighborhoods, clothing, and food. Mercury is poisonous and can be easily absorbed by humans and animals. Mercury released to the environment, whether naturally or by human activities, is transported around the world and is eventually deposited in rivers and lakes--ultimately some of this ends up in fish and other animals consumed by people.

In some places, the major route of exposure to mercury is through fish consumption. The chemical form of mercury in fish is different than the *elemental mercury* found in thermometers or used in mining. This form of mercury is called *methylmercury* and it is considerably **more** toxic than elemental mercury. Fortunately, only a small portion of elemental mercury released or lost into ponds and rivers becomes transformed into methylmercury. However, because of the extreme toxicity of this compound, it is very important that losses of mercury to the environment are controlled or eliminated, to avoid contaminating the environment and poisoning animals and people who consume contaminated fish. It is especially important that miners are aware that mercury released from mining can poison people not involved in mining.

Human exposure to mercury

For miners, mercury can be absorbed directly through the skin during the amalgamation process. However, the main route of exposure in small scale and artisanal miners is through inhalation of mercury vapors during burning of mercury – gold amalgams. The absorption of mercury vapor is very dangerous and can lead to serious health problems. Most people in the world however aren't directly affected by mining, so fish consumption is the major route of exposure for them to mercury (as methylmercury). Both mercury vapor and methylmercury affect the brain, nerves, senses (e.g., vision, hearing) and organs (liver, kidney, glands).

Elemental mercury vapor has no color and no odor. Mercury sticks to clothing worn during burning and will continue to be a source of mercury vapor long after burning has ceased. When breathed, mercury is absorbed by the lungs and is passed directly into the bloodstream where it is carried to all organs of the body. The body retains 80% of all inhaled mercury vapor. Wearing a dust mask does not afford any protection from mercury vapor. Mercury has no biological purpose and the human body recognizes mercury as harmful. The liver and kidney attempt to rid the body of mercury that is either inhaled or absorbed through the skin. The liver attempts to detoxify and get rid of the mercury via the digestive system. The kidneys attempt to get rid of mercury in the urine. However, mercury can build up in the body, especially the kidneys, and can cause serious damage.

Mercury levels in urine are the best indicators of recent inorganic (metallic) mercury exposure, especially from burning of mercury. Measuring mercury concentration in the breath is another useful means of determining recent exposure. A person who has recently burned mercury or has been burning for some time will have strongly elevated mercury concentration in their exhaled breath, as the body tries to rid itself of the mercury in the bloodstream. Elevated mercury in blood or hair is regarded as a good indicator the mercury exposure has been from eating fish containing methylmercury.

Analysis of urine, blood and hair is a common means of determining the amount of mercury in an individual and assessing potential risk. Trainers of miners should understand the meaning and usefulness of these kinds of analyses.

Urine –The normal units of reporting mercury concentration in urine are as µg Hg/g creatinine. That is, mercury is adjusted or standardized according to the amount of creatinine (an amino acid) in the urine so that results are not affected by dilution (e.g., if someone drank a lot of water they would dilute the urine and therefore the Hg concentration). The World Health Organization (a United Nations organization), considers 4 µg/L of total mercury (not adjusted for creatinine levels) in urine to be normal. A concentration higher than 5µg Hg/g creatinine is risking health effects; at concentrations above 20µg Hg/g creatinine, there is definite cause for concern and probable risk of mercury intoxication.

Blood – Mercury levels in blood are the best indicator of total (inorganic and organic) mercury exposure over time. Blood is more difficult to measure in people because specialized equipment is necessary (e.g., sterilized needles, special vials containing chemicals to prevent coagulation, etc.,) and someone trained to collect blood is required. For these reasons, measuring mercury in blood is less common than measuring in urine or hair.

In blood, a concentration of 5 – 10 µg/L mercury is considered normal. At concentrations exceeding about 200 µg/L of mercury there is a 5% risk that some neurological damage has been suffered. This means that one person in 20 with a mercury concentration in blood exceeding 200 µg/L is likely to demonstrate some impairment of brain function, such as memory loss or lack of coordination of the hands.

Hair – Measuring mercury in hair provides an excellent record of exposure to mercury, especially from eating fish. Mercury becomes very concentrated in hair which is one of the routes that the body uses to rid itself of mercury. Most of the mercury in hair is methylmercury, which is the same chemical form as is found in fish. Mercury is much more concentrated in hair (about 200 to 300 times) than in blood. It is also much easier to measure mercury in hair than in blood, because no special equipment, expertise or preservation is required to collect the samples. Because hair grows at an average rate of 1.3 cm per month, a record of exposure to mercury can be gathered by analyzing the hair in different segments, to acquire a history of exposure.

In ASM communities, especially among burners of amalgam, mercury in hair comes partially from vapor sticking to the hair, and partially from fish consumption. To eliminate this external contamination by mercury vapor, hair samples should be washed with neutral detergent, acetone and water to eliminate mercury stuck to the surface of the hair.

The concentration of Hg in hair among unexposed people is 1–2 µg of mercury per gram of hair. If a pregnant woman's hair contains 20 µg/g or more there is a strong possibility that the developing fetus will be affected. Recent research considers 5 µg/g Hg in hair as the upper limit guideline for pregnant women, to prevent damage to the fetus.

Uptake and elimination of mercury

Mercury is a potent neurotoxin; it impairs and destroys the brain and nervous system and other organs. The nervous system is made up of many different parts, so symptoms vary depending on the individual and on the amount of mercury and amount of time a person has been exposed. Mercury is very dangerous, especially to pregnant women and children. Mercury is absorbed into the lungs during inhalation where it passes directly into the bloodstream; it can also be absorbed though the skin during the amalgamation process. The bloodstream carries mercury throughout the body, including the brain and nervous system. Mercury also passes through the placenta in pregnant women, affecting the developing fetus. Fetuses and children are at greatest risk because mercury impairs proper development of nervous tissue and can cause many symptoms ranging from mild reduction in intelligence and coordination, to distortion of limbs, severe retardation and in severe cases, death. The effects of fetus exposure to mercury may take months or even years to appear. In the later years the child may develop learning disabilities.

Inhaled mercury is also deposited in the kidneys. Elimination of mercury from the body is mostly via urine and feces, but some is exhaled from the lungs as mercury can also leave the bloodstream the same way it was absorbed. Elimination of most inhaled mercury takes several weeks to a number of years. If a burner has been using or burning mercury amalgam for a long time, mercury will build up in the body. The longer a person has been exposed, especially burners, the longer it will take for the body to rid itself of mercury. This may take many years and some of the effects of exposure to mercury may be irreversible. The longer that a person has been exposed, the greater the likelihood that the person will be affected.

Medical indicators of mercury exposure

The most toxic form of mercury is methylmercury which is a product of transformation of metallic mercury discarded by miners (and other industrial and natural sources) into the environment. Methylmercury does not stay in water as it is accumulated by the aquatic bugs and animals very fast. There have been no cases of human mercury poisoning through drinking water.

The health effects (and symptoms) of mercury vapor and methylmercury intoxication are somewhat different. As seen above, the main way in which a person is contaminated with metallic mercury is through the vapor emitted by gold miners and gold shops. As methylmercury is absorbed by fish, a person can be contaminated when eating fish containing even moderate levels of methylmercury. The world's worst accident with methylmercury occurred in the 1950s and 1960s in Minamata, Japan, when a plastic factory discharged waste water containing methylmercury into an ocean bay, contaminating the fish. Eating these fish killed thousands of people and made many children retarded.

It is often difficult to diagnose if a person is intoxicated with mercury vapor. There are many things that can confuse a diagnosis, including malaria, alcoholism, and malnutrition. The likelihood that a person is affected is highest among the following people:

- amalgam burners
- people who have used or burned mercury for a long time
- children of mothers who were exposed to high concentrations of mercury during pregnancy
- children routinely present during burning of amalgam, and
- people who consume large amounts of fish from mercury contaminated ponds or rivers.

Analysis of mercury in urine, blood or hair does not necessarily indicate or diagnose if a person is intoxicated. A person who has ceased burning for more than a year, but who has been exposed to mercury for a long time, can measure low levels of mercury in blood or urine, but may still be suffering the effects of metallic mercury poisoning. The brain or other organs may have suffered irreversible damage and this cannot be detected by measuring blood or hair. Similarly, urine, blood and hair analyses cannot be relied on to diagnose people poisoned with methylmercury.

Medical exams can diagnose whether or not a person has suffered effects of exposure to mercury. A medical exam consists of an initial questionnaire about the health history of the individual followed by physical and neurological examination. Questions related to health history are needed to exclude participants with diseases that might confuse a diagnosis. Individuals are administered a series of tests that are designed to detect effects of mercury poisoning. These are simple tests and local health care professionals should be trained to perform such a series of tests in local health offices. Examples of clinical tests consider the following:

- Trouble with coordinated walking (ataxia)
- Tremors
- Test of alternating wrist movements
- Test of the field of vision.
- Reflexes: knee jerk reflex and biceps reflex.
- Finger-to-nose test
- Eyelid tremor
- Tongues tremor
- Excessive salivation
- Numbness of fingers and toes

Examples of neurological tests include

- Short-term memory and concentration tests
- Co-ordination tests
- Tests of the intensity of tremors
- Ability to draw shapes and draw between lines on a page

Properly trained individuals can detect mercury intoxication and these tests do not demand special equipment. However, these tests should only be administered by an experienced health professional because proper analysis and interpretation of data is essential. Even then, sometimes a definitive diagnosis is sometimes not possible. However, if a person has burned mercury for some time and displays many of these physical or neurological symptoms, mercury intoxication is the likely cause.

Symptoms of mercury vapor exposure

The major health concern of elemental mercury vapor poisoning is the brain, central nervous system and kidneys. Damage is often permanent and irreversible. Inhaling large amounts of metallic mercury vapor, such as when miners are burning amalgams in open pans, causes acute exposure. This can cause many symptoms including difficulty and pain when breathing, chest pains, coughing, pneumonia, and kidney failure. Chronic exposure to smaller amounts of mercury over a long period of time includes many symptoms including:

- headache
- metallic taste in mouth and bleeding gums
- tremor of fingers and toes
- poor coordination of movement of arms and legs
- difficulty writing
- unsteady walking
- slurred speech
- blurred vision and long-sightedness
- dizziness
- hearing loss
- impotence in men
- loss of coordination of hands and fingers
- inability to perform rapid alternating movements

Psychological symptoms include insomnia, irritability, fatigue, forgetfulness, difficulty concentrating, lack of energy, exaggerated emotional response, loss of interest in sexual relations, melancholy, and depression. These symptoms may not always be consistent and differ from person to person.

Unborn and young children are at the greatest risk when exposed to mercury because their organs, nervous tissue and brains are still developing. Mercury inhaled or absorbed though the skin becomes accumulated in the growing brain and can result in permanent damage to the brain, causing a reduction in intelligence, coordination, and impaired development. In severe cases of exposure, this can result in severe retardation or death of the child.

Consequences of mercury exposure

There are both immediate and long-term effects of using mercury in the gold mining process for miners, mining families and the whole community. Typically there is a low level of contamination that affects all of the community members, especially near burning areas. If mercury is used or amalgam is burned inside a house, this results in contamination of the house, the miner and his/her family. **Burning amalgam in the home or enclosed areas must be avoided**. When any burning of amalgam is conducted, a retort must be used to contain and recycle mercury in order to reduce exposure of the workers and neighbors to mercury vapor. The risk to women, unborn children and young children is particularly high, especially when burning is performed by women or children in the home. Even small exposure to mercury is dangerous. If pregnant women are exposed the child may suffer minor deficiencies in metal function even though the mother may have very mild or no symptoms at all. In addition, if the new mother continues to be exposed to mercury, this mercury will be passed from mother to baby via breast milk, causing ongoing further poisoning of the baby.

Children should not be exposed to mercury and should not be directly involved in mining activities. Exposure to mercury, hard physical labor, unsafe mines, and lack of safety equipment puts children at risk and exposes them to conditions they cannot control. This is unfair to an innocent child. There are great long-term benefits to children, families and communities when ways to prevent mercury exposure are adopted by miners.

ASM communities are also faced with a variety of other challenges, such as malnutrition, diarrhea, malaria, tuberculosis, parasites and other diseases and afflictions. The sometimes subtle symptoms of mercury poisoning may be overlooked because of the stress of facing acute illness, accidents and everyday poverty.

As already mentioned, an additional risk posed to ASM communities is sometimes exposure to mercury via fish. Fish are an excellent primary source of source of animal protein and in some places are consumed frequently. A portion of mercury lost during amalgamation can become transformed into toxic methylmercury which accumulates in fish. In general, carnivorous fish accumulate more methylmercury than plant eating fish; large carnivorous fish tend to contain the most methylmercury which they absorb from the many smaller fish they have eaten. Following is a list of fish species from Indonesia that can safely be consumed and those that should be avoided. (Miners can work with local health and environmental officers to identify the fish that are the safest to eat in their regions.) Under no circumstances should fish be consumed from the same ponds in which amalgamation is conducted.

Examples of fish safe to eat in Talawaan, Indonesia

Fish Safe to Eat	**Fish to Avoid Eating**
Nilem (detritivorous)	Tahuman (piscivorous)
Patin (detritivorous)	Tampalbor (omnivorous/piscivorous)
Saluong (herbivorous))	Buang putih (omnivorous/piscivorous)
Gete gete (omnivorous)	Cakalang (piscivorous)
Jelawat (omnivorous)	Telak or Gabus (piscivorous)

If any of the above, "safe to eat" fish are grown in amalgamation ponds, they should **NOT** be eaten.

Treatment of mercury poisoning

There is no cure for mercury poisoning. Western medical treatment for acute and chronic mercury poisoning is very expensive, and cannot reverse any damage done to the brain. The only steps that can be taken are to remove the person from any more exposure. Traditional herbal treatments are being researched, however, there is no proven solution available at this time. For now, the best treatment is education and prevention. Most importantly, this involves awareness of the hazards of exposure to mercury, especially to pregnant women and children.

Protect yourself and your family

The keys to protecting yourself and your family from mercury contamination involve simple behavioral changes or adoption of simple technologies that can not only reduce the risk of contamination, but improve gold recovery as well as recover mercury for re-use (see chapters 3, 4 and 5 above).

The following list provides a number of simple behavioral changes that if adopted can significantly reduce exposure to mercury. It is very important to prevent or minimize exposure to mercury, especially the mercury vapor produced during the burning of amalgam. It is particularly important to prevent exposure of women and children to Hg.

- Behavioral changes are essential to minimize exposure: While recognizing that behavioral change is difficult, miners should be encouraged to burn amalgam as far away as possible (perhaps 200-300 m) from other people, homes, schoolyards, churches, mosques or temples. Do not burn amalgam inside the home. Never burn amalgam in the kitchen.
- If you burn amalgam, **USE A RETORT: A simple and effective retort can be made from kitchen bowls.** If a retort is not available, burn away from people and change clothes after burning and store them in a bag away from the home; women and children must not burn and should be kept far away from burning areas.
- Do not amalgamate in a river or pond that is used for drinking, cooking, washing or growing fish. Small amounts of mercury are always lost during amalgamation and can be transformed to the much more toxic methylmercury form which accumulates in fish.

- Amalgamate in a pond dedicated for this purpose. Locate the pond well away from a river or lake to prevent small amounts of mercury from being washed into the river or lake during the rainy season.
- Burn amalgam in a well-ventilated area equipped with a fume hood and if available, equipped with a carbon filter.
- Avoid breathing mercury vapor! Using a mask does not prevent your lungs and body from absorbing mercury.
- Mercury vapor is present in high concentrations around the burning area for a very long time after burning has taken place. You and your family will be exposed to mercury long after burning has ceased.
- Adopting new technology can minimize or prevent exposure to mercury. This can include the use of an amalgamation barrel to amalgamate concentrate (or more simple solutions like the use of gloves or a stick to mix mercury with concentrate) and the burning of amalgam in a retort which will recover mercury for later use and save you money.
- Consider creating an amalgamation center for your community – a central place where burning with retorts can minimize exposure to people, and which will reduce the size of the area of contamination and reduce contamination of the environment.
- Certain fish species naturally have higher mercury than other fish species. Avoid consuming fish that eat other fish (i.e., carnivorous fish) and instead select fish that prey on insects or plants (e.g., carp, tilapia, minnows, some catfish).
- Spread the knowledge. Tell others what they should and should not do when using mercury

Basic knowledge for miners

- Mercury (Hg) is a neurotoxin and very dangerous to humans and their environment
- Gold miners are exposed to Hg mostly by breathing mercury vapor released when burning amalgam in open pans or handling copper-amalgamating plates.
- Mercury can also be absorbed by the skin by handling it without gloves.
- Mercury vapor is invisible and very easily absorbed by the lungs

- Levels of toxicity of undue mercury vapor exposure can be measured by testing urine of people
- A person who has ceased burning for more than a year, but who has been exposed to mercury for a long time, can measure low levels of mercury in blood or urine, but may still be suffering the effects of mercury poisoning.
- Having a history of exposure can cause long term damage to nervous system and kidneys, and even death
- Mercury is the most dangerous to unborn babies and young children. Therefore pregnant women must be also protected from mercury
- There is no cure for mercury poisoning
- The best treatment is prevention
- Do not burn mercury burning near homes, children or women
- Use retorts (outside) when burning mercury
- Create and share amalgamation and burning sites away from homes
- Do not amalgamate near water sources, or where water can carry sediments into rivers
- Use the most effective amalgamation methods available
- A biological (bacteria) reaction transforms at the bottom of the river and lake sediments many forms of mercury into methylmercury
- Methylmercury is one of the most toxic substances of the world
- Methylmercury does not stay in water as it is accumulated by the aquatic bugs and animals very fast. There have been no cases of human mercury poisoning through drinking water
- Methylmercury accumulates in small organism and it goes up on the food chain, i.e. it becomes more concentrated in carnivorous species
- Avoid eating carnivorous fish in contaminated areas

Chapter 9
General Health Concerns of Artisanal Mining Communities

The United Nations Millennium Goals reflect the poverty and resulting malnutrition and lack of health care of almost 4 billion people who are struggling to survive on less than US$ 2/day. Artisanal mining communities are typical of the rural communities that the Millennium Goals seek to benefit.

- 6 million children die from malnutrition before their 5th birthday every year
- 6,000 people die from HIV/AIDS everyday
- 8,200 people are infected by HIV everyday
- 300 – 500,000,000 people are infected with malaria each year
- 2,000,000 die from malaria each year
- 800,000,000 people are hungry everyday 300,000,000 are children
- 270,000,000 of these children suffer long-term malnourishment and micronutrient deficiency
- TB infects someone every second
- 5 – 10% of these people become sick or infectious at some point in their life
- If left untreated someone with active TB will infect 10 – 15 people each year
- 2,600,000,000 people (40% of the world's total population) do not have basic sanitation
- 1,100,000,000 people drink from unsafe water sources daily
- 5,000,000 people (mostly children) die of water-borne diseases every year

With this in mind we are reminded that for whatever reason we find ourselves working and training in artisanal mining communities, whether as miners or as mining engineers, technical experts, economists or teachers, we need to work with the social and health issues associated with poverty. The social issues include: frequent illegality of artisanal mining, frequent relocations of individuals, poor infrastructure, loss of adults due to disease and accidents, breakdown of family structure, gender inequity, child labor, abuse of alcohol and other drugs, gambling, prostitution and violence. The most significant illnesses that are responsible for much suffering and premature death are malaria, HIV/AIDS and TB. These are exacerbated by malnutrition, inadequate access to clean water and sanitation and by the social issues.

Malaria

Malaria is a serious, potentially fatal, contagious disease that is transmitted from one infected person to another through the bite of female Anopheles mosquito. It is caused by parasites, which are very small and can only be seen through a microscope. They feed on blood cells, invade them and ultimately destroy them. This causes anemia, loss of red blood cells, which are responsible for transporting oxygen around the body. The parasites can move to internal organs including the brain. More than 40% of the world's population is at risk for malaria.

Malaria, typically has three stages: 10 days to 4 weeks after being infected a person first experiences a headache with chills and shivering for about one hour. This is followed by a fever of 40°C or more. At this stage the person is weak, has warm, dry, reddened skin and may be delirious for three or more days. Finally the person begins to sweat, and the temperature goes down.

People suffering or recovering from malaria need plenty of liquids and food. This is especially true for children. Malaria is very dangerous for pregnant women, because it causes severe anemia, miscarriages, stillbirths, low birth weight and maternal death. If possible children and pregnant women with fever should receive immediate medical care and treatment. Children with fevers should be kept cool, by bathing them with cool (not cold) water frequently, which encourages body heat loss.

There is no vaccination for malaria yet, although preventative medication is available in some areas. When someone is ill with suspected malaria, treatment should start as early as possible, because delaying can make the disease more dangerous. Once medical treatment is started, it is essential that the full course of recommended medicine be taken. Medical treatment is not universally available in artisanal mining communities. So, taking action to stop mosquitoes from breeding near homes can help protect families and communities. These steps are much more successful when groups of people work together because mosquitoes fly all over the place. Mosquitoes breed within 2 km of where they bite people. Swamps, ponds, puddles, pits, drains, latrines, water pots, tanks, inside old car tires, animal water containers, in moisture on grass and bushes, and anywhere else where there is stagnant still water are potential breeding grounds. Covering openings in containers and tanks, filling in puddles, tipping out unwanted water, clearing bushes near houses and building houses more than 2km from stagnant water, all prevent malaria. The introduction of mosquito eating fish into ponds can be effective. Putting a little oil on the surface of pools or marshes stops the mosquitoes from breeding. In addition, the use of window and door screens protects the whole house from mosquitoes. If this is not possible, mosquito nets over the beds of the most vulnerable are very effective. These screens and nets can be treated with biodegradable pyrethroid insecticide, which kills mosquitoes.

Tuberculosis ("TB," "consumption")

Tuberculosis is a serious, potentially fatal, contagious disease that spreads from one infected person to another through the air. One third of the world's population is infected with the TB bacilli, of which 5 – 10% will develop the disease and become ill.

TB spreads most rapidly in areas where large groups of people are living together and sharing air. The TB bacilli can travel through the body of an infected person causing disease in many organs including skin, backbone, lungs and abdomen and glands of the neck, causing growths. Frequent early signs of tuberculosis include: a cough lasting over three weeks, slight fever in the evening with sweating at night, pain in chest or back and increasing weight loss. In children there may be no early cough, but instead children experience weight loss, frequent fever, swellings in neck, energy loss, lighter skin color and seizures. People who have TB and HIV/AIDS are much more likely to get sick as each disease speeds up the other.

TB is diagnosed by skin and spit tests. When one person in a home is diagnosed it is a good idea to test everybody else if possible. Medical treatment for TB exists, but is not always available in artisanal mining communities. When treatment is started it is essential that the prescribed medicine be taken for at least 6 months as ordered. Sometimes people don't want to take medicine when they feel better, and unfortunately this results in TB bacilli that are resistant to the medication. Someone who has TB needs to rest, eat a diet with protein and vitamins.

Having the ill person always cover the mouth when coughing, and sleeping in a separate room can prevent other family members from contracting TB. In addition having children vaccinated with BCG (Bacille Calmette-Guérin) and giving them plenty of nutritious meals will help prevent infection.

HIV/AIDS

HIV is a serious, potentially fatal, communicable disease that is spread from one infected person to another through having sex, giving birth and by any other behavior where an infected person's blood, semen, vaginal juices or breast milk enters another person's body.

HIV attacks the body defenses against diseases, weakening a person's ability to fight off infections and diseases. Often this takes years to occur, so many people live years with HIV completely unaware that they are infected. One of the reasons that it has spread so rapidly is because infected people often look and feel well. When the defenses are exhausted the person becomes ill and dies from another illness (very frequently TB). When a person with untreated HIV gets ill with untreated TB they often cannot survive very long.

There is no vaccination or cure for HIV. Treatment that prolongs the healthy stage of HIV is available in many areas of the world, but in countries without free health care, these drugs are often too expensive for most people.

Sexual transmission of HIV is preventable with the correct use of a new, quality latex condom with every act of sexual intercourse. While, condoms are available free in some parts of the world, they are either too expensive or not always available in most places. Male resistance to condom use has been responsible for the transmission of HIV to women. All women should be encouraged to insist on condom use even if they have only one sexual partner. HIV and other sexually transmitted diseases reveal gender power inequities all over the world. Women in poor rural communities, including artisanal mining communities, experience gender power inequities that are created and augmented by economic, social, and gender role expectations and by traditions.

Gestational (mother to baby) HIV is preventable only if there is a supply of HIV medicine and good birthing care available to the pregnant HIV positive woman. Blood to blood HIV transmission is preventable through avoidance of reusing needles and other instruments that break one person's skin and then another person's, and through testing of blood products for transmission in hospitals.

Malnutrition

In much of the world, most people eat one main low-cost food with almost every meal. Depending on the region, this may be maize, millet, rice, wheat, cassava, sorghum, banana, potato or breadfruit. This main food provides most of the body's needs. Other foods are needed to maintain health in addition, and this is particularly important for growing children, pregnant women and the elderly. These other foods include vegetable oils, sugars, vegetables, fruits, seeds, nuts, beans, milk, eggs, fish and meat, which provide protein, energy and protective factors. These additional foods become scarce and too expensive in times of extreme poverty, population movement and drought.

When these foods are available the male adults need to be aware of their own resistance to malnutrition compared to other members of the family and community and prioritize appropriately. Unfortunately this is often not understood early enough, and children die at a disproportionate rate. It is important for us all to remember how vulnerable to malnutrition a large percent of the human population is when there is no food reserve.

Local nutrition programs commonly offer lessons about food groups, meal planning around the area's staple foods and appropriate crops to grow to supplement diets.

Conclusion

Members of artisanal mining communities should be encouraged to cooperate with government staff, health care workers or NGOs who are asking for details of sick people or who are offering support for mosquito elimination, water and sanitation, HIV prevention, family planning and child nutrition programs. If available locally, individuals should know where to obtain condoms, health care, mining safety equipment, and information and support to establish safe water systems and sanitation.

It is important to consider how illness can stress a child with malnutrition to the point of death, how malaria affects a pregnant woman, and how getting infected with TB can hasten the death of a young man with HIV. In fact it is critical to understand how all of these health issues interplay and increase the stress and decrease the strength of individuals and whole communities in order to be successful working in artisanal mining communities.

Basic knowledge for miners

- Malaria
  - Malaria is a disease carried by mosquitoes that kills 2 million/a worldwide
  - Malaria is preventable
  - **Preventing malaria involves whole communities working together to eliminate breeding places for mosquitoes**
  - Prevention also usually involves netting over windows, doors and beds

    - Children, pregnant women and the elderly are the most likely to die from malaria
    - Treatment must be prompt and complete
    - Drug prescriptions must be followed exactly
- Tuberculosis
    - Only 5 – 10% of those infected with TB become ill
    - If left untreated, each of these people infect 10-15 people each year
- HIV AIDS
    - Human Immunodeficiency Virus (HIV AIDS) is a disease that is transmitted by sexual contact and blood
    - 6 thousand people die from HIV AIDS everyday
    - 8,200 people are infected with HIV everyday
    - HIV attacks the immune system, the body's defenses against other diseases
    - There is no vaccination against HIV
    - **Prevention is the best option and involves consistent, correct use of condoms during sexual intercourse**
    - Treatment during pregnancy can reduce the incidence of transmission from infected mother to baby
    - Treatment for HIV is expensive and not available to everyone infected
- Malnutrition
    - Malnutrition kills 6 million children under the age of 5 each year
    - Of the 800,000,000 people who are hungry each day 300,000,000 are children
    - Most of these children suffer long-term malnourishment and micronutrient deficiency

Chapter 10
Clean Water and Sanitation

Why clean water and sanitation are important

"Safe water supply and adequate sanitation to protect health are among the basic human rights. Ensuring their availability would contribute immeasurably to health and productivity for development"

Dr. Gro Harlem Bruntland, Director-General, WHO – World Health Organization.

About 1.1 billion people around the world lack access to safe drinking water, and 2.6 billion people lack sanitation services. The UN Millennium Development goals aims to insure delivery of sanitation to 1.75 billion people by the year 2015. Inadequate or complete lack of sanitation services leads to more than 1.5 billion cases of diarrhea every year, causing over 4 million deaths, most of whom are children under the age of 5 years. Poor sanitation also leads to 1 billion roundworm and 1 billion hookworm infections (70,000 deaths) and 200 million cases of shistosomiasis (200,000 deaths).

The health status of artisanal mining families around the world is generally very poor. In artisanal mining communities, access to health care is minimal or absent, sanitation is lacking, and while the income from gold mining leads to better quality of life, mercury intoxication significantly affects miners' health. In many instances, programs to reduce mercury exposure of mining families should address basic community health needs like water and sanitation at the same time as introducing safer and more effective mineral processing techniques. Reducing the stresses that mining families face--legal and financial, as well as health—will make it easier for miners to accept new technologies that reduce their exposure to mercury.

A key health need of mining communities is often the lack of clean water and appropriate sanitation. People require sanitary toilets that isolate excreta safely in pits, in addition to a minimum of 30 to 50 liters of clean water per person per day, in order to stop excreta transmitted infections and parasites that lock mining families into un-ending cycles of intestinal diseases that cause poor absorption of nutrition.

There are a number of proven, very low-cost technologies capable of delivering clean water and preventing the spread of disease through control of excreta and wastewater disposal. Water can be sourced from groundwater wells, surface water, or harvested rainwater. Contaminated water can be made safe to drink by removing pathogens through sedimentation, filtration, and subsequent disinfection. Water supply solutions can be centralized (e.g., a community water well) or individual (e.g., low cost household sand biofilters).

Simple provision of water supply and sanitation alone is not enough—hygiene promotion is essential. In Zimbabwe's successful sanitation program in the 1980s for example, Ministry of Health extension workers were trained in latrine construction methods, and films demonstrating latrine construction where shown to 1.5 million rural people annually; in schools, children built models of various types of latrines as part of the grade 6 curriculum.

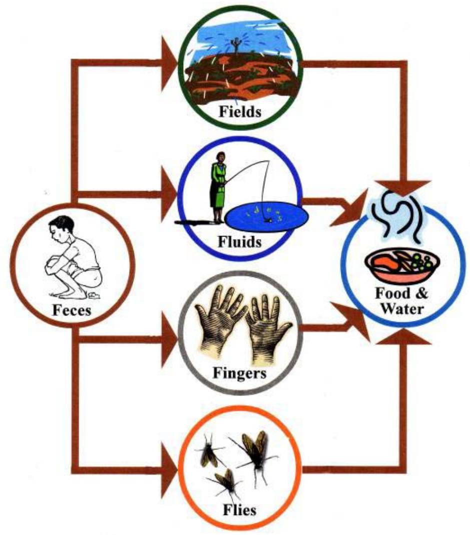

Fig.10.1 - Pathways of fecal contamination of food and water. *(Illustration L. Pevick)*

Changing sanitation practice is a complex social endeavor. There is no universal technical solution or approach to education. Because cultural and social factors vary from region to region, trainers must develop an understanding of how local communities and households function within their society, and of the factors promote and limit change. (This of course applies equally to the introduction of mineral processing technologies.) Factors that control the ability of communities to change sanitation practice include the nature of local leadership and authority, cultural beliefs and defecation practices, and gender roles that influence hygiene practice and determine who is responsible for water supplies, family health and children's defecation behavior.

Low cost clean water options.

Shallow, open wells and surface water are often contaminated in poor rural communities. Deep boreholes that tap confined aquifers are more likely to yield clean water, but deep boreholes are often too expensive and clean water from deep wells can be easily contaminated while being carried to and during storage in peoples homes. In addition, pumping and distribution systems for boreholes are costly to maintain.

Using a simple sand filter in the home can insure that domestic water is safe. Almost 500,000 people are using BioSand filters designed by the Centre for Affordable Water and Sanitation Technology (CAWST, www.cawst.org). Sand and gravel in 40 x 40 x 100 cm concrete boxes utilized the same principles used in city water purification systems world wide to remove pathogens--the sand traps the large pathogens and they die. Some smaller bacteria and viruses pass through the filter, so disinfection with household chlorine bleach or UV light from the sunshine (put the filtered water in recycled 1-2 liter clear plastic bottles on their side in the sunlight for 6 to 12 hours (http://www.sodis.ch) is recommended.

Depending on the availability of materials and the cost of labor, these filters can be manufactured for $US 10 - 40, and last for decades. Costs can be greatly reduced when community members learn how to make these filters themselves. Those who learn how to make these filters can start micro businesses and earn money selling them to their neighbors.

Fig. 10.2 – BioSand filter in Guatemala

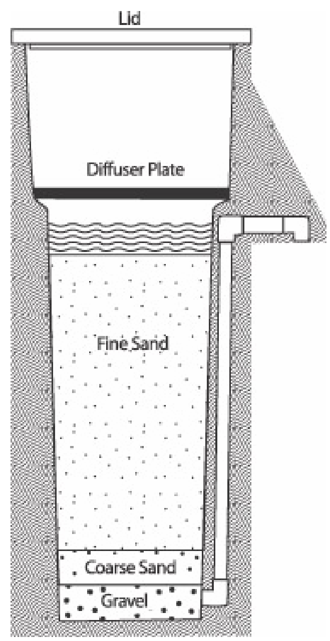

Fig. 10.3 - Schematic of CAWST's BioSand filter.

Low-cost sanitation options

Open defecation, either indiscriminate or in specific locations, is widely practiced around the world, but this practice leads to transmission of disease and the spread of the larvae of intestinal worms through flies, human and animal contact, and contaminated water. Open defecation should not be allowed in villages, and sanitation methods that confine excreta should be encouraged. A slightly better option than open defecation is to use the small pit or "cat method"; next best is a simple pit latrine, but even more effective are ventilated pit latrines which dramatically limit the access to excreta by flies which spread the pathogens.

People sometimes practice the "cat method" or digging small holes and covering their feces with soil; alternately, they dig small 30 cm deep pits which they use for a few weeks, progressively covering the feces with the excavated soil. While the bacteria in the topsoil lead to rapid decomposition of the excreta, large numbers of flies are attracted by the smell, and hookworm larvae can spread in the soil around the holes and penetrate the soles of feet of the users.

Simple pit latrines use a squat hole in a slab placed over a pit of 2 or more meters in depth. The squat hole can be sheltered by a small hut, or can be in the open-air surrounded by thatched screen enclosures for privacy. The slab is usually raised above the surrounding ground level to keep surface water from running into the pit; the slab is sometimes elevated in regions where the groundwater is near the surface. The pit itself should be lined if likely to collapse due to soil instability. Pit latrines are low-cost, easy to build, and the operation principals are easy to understand; however they can smell considerably, and unless the squat hole is tightly covered, flies (and mosquitoes if the pit is wet) are attracted. Simple pit latrines can also utilize 40 cm diameter by 8 meter deep boreholes excavated by an auger. These boreholes can be excavated relatively quickly, but have a short life due to their relatively small volume. Because of their depth, borehole latrine pits increase the risk of contaminating groundwater.

Fig. 10.4 - Open defecation leads to spread of disease and should be discouraged whenever possible. *(Illustration L. Pevick)*

Ventilated pit latrines were a Zimbabwean invention in the early 1970s. Sometimes these latrines are called "Ventilated Improved Pit" (VIP) latrines, or "Blair toilets" owing to their genesis at the Blair Research Institute near Harare. VIPs represent a substantial improvement over a simple pit latrine because odor and fly nuisance is dramatically lowered by a pipe that ventilates the pit (tests have shown that ventilated latrines have only about 1% of the flies found in simple unventilated latrines). The vent pipe is heated by solar radiation which creates an updraft, pulling air through the squat hole and exhausting the smell above the latrine enclosure. Flies are attracted to the exhaust odor at the top of the vent pipe, but are prevented from entering by a screen. Flies are also attracted by light, so the enclosure is kept as dark as practical so that any flies that enter through the squat hole try to escape toward the light at the top of the pipe--their exit is blocked by the screen at the top of the vent pipe where they eventually die and fall back into the pit.

Other more complex and costly sanitation options include pour-flush latrines, composting toilets, septic tanks, aqua-privies, and pump-able vaults and cesspits.

The World Health Organization has published a comprehensive guide to the complete spectrum of appropriate sanitation options for the developing world, "A guide to the development of on-site Sanitation" building on the work of Peter Morgan and Duncan Mara (e.g., "Ventilated improved Pit Latrines in Zimbabwe"). These papers provide complete engineering specifications and drawings for site selection, safe pit excavation, superstructure construction, and latrine maintenance, and should be studied by trainers who wish to design a sanitation program for ASM communities. Both papers are available on the Internet and are referenced at the end of this chapter. ASM trainers can often find experienced water and sanitation experts in local ministries of health and environment.

VIPs are a good solution for rural and peri-urban sanitation needs. VIPs have been widely accepted in the developing world. In Zimbabwe, for example, more than 500,000 have been built over the last 30 years, owing to the effective promotion and hygiene education by the Ministry of Health's extension staff.

Where to put latrines

Care has to be taken when locating latrines near drinking water sources. Effluent can migrate from latrine pits and contaminate water. Pathogens can be carried some distance in the groundwater, especially in fractured rocks during high rainfall events. Soil can filter large protozoa and some bacteria; smaller organisms are removed largely by adsorption to the surface of soil particles, a mechanism that is favored by slow flow rates in low pH and clay soil. Contaminant flow in groundwater is variable and depends on local hydrogeological conditions.

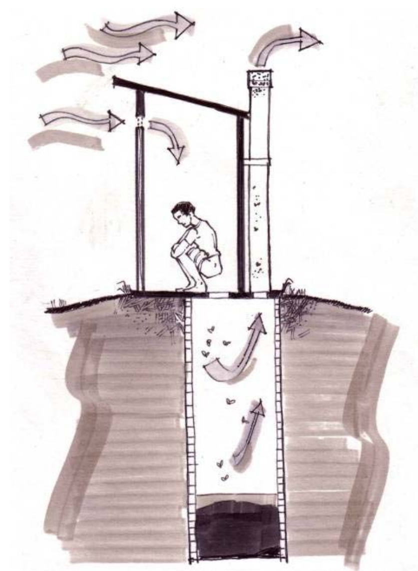

Fig. 10.5 - Ventilated pit latrines (VIP) are host to only 1% of the flies that are attracted to simple pit latrines.
(Illustration L. Pevick)

Pit design

Sludge accumulates at a surprisingly low rate. In Zimbabwe, for example, sludge accumulation rarely exceeds 0.02 m^3 per year/person when the latrine is washed down regularly and where paper is used for anal cleaning. Sludge accumulates at about twice this rate when the pit is dry and where solid objects are used for anal cleaning. A wet 1.5 meter diameter pit 3 meters deep can serve a family of 6 people for 35 years.

VIP pits are typically 1.5 to 1.75 meters in diameter, and about 3 meters deep. Partial or full cement mortar pit linings prevent collapse and access by insects and rodents. The hole is covered with slightly larger diameter, 7.5 cm thick slab that is usually pre-cast on site. Superstructures (huts) can be rectangular or spiral shaped (spirals that open towards prevailing winds scoop the air and push it into the squat hole, keeping odors out of the superstructure; but it should be kept in mind that the direction of the spiral—right- or left-handed—can have negative meanings in some cultures. Where no doors are used, screens or fences can be positioned to insure privacy.

Where mosquitoes are a problem due to high groundwater levels causing flooding of the pits, periodically covering the surface of the water with 5 mm polystyrene balls makes it hard for mosquitoes to breed.

Pit excavation

Loose ground is liable to collapse, either while the pit is being dug (endangering the excavator) or later while the latrine is in use. A safe way to excavate a pit is to use a *caissoning* method where pre-cast concrete rings are laid one on top of another as a worker inside the rings digs soil from underneath the bottom edge of the ring—as the digging proceeds, the stack of rings pushes itself downward into the soil, protecting the worker. Ferro cement reinforcing linings can be constructed by pushing concrete mortar into several layers of chicken wire which is stapled into the pit walls.

Floor slab

The 6.5-7.5 cm concrete floor slab should be reinforced with chicken wire (about 4 layers), or scrap steel reinforcing bars spaced 15-20 cm apart. Holes are left in the slab casting to accommodate the squat hole and vent pipe, and footrests are added later. The surface of the slab is toweled smooth, and the area near the squat hole is sloped slightly inward.

Slabs can also be made of timbers covered with concrete or soil (note that soil floors in latrines can lead to hookworm infection). Rotting of the wood supports can lead to weakening and collapse, as do termites and other insects. Indeed, in some places people tend not to use latrines with wooden floors for fear of falling into the pit.

Mixing the cement for the slab is not a trivial matter. A rule of thumb is to keep the concrete mixture as dry as possible, but keep the cast slab as wet as possible while curing. If kept moist while curing for 3 days, it will achieve 80% of its potential strength, but if allowed to cure moist for 7 days, it will achieve maximum strength. Slabs are usually cast with concrete made of 4 parts aggregate (1-2 cm), 2 parts builders sand, 1 part cement and 0.5 parts water. Use a little more water when the aggregate is very dry in arid climates.

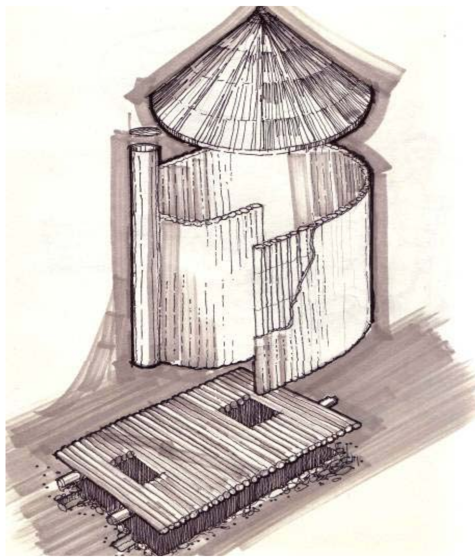

Fig. 10.6 - A spiral shaped, low-cost mud, wattle and thatch VIP on a wooden platform. *(Illustration L. Pevick)*

Latrine structure and vent

The pit is ventilated by a pipe or brick chimney which is attached to the outside of the superstructure, and facing the equator in order to maximize the updraft by maximizing exposure to solar radiation. Vent pipes can be made from local reeds, wire and cement mortar. Flies are attracted to both odor and light. The vent pipe's suction insures that as little odor as possible emanates from the squat hole. If a door is used, it is necessary to provide an air intake hole in the superstructure to enable the suction effect (usually this is placed above the door). Keeping the superstructure as dark as possible insures that flies will be trapped when they try to escape toward the light at the top of the stack. Cobwebs inside the stack from spiders feasting on the trapped flies can block airflow, and should be flushed periodically with a bucket of water.

The superstructure can be built with bricks, or with mud, wattle and thatch. If thatch is used, it should be thick enough to keep the inside suitably dark. The vent pipe should be about 15 cm inside diameter if made of smooth material like PVC pipe, or at least 23 cm diameter if made out of rough materials like bricks. A 1.2 to 1.5 mm mesh fly screen should be wrapped over the top of the pipe. Because the vapors from the pit are slightly corrosive, stainless steel and aluminum last much longer than galvanized or plastic screens (which are destroyed by sunlight).

Basic knowledge for miners

- The international community has placed high priority on helping communities achieve clean water and basic sanitation. Communities should know this and pressure their government and NGOs for water and sanitation assistance
- 2.6 billion people in the world lack sanitation services
- Lack of sanitation services leads to more than 1.5 billion cases of diarrhea every year causing over 4 million deaths, most of whom are children under the age of 5 years.
- Poor sanitation also leads to 1 billion roundworm and 1 billion hookworm infections (70,000 deaths) and 200 million cases of shistosomiasis (200,000 deaths) per year
- Communities can implement simple programs themselves
    - Historical gender roles and cultural resistances need to be acknowledged
- Domestic sand water filters are cheap, effective and last for decades
    - BioSand filters remove all large pathogens (worms and parasites), and about 95% of bacteria
    - Filtered water can be easily disinfected with chlorine bleach or sunlight
- Ventilated pit latrines (VIPs) are almost completely nuisance free—no smell, flies or mosquitoes
    - VIPs are long lasting and inexpensive
    - Easy to build

Bibliography

DIFD, 1996, Guidance manual on water supply and sanitation programmes. http://www.lboro.ac.uk/well/resources/Publications/guidance-manual/guidance-manual.htm

WHO 1992, A Guide to the Development of on-Site Sanitation. http://www.who.int/docstore/water_sanitation_health/onsitesan/

Morgan, P.R., and Mara, D.D., Ventilated improved pit latrines: Recent developments in Zimbabwe, 1982, World Bank Technical Paper Number 3. http://www-wds.worldbank.org/servlet/WDS_IBank_Servlet?pcont=details&eid=000009265_3961003190433

Chapter 11
The Rising Value of Gold

For centuries, gold has been the world's most recognizable form of economic exchange. The value placed on gold as a symbol for wealth has made gold mining, especially artisanal gold mining, one of the oldest, most reliable extractive industries. But in 1944, following the Second World War, the representatives of 44 nations gathering at Bretton Woods, New Hampshire, fixed the price of gold at $35 per troy ounce (31.1 g). This system tied the value of gold to the U.S. dollar, made it illegal in many places for private citizens to own gold, and put a cap on the amount of gold central banks were permitted to hold.

When the Bretton Woods system eventually collapsed in the middle of the 1970's, many people expected there would be an immediate rush to produce and horde gold. In fact, this rush did not happen until the 1980's when the great gold rush of Brazil exposed the newfound importance on gold. In periods of economic uncertainty, central banks and entrepreneurs still revert to gold to hedge their bets against the fall of paper currency. And in September 2001, even as people were just beginning to absorb the meaning of the fall of the World Trade Towers, the whispering on the floor of the stock exchanges had already turned to a shout: Buy gold.

Since then, the international price for gold has more than doubled. Gold is currently exchanged on the international market for more than $US 600 an ounce (31.1 grams), and some analysts are predicting the price will continue to climb for several more years. While predicting the price of gold is difficult, what is known is that central banks in Russia, China, and other powerful countries are again buying up gold bullion, in some cases doubling their current reserves.

Meanwhile, consumer demand for gold is also at an all time high. In countries like India and China, where there is high population growth and an increasing middle-class, the ornamental value of gold is creating high demand for more gold production and manufacturing of jewelry.

The rise and fall of the value of gold does have some impact on the overall number of artisanal gold miners. Yet, because starting out in artisanal gold mining is relatively inexpensive, even when low international gold prices make large-scale mining uneconomic, artisanal gold mining tends to persist. But now the rising price of gold is creating more demand for new sources, and artisanal gold mining is expanding faster than at any time in history.

Artisanal gold miners produce roughly one-quarter of the world's primary gold. There are thousands of remote artisanal gold mining communities spread across 55 countries in Latin America, Africa, and Asia. As many as 15 million people are thought to be mining gold artisanally, and 80-100 million people rely on the economic matrix of small-scale gold production.

While the gold rush phenomenon is global, artisanal gold mining practices and experiences vary widely from place to place. Miners use a broad range of mining methods, come from dozens of language groups, and have different kinds of social, economic, and political arrangements. There are full- and part-time miners, some relying on gold as their only source of revenue, and others using it as supplementary income during periods of economic drought. Levels of organization also vary widely, from permanent communities with established labor organizations, mining cooperatives, and legal status, to migratory groups and itinerant workers operating illegally as part of the world's "informal" economy.

The high gold price is one of the reasons for the growth of artisanal mining, but in the 21st Century artisanal gold rush started well before the price of gold increased. It is predominantly a developing world activity linked closely to poverty. On average, an artisanal gold miner earns about two to three dollars a day – which is much more than what somebody living in extreme poverty would otherwise earn.

Part of the appeal of artisanal gold mining remains the prospect of striking it rich. Indeed, the idea of a gold rush still evokes images of prospectors plucking plum sized nuggets from the bank of the river and retiring on the profits, though even in the great 19^{th} century gold rushes stories of the great find could be profoundly exaggerated. Today in gold rich regions it is still common to hear rumors circulating about someone who did hit the "mother lode". When it happens a "shout" goes out, and news spreads rapidly by word of mouth. Usually the value of the discovery fluctuates dramatically and depends on the level of geological information available and if the miners have the mineral claims in good legal situation. Junior exploration companies, for example from US, Canada, Australia, are well-known for negotiating prospects with artisanal miners. When the company is serious, a miner can share the risks of finding more gold with the company. If a miner wants to negotiate his/her legal mineral title with a mining company, he/she must understand that the company will not pay for a claim just based on what the miner asks or "supposes" that it is underground. The company needs geological proof to establish a gold reserve. This implies geological studies, geochemistry, geophysics, drilling and sometimes, metallurgical tests to see if the gold is easily extracted by cyanidation (which is the main process used by major companies). Unfortunately, most artisanal miners do not have mineral titles or, when they have, they are not in good shape. It is also common to see miners that want to negotiate their titles with companies but they want all money up front because they are bankrupted or they want to get out of the mining life. Very rarely mining companies accept this kind of deal. Miners should be cautious to protect their interest when negotiating with mining companies. Many junior exploration companies do not have knowledge or even intention of producing gold, and there is a history of junior companies misrepresenting their intentions and the value of gold properties to the public.

In fact, today's artisanal gold miners are one of the most marginalized, impoverished, and vulnerable groups of people, and high international prices are not always reflected by substantially higher profits for artisanal gold producers. The core development issues identified by the United Nations Millennium Goals are critical for gold mining communities. Gold miners operate in a political and legal no-man's land where mineral rights and land title are often poorly defined, poorly enforced, or both. Disease is epidemic: In extreme cases, seventy-five percent of people in artisanal gold mining communities are HIV positive. Toxic chemicals – especially mercury – are used in ways no organized labor movement would accept for industrial workers, or any responsible government should permit given what is known about the health effects from mercury exposure. Malaria and typhoid are widespread, as are malnutrition, child labor, gender discrimination, and lack of basic sanitation services and access to clean water.

Yet, for many millions of miners, gold is the quickest, and in many cases the only locally available cash crop. Throughout the world, there are still literally billions of people who lack the capital, the trade networks, and the property rights to be active participants in the cash economy. Gold is one of the few commodities requiring little investment in infrastructure. Its market value is high enough that if a trader develops enough reliable producers he can afford the expense of flying into remote areas to buy raw gold. Not so for the artisanal gold producer, for whom the expense of leaving the bush would immediately wipe out earnings from his meager grams of gold. Meanwhile, this system works out well for governments which benefit by taxing the export of the gold without having to invest anything in rural infrastructure.

In truth, there are two gold production economies: One operated by large companies with the resources to invest in the equipment, technology, and personnel to process enough gold-bearing ores to earn billions in profit. And a second economy in which local producers are trapped by poverty that pushes them towards mining without offering any opportunity for capital development.

To overcome this poverty cycle, the local price for artisanally produced gold needs to be fixed at a higher rate. Unfortunately, the present structure of the gold supply chain does not allow for this. Currently, all gold – artisanal and industrial – eventually ends up at the same handful of refineries around the world. Artisanal miners lose profit by not having direct access to these refineries. One answer to this dilemma may be, as the Government of Tanzania recently demonstrated, to establish small-scale refineries dedicated to purchasing and processing gold only from artisanal producers. Another solution could be to create value added products or certified small-batch commodities similar to ongoing efforts in the agricultural sector to create Fair Trade coffee, rice, chocolate, and cotton industries. In these schemes, additional costs are passed on to consumers who pay premium prices on the assurance this premium finances progressive social and environmental development for local producers.

For artisanal miners, even as gold's value is booming, profit is not distributed equitably to local producers and the natural capital of local communities is being diminished. Rather than financing sustainable community development, higher gold production can strip the land bare of its mineral wealth and replace it with contaminated ecosystems and social deprivation. For artisanal gold mining to lead to greater prosperity and less poverty, artisanal gold communities need organizational tools to deliver their gold more directly to market. In turn, these additional earnings need to be transformed into social capital – mining, environmental and primary school education, and health care and economic diversification – to support the long-term well being of artisanal gold mining communities.

Basic knowledge for miners

- The price of gold changes every day on the international gold market.
- Gold buyers pay miners less than international rates because
    - they want to make a profit to compensate for the risks they take
    - miners' gold is not pure
- Miners can increase the amount of money they receive for their gold if they

    - Develop their own collective marketing systems in order to share the marketing risks and benefits
    - Add value to their gold
        - Make jewelry
        - Certify that their gold is produced in the best way they can by demonstrating good social and environmental practices—communities can work with NGOs to establish Fair Trade standards that are appropriate to local condition
- If miners want to negotiate their legal mineral titles with mining companies, they must understand that the companies will not pay them based on what the miners ask. The companies need geological evidence to establish a gold reserve. This is mandatory in all Stock Exchanges. In this case, miners must be prepared to make an association with the companies and share the risks of the geological exploration.
- Miners must be cautious when negotiating with companies. Some companies want to make money in the Stock Exchanges in their countries and do not intend to produce any gold.

Green, T., 1968. The World of Gold: *The History, the Lure, and the Power of Man's Most Precious Metal.* Simon and Schuster, New York, p.99.

Kisembo, P., 2005. Tanzania embarks on value addition to gold exports. The Guardian, Dec. 2, 2005