



# Global Mercury Project

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



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## Equipment Specification for the Demonstration Units in Sudan

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# 1. Background

## 1.1. Number of Miners and Gold Production

The chosen artisanal gold mining site lies in the middle of Ingessana Hills, 80 km to the Southwest of El Damazin town, the capital of the Blue Nile State. The mining sites are scattered around **Gugub** village, which lies ~10 km Northwest of the Bau town; the administrative center of the Inagassna Hills District. Southern Blue Nile region is accessible by a 520 km long Khartoum-El Damazin asphalt road. El Damazin is connected to Bau and other villages of the Ingessana Hills by dirt roads. In dry season, it takes 2 hours to drive from El Damazin to reach Gugub, the main artisanal gold mining village or Bau. Blue Nile River is the major drainage in southern Blue Nile region and it is fed by a network of big seasonal streams that drain the highlands east and west of the river into the main course. The seasonal waters end up into the western banks of Roseries Dam reservoir at a point around 20 km South of the El Damazin town.

There is no reliable information on gold production in Ingessana Hills prior to late 1996. Although artisanal gold mining activities in the Ingessana Hills is relatively recent, the impact on the economy of the district is substantial. Chromite mining activity in various locations in the Ingessana massif started in 1960s.

Artisanal gold miners in the Ingessana Hills are spread in Gugub, Taga, and Salbal villages. Gugub village of ~1000 inhabitants is the major center of activities. Gugub and the surroundings comprise about 6 major artisanal gold mining sites. At present, Khor Gidad ~7 km (driving distance) North of Gugub and Khor Neiwi ~5 km northeast of Gugub are the main sites. There are between 500 and 800 artisanal miners at the mining area of Gugub. Most miners excavate very competent and hard quartz veins, dipping 45°, and extract material that is manually ground. The work is basically conducted by women (more than 50% of the labor force; in the rainy season this can reach as much as 90%, as men go planting). They cut the rocks with hammer and picks at depth no deeper than 20 m. They do not use explosives. As they extract around 0.3g of Au per day, according to information from a local dealer, the quartz veins must have a grade higher than 30 g Au/tonne. Miners also work with alluvial material and host altered rock. In this case they can crush and grind more material to produce up to 10 grams of gold per day. It is estimated that, each miner produces from 0.5 to 1 g Au/day<sup>1</sup>. This gives about 150-300 kg Au/a. Since 1997, they have produced about 3 tonnes of gold in the Gugub area. Miners, men and women, extract manually both alluvial and primary gold. Women in the 13-35 years age range and children participate in alluvial pitting, rubble panning and bring water for domestic use.

## 1.2. Processing Methods and Mercury

Artisanal gold mining in Gugub is practiced by both Dawala and Ingessana tribesmen without legal titles. The miners do not comply with the provisions provided in the Mines and Quarries Act (1972). Given the adverse situation created by the civil strife around Kurmuk and Queissan border areas in 1996, and in an effort to develop the sub-sector in a sustainable way, the Government tried to legalize the gold mining in southern Blue Nile and elsewhere by granting special licenses.

Few mill owners introduced hammer mills into the area in 1997-1998 but authorities soon drove them out. The primary quartz veins are mined manually from pits as deep as 20 m and the extraction capacity does not exceeds 20-25/day per individual. Rock crushing and grinding is currently performed manually by grindstone or steel mortar and the grinding capacity (to –

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<sup>1</sup> Ibrahim, M.S., 2003. Information about the Project Sites in Sudan. Report to GEF/UNDP/UNIDO Global Mercury Project. October, 2003. 10 p.

0.074mm) is less than 5 kg/day/individual. Most of the hard work is done by women. Men usually control the earnings from gold sale proceeds and have the final say in family affairs. Panning is conducted manually in excavated pools using traditional wooden pans and mercury is added to the pan at the end of the concentration process. Apparently, all fine gold is lost with the light fraction of tailings. One of the main local problems is the lack of water in mid summer. Water is provided by Ingessana women, bringing water for sale from ~2 km away. They carry a pair of 4-gallon plastic containers on their shoulder with the aid of a stick for making balance. The eight gallons of water cost S.D.50 (US\$ 0.2). As the gold amalgam is roasted in bonfires, the amount of Hg in the resulting *doré* is as high as 20%. When miners sell the gold to dealers, they do not melt the beads and pay everything as pure gold. When dealers go to Khartoum or Omdurman to sell the gold, the jewelries melt the bead resulting in 20% of loss and consequent emission of Hg vapor to the cities. Obviously dealers complain that they lose money in this process. The solution is to implement more efficient ways to retort amalgams and to melt gold before being sold to the jewelries.

The amount of mercury emitted in the Gugub area was estimated by Ibrahim (2003 – op.cit.) around 0.3-0.4 tonnes/a. The high price of mercury (US\$ 30/kg) is still controlling the levels of Hg releases. Mercury is provided to miners by local gold dealer. They lend a known amount of Hg to the miners with the promise that they will have the first option to buy the produced gold. When miners return the excess Hg, the gold dealers charge them for the mercury lost and buy the gold. Based on the estimate from some local gold dealers the ratio  $Hg_{lost} : Au_{produced}$  is around 1.4 but can range from 1 to 1.5. Currently in Gugub there are 12 established gold dealers (there were 14 dealers 2 months ago) buying about 6 to 10g Au/day. There are other outside dealers also buying gold in the area.

## 2. Proposed Solution

There is no milling center in the Gugub region. Most individuals mine and process in small groups which is basically a family affair.

The level of education of miners and millers is not high and it seems a bit problematic to introduce a new type of organization in the area. Preliminary surveys in the area revealed that a large majority of the miners agree to work in association but in small groups. Organized Processing Centers must be promoted by the Government and incentives must be provided for someone interested in starting a business on this matter.

An option to introduce the concept of a Processing Center is through a demonstration site owned by the Government to provide fair access to all people involved in the mining activities within the region. Some pieces of equipment can be assembled to teach miners, panners and millers how to process ore with less environmental and health impact. Business matters can be discussed with miners. The focus of the initiative should be on TRAINING not custom processing services.

### 2.1. Transportable Demonstration Units (TDU)

The artisanal mining activities in the Ingessana Hills is extremely widespread. The area occupied by the artisanal miners can easily be larger than 50 km<sup>2</sup>. There is a need to introduce the GMP initiative and technological demonstration of appropriate equipment throughout the mining area, and it is easier to bring a transportable demonstration unit to several thousand people than to bring several thousand (or even tens and hundreds of thousands) of people to a static demonstration unit. A static GMP demo unit located in Gugub would be very far from these areas and the nomadic characteristics of the miners would leave behind the plant as soon as they move.

One of the big challenges in Sudan is how to improve the mining methods. The level of production of individuals who with picks and hammers extract hard ore is too low. The quartz veins are very

competent and alternative processes to demolish the veins without the use of explosive or to mine eroded material, could be brought to their attention. Gold processing is extremely primitive and any simple solution to increase their recoveries would bring an important improvement. However, it seems that miners do not accept new procedures quite easily. For example, Cleangold sluice was tested at the site. At the end of the panning with this new type of equipment, it was very visible the amount of very fine gold concentrated. The miners became astonished with this simple test but the tailing owner, an old lady, was very skeptical and took the whole concentrate and mixed back with the tailings saying that she will do the same at home using her old pan. This is a clear indication that cultural issues in the area can be a strong impediment to introduce new techniques.

The establishment of static Processing Plants would introduces further problems:

- A static GMP demonstration unit would logically be located in a high-producing area, amongst existing sites. After scarcity of the easily exploitable ore, miners would move to more promising areas abandoning the plant.
- A centrally-located, static GMP demo unit in the vicinity of mills would tend to be viewed as a production facility by ASMs rather than a learning facility.
- Problems of land tenure, services, mineral rights, etc., would be involved with a central static demo unit.
- The artisanal small-scale miners (ASMs) are nomadic. It would be logical to have a demo unit that moves with the people and the gold strikes.

As discussed above, for these and many other reasons it would be beneficial to have a mobile or easily trans-locatable demonstration facility. In addition to overcoming certain problems listed above, this facility would provide the following advantages:

1. easier to implement than fixed demonstration/training centers;
2. a transportable training unit would prolong the demonstration effect beyond the project lifetime;
3. as artisanal miners have nomadic characteristics, the training units go after them and not vice-versa;
4. a variety of technical options for gold concentration, amalgamation and retorting can be demonstrated to miners and millers; it is up to them to select what is affordable, appropriate and durable according to their convenience;
5. easy to change and adapt new pieces of equipment used for demonstration without the need for concrete foundations, etc.;
6. more miners and public can be outreached than in fixed demonstration/training units; more people will receive brochures and other educational material;
7. a continuous “supply” of new ASMs to educate, rather than the same handful who would be visiting custom mills close to a static demo unit.
8. the ownership of the training units is easy to decide (Government, University, NGO, etc); no land or mineral title is required;
9. a Miners’ Association (when organized) can embrace this idea without having conflict of interest; the directors will not be the only ones to have benefits;
10. the units have high flexibility in terms of the subjects to be presented to the miners; the ability to add “peripheral” education by addition, for example, health & sanitation, bookkeeping, legal issues, etc);
11. geochemical and medical teams can make use of the units to assess environmental impacts and neuro-toxicological effects of mercury;

12. it is possible to demonstrate the use of safety equipment (e.g. different types of masks for dust, Hg vapour, chemicals);
13. it is easy to incorporate shows (as in a “circus”) to attract miners and public to watch skits and movies about environmental impacts and mercury pollution; this theatrical performances must be designed to be played with the mining communities highlighting local aspects and incorporating concepts of environmental and health protection;
14. the technical demonstration and classes can be conducted either at the mine sites or at populated centers (awareness campaign);
15. it is possible to set up portable classrooms to teach some basic technical concepts;
16. ease of adding space for further infrastructure or equipment by simple addition of a trailer to the primary mobile carrier (truck);
17. the units can bring ideas to improve the livelihood of different mining communities such as suggesting economic diversification activities or value-adding techniques (e.g. handcraft, fish farming, agriculture, brick making using tailings, etc);

One of the main drawbacks of this initiative is the fact that miners may have the impression that the transportable demonstration units is a solution for processing ore in many different sites, which is consistent with their nomadic nature. In fact, mobile processing plants are useful to increase gold production but, as a side effect, they disperse even more mercury pollution and environmental degradation. The training units should be assembled to accommodate different types of equipment not necessarily connected to each other. These units must work as pilot plants only for TRAINING purposes.

## **2.2. Implementation Process**

The steps to implement the transportable demonstration unit (TDU) in Sudan are:

1. selection of the local institution (within the Government) to own and look after these units;
2. discussion of the concept and detailed plan with stakeholders;
3. decision about who will operate the TDU and its sustainability;
4. selection of trainers and elaboration of training material (and eventually awareness campaign movies, brochures, posters, etc.)
5. operating plan and schedules for training are established;
6. contract an engineering company to manufacture, install and start-up the TDU;
7. contract trainers and unit operators.

A clear letter of understanding should be established between UNIDO and the institution that will own the TDU to guarantee that the objective and mandate of the training units will not be diverted (for example to be used as a production unit). In Sudan it has been identified that the Geological Research Authority of Sudan (GRAS), counterpart of UNIDO in the GMP, has all technical attributes and personnel to be in charge of such TDU.

The concept and design of the TDU must be thoroughly discussed with the Sudanese stakeholders including Government agencies, miners and millers’ representatives, equipment manufacturers, academics, NGOs, etc. Details of the design and operation of the units must be discussed and suggestions to improve the design must be incorporated.

The idea of implementing the TDU in Sudan was discussed with Government representatives and other mining experts in April 2004 and it was a consensus to focus the training on organizing processing centers where miners can have better benefits of cleaner technologies.

### 2.3. Components of a TDU

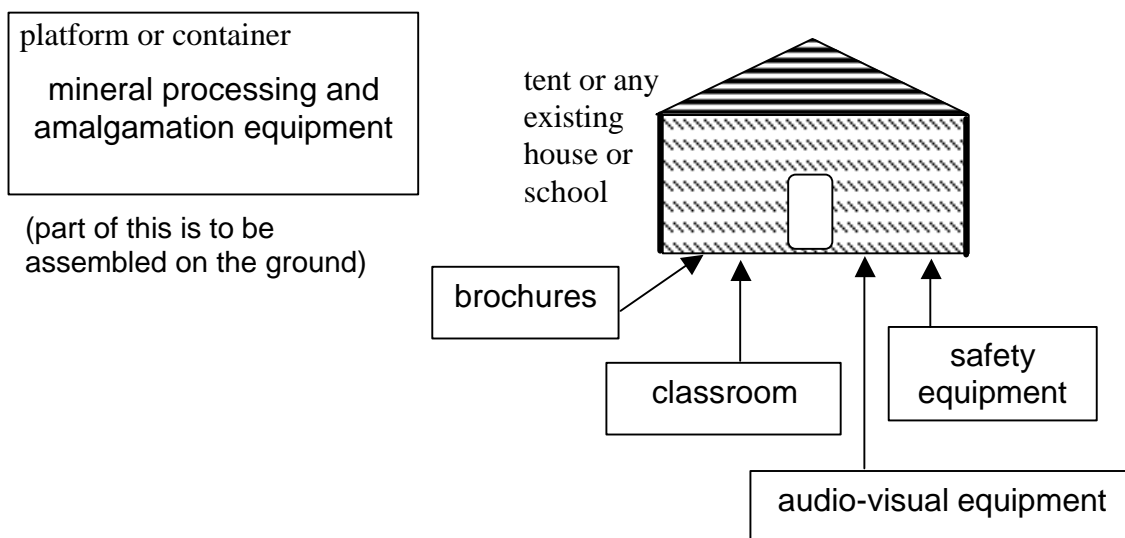
In order to design the transportable demonstration units, the main components of the units must be studied. The main components of the TDU are:

- a platform (or container) to transport and secure all pieces of equipment
- a tent or any type of structure to be used as a portable classroom
- a generator

The main pieces of equipment can be assembled on a fixed wooden platform and other machines, the heaviest ones can be settled on the ground. A heavy truck, preferably of 7 tonne capacity, can move the pieces of equipment from one site to another. The demonstration plant can be either mounted on one site for example for 2 or 3 months or simply assembled in a container. This later reduces chances of vandalism. It seems cheaper to rent a truck to move the unit from one site to another than to purchase a vehicle.

The main pieces of equipment to demonstrate gold processing and amalgamation techniques are not connected. The trainers use them to demonstrate the principles and advantages of each machine and it is up to the miners to up-scale, modify, improve or purchase the machines from a local supplier. A tent or a local simple structure made of wood and straw or an existing classroom is used as a classroom, office, and laboratory (e.g. health assessment and Hg analysis using portable Hg analyzer or colorimetric semi-quantitative techniques).

The main components of a transportable unit is shown in the diagram below:



It is advisable to adopt a “bottom-to-top” approach for the demonstration plants and a “top-to-bottom” approach for the instruction of trainers and training of Government representatives. In this case, the trainers and local leaders will be trained in practical and theoretical subjects related to ASM. The implementation of the demonstration units will be done in existing mining/milling areas and preferentially using tailings as the initial material to be treated. As long as gold is recovered from tailings, this should bring more credibility to the trainers. Subsequently, primary ore can be used in the demonstration units comparing the performance of different types of equipment.

### 3. Selection of Processing/Amalgamation Equipment

The pieces of equipment to be demonstrated to the miners must follow some criteria:

1. must not be very complex (technical knowledge)
2. must be easily accessible (preferentially locally manufactured)



3. must be inexpensive and locally maintained

The main pieces of equipment should demonstrate all steps of a simple mineral processing cycle normally used by artisanal miners. This includes:

1. Comminution/Classification
2. Gravity Concentration
3. Amalgamation
4. Retorting

### **3.1. Comminution/Classification**

It is not trivial to suggest simple comminution equipment, as there is no universal recipe for the most expensive unit operation in mineral processing. Comminution in conventional mining operations is usually conducted in closed systems with classification (e.g. screens or hydrocyclones). This is a way to control overgrinding as well as to achieve the gold liberation size. As no information is available about the **gold liberation** grain size, the principle of testing different grinding times is the only one available to evaluate liberation. Concepts like this can be passed to the miners, who can use a small ball mill and a gravity separation equipment to test their ores. This will definitely improve their gold recovery by gravity concentration. In order to reach the liberation size, comminution equipment must work in closed circuit with classification (e.g. screening) processes. Unfortunately most of the ASM operations conduct their comminution process in open circuit, without any classification. When using sluice boxes, the only classification observed is a rudimentary screening process to eliminate coarse pieces of gravel. These concepts must be discussed with miners in order to implement more efficient techniques. The most popular mills used by ASM are discussed as follows.

#### **3.1.1. Crusher**

The main process used by Sudanese artisanal and small-scale miners (ASM) to crush big blocks of primary ore is a manual hammer. Pounding the ore blocks with a metallic hammer against a heavy metal plate or a rock monolith, miners reduce big block to a size of below 50 mm to feed the fragments into an iron mortar where the ore is ground. A small jaw crusher handling 500 kg/h of material to reduce it to  $-1/4''$  (6.5 mm) it is enough to show the concept of mechanical crushing. This is an important part of the comminution step and must be part of the demonstration unit.

**Table 3.1 – Technical Data of a Small Jaw Crusher (Clarson 6’’x 3’’)**

<b>Specification</b>	<b>Characteristics</b>
Jaw Opening	6’’ wide x 3’’ gap
Max Capacity	0.5 tph
Max Feed Size	2’’(50 mm)
Jaws	Ni-hard steel
Jaw Profile	Ribbed
Product Size	nominal 100% passing $-9$ mm
Drive	V-belt drive, 275 rpm
Power	2.2 kW
Extent of Mechanization	Fully mechanized
Shipping Weight	220kg
Price	US\$ 5000

#### **3.1.3. Ball Mill**

As no information about gold liberation is available, the selection of grinding equipment becomes difficult. In a visit to Gugub it was observed that ASM have been grinding quartz ores in a iron mortar to grain sizes below to 0.1 mm, which indicates that gold must be fine. Preliminary

concentration tests have also demonstrated this. It seems that the fine gold nature claims for a fine grinding system. In this case a hammer mill would not be efficient. Tumbling mills, such as ball or rod mills are the most efficient grinding equipment but they are expensive and demand skill to work correctly. An efficient grinding needs control of critical speed, number of balls, ball sizes, pulp density, power draw, foundation, etc.

One of the main challenges of introducing ball mills is the lack of water in Gugub region. Ball mills can also work dry but this requires at least 30% more power than wet grinding. The ball mills must be hermetically closed to avoid escape of dust. It is clear that introduction of water in the mills will be very beneficial. In dry grinding the contact between particle and balls is lower than in wet milling. Gold can also be easily flattened and retained inside the mills when dry grinding is practiced. Wet grinding does not generate dust and the energy required to grinding is lower than dry grinding. In the demonstration units it is suggested to test dry milling in an adequate small well-sealed mill as well as wet milling using high percentage of solids, as much as 80%.

Despite the low production rate of these suggested portable ball mills, the concept of having many small-batch-ball mills instead of large ones seems interesting. Miners and millers can follow a step-by-step approach acquiring one mill after another and then increasing their milling capacity. This is not the best solution in terms of energy consumption, but definitely is adequate for the financial capacity of the miners, employs more people and it is a fully accepted concept in many ASM regions. The specifications of a similar ball mill with this capacity are given below.

**Table 3.2 – Technical Data of a Small Batch Ball Mill**

Specification	Characteristics
Size	Ø0.48 (1.6 ft) x 0.6 m (2ft) long (internal)
Lining	25mm thick steel shell and ends, unlined
Critical Speed	$N_c = 42.3 D^{-0.5}$ (in m) = 61 rpm
Operating Speed	70 - 75% of critical speed; 45 rpm
Feed Capacity	40-50 kg/batch
Feed Size	12mm max
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 Charge Volume	40% of the mill volume
Ball Charge	350kg
Ø max of ball	44mm (see below)
Ball Size for First Charge	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 Vee Belt
Installed Power	2.2 kW
Price	US\$ 8340

Note: Calculation of the largest ball (B) diameter (in mm)

$$B = \sqrt{\frac{F}{K}} \cdot \sqrt[3]{\frac{S_g \cdot W_i}{100 C_s \cdot \sqrt{3.281 D}}} \cdot 25.4 \dots\dots\dots B = 44 \text{ mm}$$

where:

K = constant for closed wet grinding systems = 350

F = feed P80 in  $\mu\text{m}$  = 2 mm = 2000  $\mu\text{m}$

Sg = specific gravity of the mineral = 2.7

Wi = Work Index = 10

Cs = fraction of the critical speed = 0.70

D = mill internal diameter (in meter) = 0.48

#### 3.1.4. Size Classification

Size classification is extensively used associated with grinding circuits to prevent the entry of undersize particles into the grinding machines, to prevent oversize material from passing to the concentration stage and to prepare a closely sized feed that improve the gravity concentration process<sup>2</sup>. Screening is the simplest and cheapest process for industrial sizing but is generally limited to material coarser than 100 mesh (0.15 mm). Spiral classifiers and hydrocyclones are widely used to classify fine particles. As gold liberation is the main factor to obtain high gold recoveries, size particle classification provides control on the gold liberation of the ground product. Unfortunately, very few artisanal miners appreciate this simple control principle and operate their grinding systems in open-circuit, i.e. no classification is used. Rudimentary wood or metal-framed screens can be locally manufactured for wet screens but the screens are not easily available. These can be made of brass or stainless steel or eventually, improvised with nylon screens. A spiral classifier is fed with the grinding product and the pulp is diluted to 50% solids. It uses a continuously revolving spiral to move sands up the slope, while fine flow down with water. The overflow becomes coarser with increasing dilution and pulp density control is the main problem of the spiral classifiers. Mechanical classifiers like this could be demonstrated to miners but it is an expensive piece of equipment and some skills are needed to operate it. It has been seen in Zimbabwe a rudimentary but yet useful mechanical classifier. The pulp from concentrators or amalgamating-copper plates is added to a small cemented tank and the coarse material is scooped out to the top of an inclined wall by a belt with pieces of rubber paddles. This is similar to a bucket classifier, but buckets bring the advantage of dragging more material than paddles. Hydrocyclones are very efficient for desliming and not very complicated to be manufactured. However, the principle of hydrocycloning is complex and a proper design requires skills. An elutriator can also be efficiently used as a hydraulic size classifier. Controlling the water speed, the rising flow carries the fine particles. Other designs with different diameters and conic shapes can be easily manufactured in plastic using garden and kitchen materials.

As water is scarce in Gugub, for the demonstration unit it is suggested to manufacture a 3-deck-portable screening set in which sieves can be replaced at any moment. The deck should be 0.6m long, 0.4m wide and 0.2m high. This can work dry or wet and it will provide more control to the ball-milling process. The first screen is a robust grizzly, with large opening (12 mm) to support the weight of the balls being removed from the mill. The balls can be washed or brushed (when dry milling is practiced) on this screen. The second screen has opening of 1 or 2 mm to protect the finest screen in the third deck. In the third deck, screens with 0.5mm and 0.2mm (or finer) can be used. The undersize material is collected in a 200 or 300L plastic container.

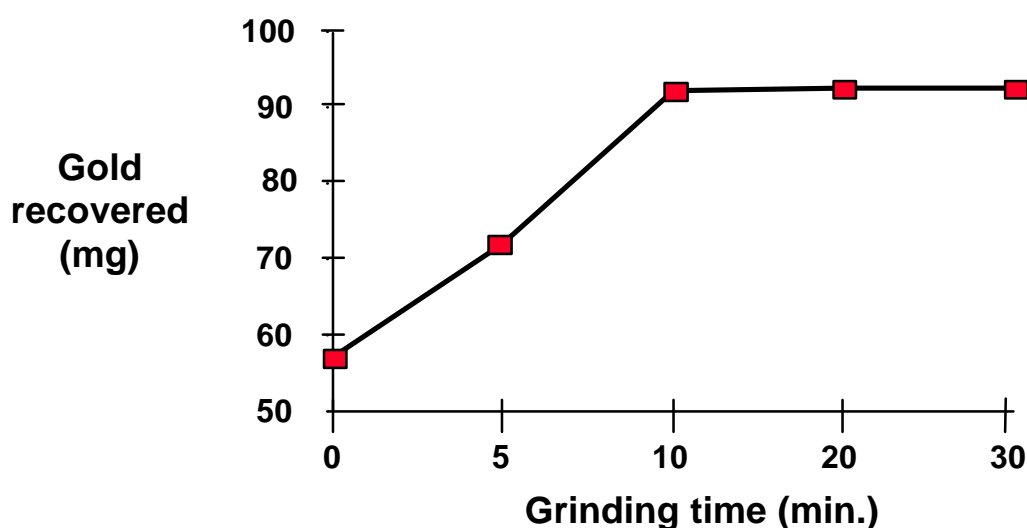
#### 3.1.5. Checking Gold Liberation

The classical procedure of using microscopy to check liberation size of the mineral of interest does not work properly for gold, as its concentration is usually very low. It is not trivial to establish the degree of liberation of low-grade minerals such as gold. There are a series of techniques to evaluate gold liberation using screened fractions. During the training, miners and trainers can run a sequence of tests with tailings or ore to determine the gold size liberation. A homogenized pile of tailings or crushed material (about 1000 kg) is formed and thoroughly mixed. About 100 kg of material is ground at a specific time. As the ball mill has maximum capacity of 50 kg, the material has to be ground twice. After grinding each 50 kg, the interior of the mill is emptied (washed) and the

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<sup>2</sup> Wills, B.A., 1988. Mineral Processing Technology. Oxford, UK, Pergamon Press, 785 p.

material is discharged on the screening deck. The undersize fraction (pulp of 20-30% solids) of the ground material is pumped to be concentrated using one of the gravity concentration equipment herein described. The concentrate is subsequently amalgamated and retorted. Increasing the grinding times, for example 0 (no grinding), 5, 10, 20 and 30 minutes, it is possible to observe that more gold has been recovered, if the original pile of run-of-mine material is well homogenized. The amount of gold obtained when grinding and processing each 100 kg of material is registered. The oversize fractions retained in screen 2 and 3 are dried and weighed. A curve of the amount of gold recovered by gravity concentration and amalgamation versus grinding time or grain size (e.g. P80 in screens 2 or 3) provides a clear visualization of gold liberation. An example of this procedure can be seen below, when a tailing was used to check gold liberation. In this case, it is clear that the recommended (re)grinding time of this tailing is 10 minutes; consequently the liberation grinding size is also obtained.



### 3.2. Gravity Concentration

Often gravity separation methods are confused with size classification as coarse particles of light minerals can behave like a small particle of a heavy mineral. The most effective gravity separation processes occur when applied to narrow grain size. The most important factor for a successful gravity separation is liberation of the gold from the gangue minerals.

The main advantages of gravity concentrators over hydrometallurgical methods are:

- relatively simple pieces of equipment (low capital and operating costs)
- little or no reagent required
- can be applied from relatively coarse particles to fine size materials

Some of the most popular gravity concentration pieces of equipment suggested to the TDU in Sudan are discussed as follows.

#### 3.2.1. Sluices

Sluice boxes are the most popular gravity separation process used by artisanal gold miners worldwide as they can be locally manufactured, they do not require power, and provide high enrichment ratio. They are of simple construction and easy operation. The introduction of sluice boxes will provide better gold recoveries than the process (panning) actually seen in Gugub. The lack of water can be a hurdle, but without previous tests, it seems difficult to recommend a dry pinched-sluice to pre-concentrate the ore. Rather, it is recommended to establish an efficient way to clarify and recycle water for the sluicing process.

The principle of operation of a sluice box is simple: heavy particles in a water stream settle and become trapped by riffles or mates. A very comprehensive report on sluice boxes is provided by the British Geological Survey (BGS, 2002)<sup>3</sup>. For an efficient separation, BGS (2002) lists the main parameters and recommends the following:

- ore slurry: steady and pre-screened slurries (screen <25 mm, ideally 5mm)
- pulp density: <15% solids (weight/volume), e.g. 15g of solids in 100mL of water; pulp density depends on grain size; for fine fractions or clayey ore, 3 to 5% solids is used
- flow velocity: depends on box width and slope: if speed is too slow, the sluice box becomes blocked; if it is too fast, gold is washed away; recommended flow speed is 1 to 2 m/sec
- stream depth: 20 to 30 mm
- sluice slope: 10 to 15 degrees
- sluice length: 2 to 5 m
- width: depends on desired flow speed; usually it is between 0.5 and 2 m
- water need: 30 to 70 m<sup>3</sup>/h/m of width; then a 1m wide sluice box working with a 5% w/v pulp can process from 1.5 t/h to 3.5 t/h of material.

Miners believe that the long sluice boxes improve gold recovery. However it is observed in long sluices that most gold is recovered on the first 2 or 3 meters where the flow speed is slower than at the sluice end. This is the main reason why Brazilian “garimpeiros” (ASM) devised the 2 or 3-deck sluice boxes. Each deck is approximately 2.8 to 3 m long, 1.5 to 2 m wide and placed in zigzag. The top box discharges the pulp on the second box. This breaks the flow direction and reduces the water speed, promoting additional gold recovery at the beginning of the second (and third) deck. It is also possible to have different lining materials in each deck. These 2-deck sluices are common in Brazil, Suriname and Guyana. They operate with hydraulic monitors of 4, 6 or 10 inches and the 5% solid ore pulp is pumped to the sluice boxes at a rate of 4 to 5 m<sup>3</sup> ore/h (6-inch pump) to 7 to 9 m<sup>3</sup>/h (10-inch pump). This means that up to 24 tonnes/h of material can be processed.

The width of a sluice box is a much more critical parameter than the length. Narrow-width sluice boxes promote high-speed flows and this consequently affects gold recovery. Pinched sluice boxes (variable width) is used for pre-concentration. The height of the sluice box usually respects the riffle height: sluice width ratio of 0.3. This means that, for a sluice box 1.2 m wide, the sluice height must be around 0.36m.

The choice of the adequate trapping mechanism is key for an efficient gold concentration. Sluices using riffles (1 to 3 cm high) are usually appropriate for coarse gold (> 0.4 mm). As the riffles create turbulence, this reduces the chances of trapping fine gold. For fine gold particles, the shape of gold particle and quality of the matting material has great influence on the gold recovery. Priester and Hentschel (1992)<sup>4</sup> list the lining materials used by ASM in different parts of the world:

- rubber matting
- sisal mats
- fine and coarse fabric e.g. corduroy, cord velvet
- carpets
- meshed hemp or grass cords
- metal grid
- split bamboo

Gold recovery can be increased by frequent clean-ups of the sluice box. In this case rubber liners are more practical to clean and so not need rifles to fix them to the box bottom. MINTEK (South

<sup>3</sup> BGS – British Geological Survey, 2002. Good Practice in the Design and Use of Large Sluice Boxes. Booklet prepared by Styles, Simpson and Steadman. Report CR/02/029N. 39 p.

<sup>4</sup> Priester, M & Hentschel, T., 1992. Small-scale Gold Mining. Published by GATE/GTZ. Vieweg, Germany. 96p.

Africa) devised interesting sluice boxes (strake) with rubber-mat glued to it. Black ribbed vinyl mats are also useful to recover gold and easy to clean but it costs in USA, about US\$15/m<sup>2</sup>.

In terms of mats, it is interested to demonstrate to miners different types of sisal clothes and carpets. The most adequate carpet used in ASM operations is the 3M Nomad Dirt Scraper Matting in particular the type 8100 which consist of a coiled vinyl structure. This is usually recommended for relatively coarse gold. The price of this carpet in ASM sites can reach up to US\$ 40/m<sup>2</sup>. 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 speck of rice-medium size) and “Multiouro liso” (which is good for 100 mesh-fine gold). These carpets can cost around US\$ 10 to 15/m<sup>2</sup> which is cheaper than the 3 M carpets. However these carpets are not easily accessible to ASM in Africa.

Extensive use of sisal clothes as sluice-box liners to concentrate gold was observed all over the mining operations in African countries. The main problem is the use of very opened sisal clothes, that can work properly for coarse gold but it is unlikely efficient for medium and fine gold particles. Sisal clothes can cost as low as US\$ 3/m<sup>2</sup>, are available in most African countries, and, depending of the type, they can be used for coarse, medium and fine gold recovery. It is a matter of trying different types. This definitely must be further investigated and tests can be done together with the miners to establish the ideal type of sisal cloth.

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) seems an interesting alternative to be demonstrated to ASM. The cost in USA of this sluice is around US\$100. The company also provides pumps (3 to 8 inches) and a large variety of accessories. This small portable sluice (weighing 5kg) had capacity of processing up to 5 tonnes/h of ore. It is suggested to manufacture some aluminum or wood sluice boxes or simply use the Keene’s boxes without riffles but with different types of mats. The demonstration unit should be able to show the advantages of different types of lining (sisal cloth, carpets, rubber, etc.) to miners.

Another interesting sluice box is the one manufactured by **Cleangold**, a company based in Lincoln City, Oregon. The Cleangold sluice uses polymeric magnetic sheets, with the magnetic poles aliened normal to the direction of the flow, inserted into a simple aluminum sluice box. Magnetite, a mineral usually found in gold-ore deposits, forms a corduroy-like bed on the sluice floor, which appears effective at recovering fine gold. This sluice box can be available in any size and a 2ft x 6in (60 x 15 cm) sluice costs US\$ 75 in USA. The main advantage of this sluice is the high concentration ratio. Gold becomes trapped in a magnetite layer and the sluice can be scrapped and washed into a pan. Using a magnet, the magnetite is removed and a high grade of gold concentrate is obtained. In many cases the use of mercury to amalgamate the concentrate is not necessary. However, as the magnetic separation of the concentrate can carry some gold, amalgamation or even leaching of the concentrates is recommended. In one test comparing the Cleangold sluice with a Knelson 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 re-passed in a 2ft long Cleangold sluice box without re-grinding. About 11% of gold was recovered and the



*Cleangold Sluice box (60 x 15 cm)*

concentrate analyzed 2850 ppm Au. The company representative mentioned that they can manufacture a 60 x 50 cm Cleangold sluice box and it would cost around US\$ 165 (in USA).

Cleangold was also successfully tested in Gugub and the ability of concentrating fine gold was demonstrated to the local miners.

It is suggested for the TDU a static set of 2 Cleangold 60x50 cm sluices (making a 1.2 m long sluice) with a steel structure to allow slope adjustment. This structure can easily be locally manufactured.

### **3.3. Amalgamation**

It was not observed miners amalgamating the whole ore in Sudan, but just gravity concentrates obtained in panning. Manual amalgamation of concentrates using pans is environmentally better than the amalgamation of the whole ore, however, if not properly conducted, this exposes operators to high levels of mercury vapor. In addition, this manual process can take more than two hours.

Ideally the best situation is where mercury is avoided all together by alternative processes such as MINTEK – iGoli or CETEM- Saltem processes where gravity concentrates are leached with chlorine solutions. However these options are not as simple and inexpensive as amalgamation.

The best practice would be the establishment of a Processing Center, like in Venezuela, where gravity concentrates are amalgamated by skilled operators. Concentrates could also be leached in these centers using chlorine, or even cyanide. This seems a natural evolution of the artisanal mining processing system when the miners and millers become more educated and organized. Meanwhile the training efforts must be concentrated on reducing mercury losses and occupational exposure. Any process to be introduced must also bring a financial gain to the miners otherwise they will not accept the technical innovations.

Assuming that amalgamation is still the most accepted gold extraction process in the ASM regions, the initial approach should be the reduction of the mercury emissions. Some pieces of equipment capable to improve the amalgamation step are described as follows.

#### **3.3.1. Amalgamation Barrels**

Barrel is the most efficient amalgamation process. They are used to amalgamate gravity concentrates. Recovery of gold from heavy mineral concentrates can be higher than 90%. Amalgamation barrels with capacity to amalgamate up to 30 kg of concentrate per batch are adequate to the demonstration units. It is very important to avoid the impression that these barrels can be used for grinding primary ores. This incorrect practice has been responsible for large mercury losses in Indonesia, where miners add iron rods and balls into the barrels to grind 40 to 50 kg of primary ore for 4 hours with 1 kg of mercury. It has been demonstrated how grinding reduces the ability of gold to be amalgamated. In these cases, mercury loses coalescence, i.e. breaks down in droplets (“flouring effect”) and mercury is lost. The action in amalgamation should be attrition of mercury with gold rather than impact. In Sudan is common to see miners mixing mercury with gravity concentrates using bare hands in the concentrating pan.

The suggested elliptical amalgamation barrel has a “pelletizing” disk format with control of the slope and promotes high contact of mercury with gold particles. The use of large rubber balls promotes good contact between mercury and gold specks. As most of the Sudanese miners amalgamate very small portion of the gravity concentrate obtained by panning, it is suggested to have small barrels, as the one suggested below.

**Table 3.3 – Technical Data of a Disk Amalgamation Barrel**

Specification	Characteristics
Size	tilted disk Ø0.30m x 0.10m wide
Lining	8mm thick steel shell, rubberized
Max Speed	30 rpm
Max Feed capacity	17 kg concentrate/batch
Ball Material	Rubber
Ball Size	50 mm
Number of Balls	5 to 8
Amalgam Trap	Adjustable discharge tray with mercury trap and adjustable copper plate
Extent of Mechanization	Partially mechanized, batch manual discharge
Mode of Operation	Batch
Discharge Type	Lateral door
Installed Power	2 kW
Drive	Vee Belt
Shipping Weight	100kg with frame and access ladderway
Price	~US\$ 2000

Amalgamation barrels can also be made of plastic PVC but in some African countries this can be more difficult to find and costly than steel. This is definitely very beneficial as no iron balls can be introduced in the barrels and the mercury flouring is avoided.

The pulp of concentrate with 50 to 60% solids should not exceed half the barrel volume.

The amount of mercury used for amalgamation is usually a function of the gold grade in the gravity concentrate. As this information is usually not available a common addition of 10 to 20g Hg per kg of concentrate (1:100 to 1:50 Hg:concentrate ratio) is sufficient to promote good amalgamation. Amalgamation time above 40 min usually promotes mercury flouring.

The main inconvenient of amalgamation barrels is the relatively high concentration of Hg in the tailings. Amalgamation tailings from barrels, as observed in Poconé, Brazil, have from 80 to 200 mg/kg of Hg<sup>5</sup>. It is also common to find amalgamation tailings with 500mg/kg (ppm) of Hg. This is a result of mercury flouring, i.e. loss of mercury coalescence. A restrict control to avoid mercury flouring is needed when operating barrels. This is done adjusting amalgamation time, adding reagents and reducing stress on the concentrate pulp.

Use of chemicals such as potassium permanganate or even sodium cyanide to reduce mercury surface tension and clean gold particles surface may improve the amalgamation process, but the benefits for gold extraction do not take into consideration the occupational risks and the environmental effects. One gram of NaOH per kg of heavy mineral concentrate to be amalgamate is an efficient method to improve amalgamation without solubilizing mercury.

### 3.3.2. Amalgamation Plates

Amalgamation Plates are stationary metallic sheets usually dressed with a thin layer of mercury (usually 150g Hg/m<sup>2</sup> of plate) use to amalgamate free gold particles in ores ground coarser than 1.5 mm. Working with 10% of slope these plates receive pulp of auriferous ore (10 to 20 % of solids) and the amalgamation takes place when gold particles contact the plate surface. The velocity of

<sup>5</sup> Farid, L.H.; Machado, J.E.B.; Silva, O.A. (1991). Emission Control and Mercury Recovery from Garimpo Tailing. In: *Poconé: Um Campo de Estudos do Impacto Ambiental do Garimpo*, Ed. M.M.Veiga and F.R.C. Fernandes, CETEM/CNPq, Rio de Janeiro, Brazil, p. 27-44. - in Portuguese



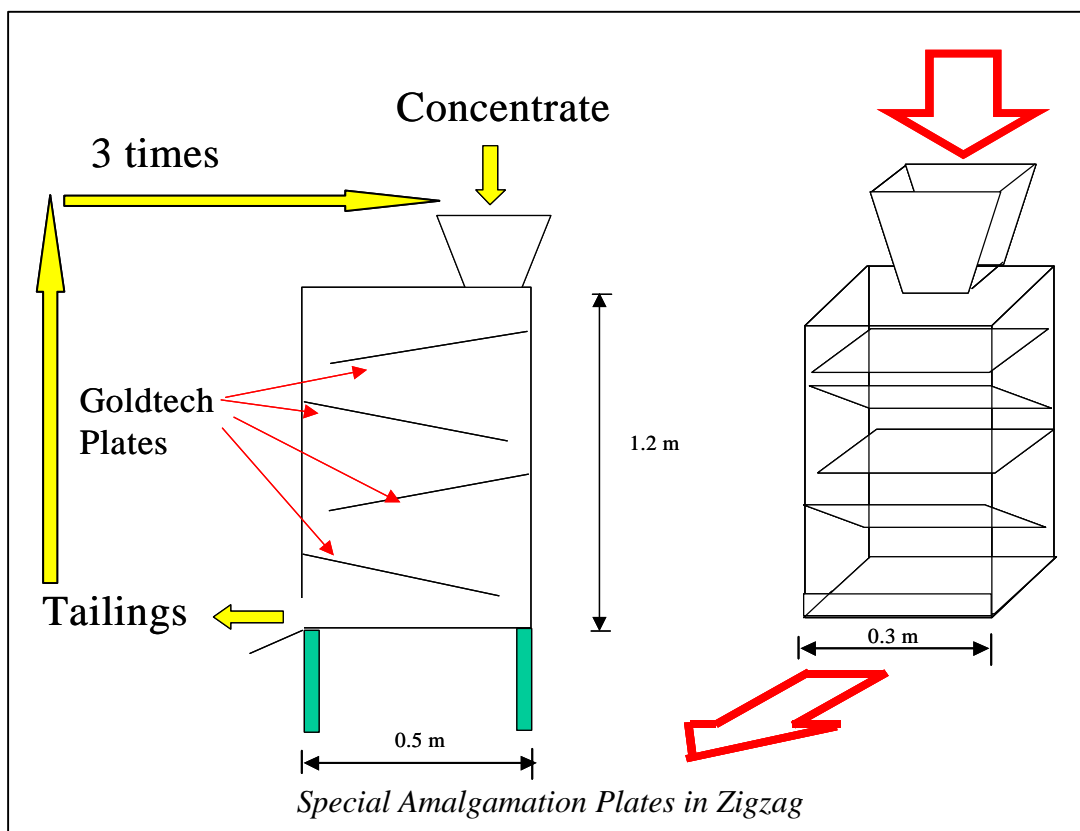
flow has to be sufficiently low that the precious metal particles can sink to the plate surface and yet high enough that other mineral constituents of the concentrate do not remain on the plate. The most common plates used in ASM operations are made of copper. The efficiency of the process depends on the operator ability, but usually is low due to the short time of ore-mercury contact. The method works better for alluvial gold but it is very limited for primary ore in which quite often gold is not completely liberated from the gangue minerals. About 0.3 m<sup>2</sup> of plate is required to treat 1 tonne of ore/24 h for pulps with 20% solids. Amalgam is removed (scraping) periodically interrupting the process. Abrasion of the mercury surface releases droplets that contaminate the tailings. Acidic water may also cause brown or green spots on the copper plate and mercury is also lost. A large majority of artisanal miners do not use a mercury trap at the end of the plates. In Venezuela, tailings from amalgamation Cu-plates typically contain 60 to 80 ppm Hg.

A new technology was developed in Brazil and commercialized by two manufacturers: Goldtech and Rio-Sul. A thin coating of Hg and Ag is electrolytically deposited onto a metallic plate (brass, galvanized steel, copper, etc.). About 80 g Hg/m<sup>2</sup> of plate is added to the plates to amalgamate gravity concentrates. Gold is captured and firmly fixed to the plate surface. Hg losses are minimized. When the plates are fully loaded, amalgam is removed by washing with a plastic scraper. This kind of plates has been successfully tested in Brazil to remove Hg from contaminated tailing. In recent test in Venezuela, tailings from ordinary Cu-plates containing in average 62.2 ppm were submitted to a cascade system with four special-plates. More than 95% of Hg was removed from tailings. Those plates are not indicated to capture gold from the whole ore but only to amalgamate gravity concentrates or to clean contaminated tailings. A wood structure was built to hold 4 Goldtech 40 x 30 cm plates placed in zigzag, as seen in the diagram below. About 10 g of mercury per plate is added. About 10 kg concentrate from carpet sluice boxes was passed 3 times in less than 10 minutes. Then, the plates are removed from the wood structure and the amalgam was scrapped off.

The main advantages of using the special-plates to amalgamate gravity concentrates are:

1. amalgamation process is faster
2. no heavy mineral-amalgam separation
3. minimum Hg loss in the amalgamation tailings

The process of manufacturing these special plates in Sudan should be investigated as the price CIF per plate in Brazil is still expensive: US\$ 200 (Goldtech plate 40 x 30 cm) and US\$ 600 (Rio-Sul plate 60 x 40 cm). In any case, this is the best system to promote clean and fast amalgamation of gravity concentrates.



**Table 3.4 – Technical Data of a Box with Special Amalgamation Plates in Zigzag**

Specification	Characteristics
Box Size	1.2 x 0.5 x 0.3 m (internal)
Box Material	Naval Plywood (2cm thick) or C-Steel
Type of Plate	Goldtech 40 x 30 cm (or Rio-Sul 60 x 40 cm)
Number of Plates	4
Arrangement of Plates	Zigzag and cascade
Plate Slope	10°
Max Feed Capacity	100 kg concentrate
Pulp Density	<10%
Extent of Mechanization	Manual
Mode of Operation	Batch
Discharge	Frontal
Price	US\$ 1500

### 3.3.3. Comparing Barrels with Special-Amalgamating Plates

The advantages and disadvantages of using barrels or special amalgamating plates to extract gold from gravity concentrates are shown in the Table below. The main problem is to restrict the use of these special plates to amalgamate just concentrates. As ordinary copper-amalgamating plates are widely used to amalgamate the whole ore, miners can have the impression that these special plates can be used in the same way. This is a mistake as the intense attrition of tonnes of ore pulp on top of the special plates will degenerate the superficial silver amalgam and release mercury to the tailings. Miners can also misuse the amalgamation barrels as ball mills, adding iron balls while amalgamating concentrates or, even worse, the whole ore. This, as seen above, causes huge mercury losses.

**Table 3.5 – Comparing Special Amalgamating Plates with Barrels to Amalgamate 100 kg of Gravity Concentrate**

	<b>Zigzag Box with 4-Special Amalgamating Plates (40x30cm)</b>	<b>Amalgamation Barrel + Elutriator (or Spiral-pan)</b>
Amount of Hg needed (g)	40	1600
Typical Hg conc. in tailings (mg/kg)	<1	200 – 500
Amalgamation time required (min)	10	40
Time to obtain amalgam (min)	20 (scrapping the plate)	20 (using spiral pan)
Need to squeeze amalgam to remove excess Hg	yes	yes
Relative amount of excess Hg	low	high
Dangerous misuse	use the plates to amalgamate the whole ore	use the barrels to grind ore together with Hg
Main problem	occupational exposure of operators to Hg vapor	mercury flouring
Skill needed	low	medium/high
Price (US\$)	1500	4500 (including spiral pan)

### 3.3.4. Separation of Heavy-minerals from Amalgam

When amalgamation of gravity concentrate is conducted in a barrel, the heavy minerals must be separated from the amalgam (+ excess Hg). When amalgam-heavy mineral separation is made by panning at the creeks margins, mineral portion with residual mercury overflows to the watercourses creating "hotspots" which are highly contaminated sites. Mercury from these sites can react with organic matter and be methylated by a biotic process. The tailing generated in the amalgam-heavy mineral separation may contain as much as 500 mg/kg (ppm) Hg. In Gugub most of the amalgamation tailings are left in the pools or miners take these tailings to their homes to be re-ground and re-amalgamated.

The main techniques to separate the amalgam from the heavy minerals are described below:

#### Panning

Panning in the water box or excavated pools is one of the most adopted method to separate amalgam (with excess mercury) from heavy minerals concentrate. The methodology is not very efficient but simple and inexpensive. This however promotes long contact of the operator's hands with mercury. When panning is conducted in a water box or cemented tanks, the amalgamation tailings are temporarily stored. The extraction of mercury from contaminated tailings is usually not practiced by ASM. The main option for cleaning mercury from tailings is the use of special-amalgamating plates described above. In this case, it is much better to use the special plates to amalgamate concentrates in first place.

#### Spiral Pan

Spiral Pan is a tilted plate with a spiral riffle on the surface of the pan which moves the amalgam and excess mercury into the center of the wheel where it is collected. The heavy-mineral portion is discharged at the edge of the wheel. It is fully mechanized and the pan angle controls the efficiency of the separation. A water pipe with thin holes crosses part of the spiral section to wash the minerals down. The simplest pans are made of polypropylene plastic with diameter ranging from 30 to 50 cm. The wheel rotation speed is controllable (from 15 to 22 rpm) thanks to a 12 V motor (adaptable to car battery). The feed capacity is around 30 kg per hour. There are many spiral pan manufacturers in USA, many of them can be found in the Internet. The prices of these spirals range from US\$ 300 to 500 depending on the level of accessories. The weight of the whole setting is less



Spiral Pan

than 10 kg. In terms of heavy-mineral-amalgam separation, the spiral pans provide better control than an elutriator and the final amalgamation tailing contains less mercury. Both techniques are worthwhile to be demonstrated to miners.

### 3.3.5. Removing Excess Mercury

The universal process used by most artisanal miners to remove excess mercury from amalgam is filtration squeezing the amalgam in a piece of cloth. The cloth retains the amalgam (paste) and permits mercury to flow through the fabric or

chamois pores. Despite the low absorption of mercury through the miner's hand, it is always advisable to wear gloves during this artisanal procedure. This process usually results in amalgam with 40 to 50% Hg.

A creative solution to remove excess Hg from amalgam without using the hand squeezing process was developed in a Processing Center in Venezuela. The amalgam with excess mercury is transferred to a porcelain crucible, covered with a piece of fabric on top and placed in a centrifuge. The centrifuge runs for 1 or 2 min. and the resulting amalgam has less than 20% Hg.

This can be brought to the miners' attention in the demonstration units. This can be built adapting a domestic food processor (centrifuges).

## **3.4. Retorting**

An efficient method to separate mercury and gold from amalgams is by heating above 350 °C. Mercury becomes volatile leaving gold behind in solid state. A retort is a container in which the gold-mercury amalgam is placed and heated; volatile mercury travels up through a tube and condenses in an adjacent cooler chamber. With retorts, mercury recovery is usually higher than 95%. Substantial reduction in air pollution is obtained. There are a large variety of retorts. Some of them are made with stainless steel while others use inexpensive cast iron. Mercury losses during retorting are usually less than 5%, but this depends on the type of connections or clamps used.

This operation unfortunately in most artisanal mining sites around the world is usually conducted burning amalgams in pans or metallic trays using a blowtorch or bonfire. In Sudan it is very popular the use of bonfires to burn amalgam. The miners place the amalgam on a steel plate or shoe-polishing tin to be burned in a bonfire. As the temperature is not high enough and the time of burning is too short (miners leave the amalgam for 10 minutes), the final gold *doré* contains up to 20% of residual mercury. The only control of the burning is visual. As long as the amalgam ball becomes superficially yellow, the miners remove the *doré* from the fire. Inside the bead it is possible to see residual mercury. As most gold buyers know this fact, they reduce the *doré* purchase price. When better retorting techniques are introduced, the gold price must be negotiated with dealers, showing that less mercury has been retained in the *doré*.

As occupational exposure is the main pathway in which mercury enters the human body in artisanal gold mining areas, it is suggested to demonstrate the advantages of using different retorting processes. In places such as Lao PDR, where mercury in mining areas is purchased by US\$ 80/kg it makes sense to use the economic argument to convince miners to recycle mercury. In Sudan, the price of one kilogram of mercury is around US\$ 30/kg. In spite of being almost seven times higher than the international mercury price, this is still cheap, i.e. equivalent to three gram of gold. So, the economic argument should be replaced with other strategy. Despite the introduction of retorts

through many programs (CETEM, UNIDO, Projekt-Consult GmbH, ITDG, Organization of American States, etc) and obvious benefits associated with their use, artisanal miners are reluctant, primarily due to a lack of concern for environmental and health impacts relative to other issues. The most effective argument to convince miners to use retort is using social and cultural issues. For example, in 1985, the Secretary of Mining of Goiás State, Brazil, started a campaign promoting retorts that included a brochure illustrating the effects of mercurialism. Impotence was stressed as one of the initial symptoms, which is somewhat inaccurate and therefore questionable from an ethical standpoint, but was extremely effective in capturing the attention of miners.

It is important to understand the main reasons by which miners do not use retorts. Engineers tend to look for the efficiency of the retorting process, when in many cases, efficiency is not the dominant factor to introduce a cleaner technology. The arguments are site-specific and sometimes fraught with misperception. However in some cases there are actual reasons that must be considered when introducing retorts in a mining site. Some of the most common arguments used by miners for not using retorts are listed below (Table 3.6). All these factors must be taken into consideration in order to recommend the adequate type of retort in a specific mining region. In some cases gold buyers use the miner's perception to lower the purchase price. This is common when miners sell brown retorted gold.

The *doré* volume after retorting usually has the same volume as the amalgam. The amount of mercury in the *doré* depends on the retorting temperature. A well-done retorting would result in a *doré* with 1 to 2% Hg. Using blowtorches, the retorting time ranges from 10 to 20 minutes, in a 1 or 1½" crucible retort. Shorter time provides *doré* with high content of Hg. Usually this is not seen by miners, as the surface color is yellow. When using blowtorches, it is possible to melt gold in the retort crucible. Brazilian miners use to add some borax and a little dash of potassium nitrate to melt gold and remove impurities. This operation must be conducted in a fume hood equipped with filters. Activated carbon soaked with potassium iodide makes a very efficient filter to retain residual mercury vapor.

**Table 3.6 – Arguments Used by Miners for Not Using Retorts**

<b>Arguments</b>	<b>Reasons</b>	<b>Possible solution</b>
it takes time (sometimes miners become vulnerable to bandits attack when retorting)	low temperature	use air blower in bonfires or blowtorch; avoid crucible made of refractory material such as clay
it needs experience to operate	heating process must be uniform when using blowtorch	training
gold is lost during retorting	iron retorts: amalgam is not visible; bad perceived by miners	glass retorts can demonstrate that gold will not evaporate together with Hg or be trapped
gold sticks to the retort crucible	sometimes gold adhere to crucible bottom	<ul style="list-style-type: none"> <li>• crucible must be filled with soot, or baby powder or a thin layer of clay;</li> <li>• avoid overheating (beyond red color)</li> </ul>
Hg loses coalescence	sometimes condensed Hg disintegrates in fine droplets	NaCl and radio battery to re-activate Hg
gold becomes brown	unknown; probably due to a superficial reaction with iron	<ul style="list-style-type: none"> <li>• still not well studied;</li> <li>• oxidizing atmosphere or use of stainless steel crucibles;</li> <li>• melt gold;</li> <li>• hammer gold <i>doré</i></li> </ul>

Regarding the type of retort to be demonstrated to miners the strategy must be: ANY RETORT IS BETTER THAN NOTHING. Even a crude method of retorting described in the "Gold Panner's Manual", a favorite of North American weekend prospectors, is better than burning amalgam in open pans or kitchen ovens. This simply involves "baking" the amalgam in the scooped out cavity of a potato. Readers are advised not eating the potato after processing.

The best retorts to be advised to miners are those made of local and easily accessible materials, non-expensive and easy to demonstrate. Durability can be a factor, but as long as the retorts are cheap and accessible, this becomes less relevant for miners.

In the demonstration unit it is suggested to have a large variety of retorts, from the simple to the most sophisticated one, to provide options to miners. It is definitely up to the miners to choose the most convenient and affordable type of retort for him/her.



*Indonesian gasoline-air blowtorch*

manufactured. Air-blowers are definitely needed to be included in the demonstration units in particular in most African countries where most miners use wood as the main heating source. Burners (such as camping stoves) using gasoline, paraffin, butane liquid propane should also brought to miner's attention.

### 3.4.2. Home-made Retorts

Home-made retorts are not very efficient but are easy to be manufactured with local materials. One option is the use of standard plumbing pipes and connections to make retorts with crucibles (end plug of plumbing pipes) from ¾" to 2". Smaller crucibles promote faster retorting. For those miners retorting more than 5 grams of amalgam per batch, retorts with crucible of 1½" are advisable. This costs less than US\$15. This idea, devised by prof. Raphael Hypolito<sup>6</sup> from Brazil, has been adopted by many organizations and

### 3.4.1. Increasing Temperature

Another important factor to be considered when suggesting a retort, is the source of heat. Using blowtorches with propane gas (as in most Latin American countries) or with gasoline-air (as in Indonesia), the temperature on the amalgam can easily go above 400 °C promoting efficient mercury elimination from amalgam in less than 20 minutes. In a bonfire, more than one hour is needed to remove more than 90% of mercury from a 5 g-amalgam. When a bonfire is used, an air-blower is needed to speed up the process and to justify the use of retorts. Manual or foot-operated blowers have been used in Sudan to forge steel. These blowers can easily be locally

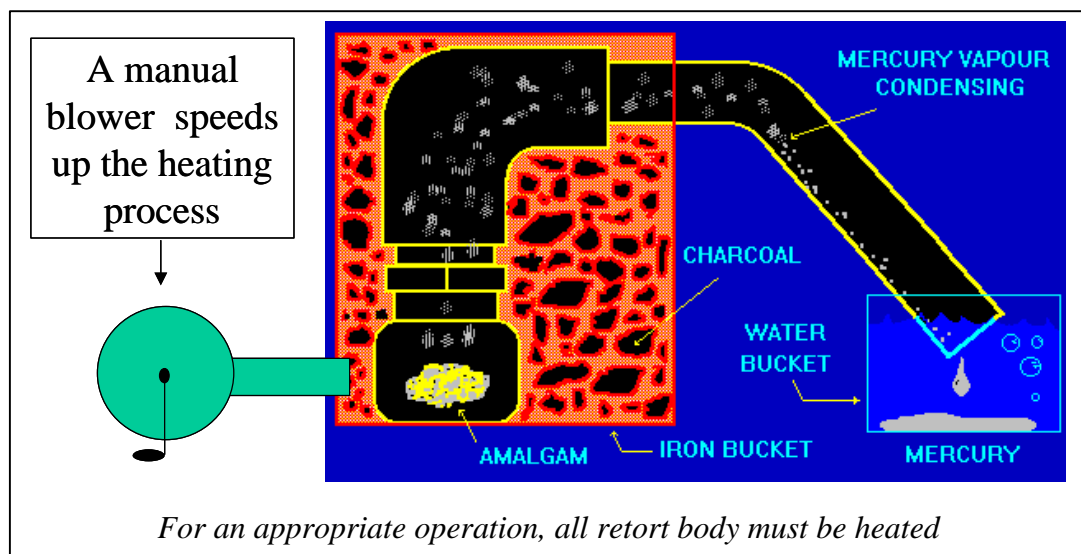
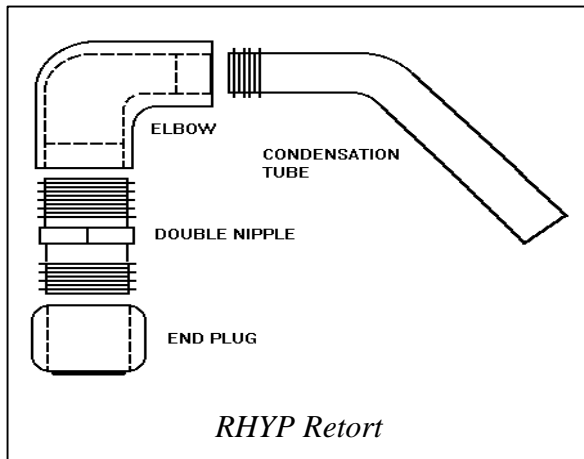


*Air blower tested in Gugub; this increases the temperature of a bonfire*

<sup>6</sup> Veiga, M.M.; Meech, J.A.; Hypolito, R., 1995. Educational measures to address Hg pollution from gold mining activities in the Amazon. *Ambio*, v. 24, p.216-220, 1995. Royal Swedish Academy.



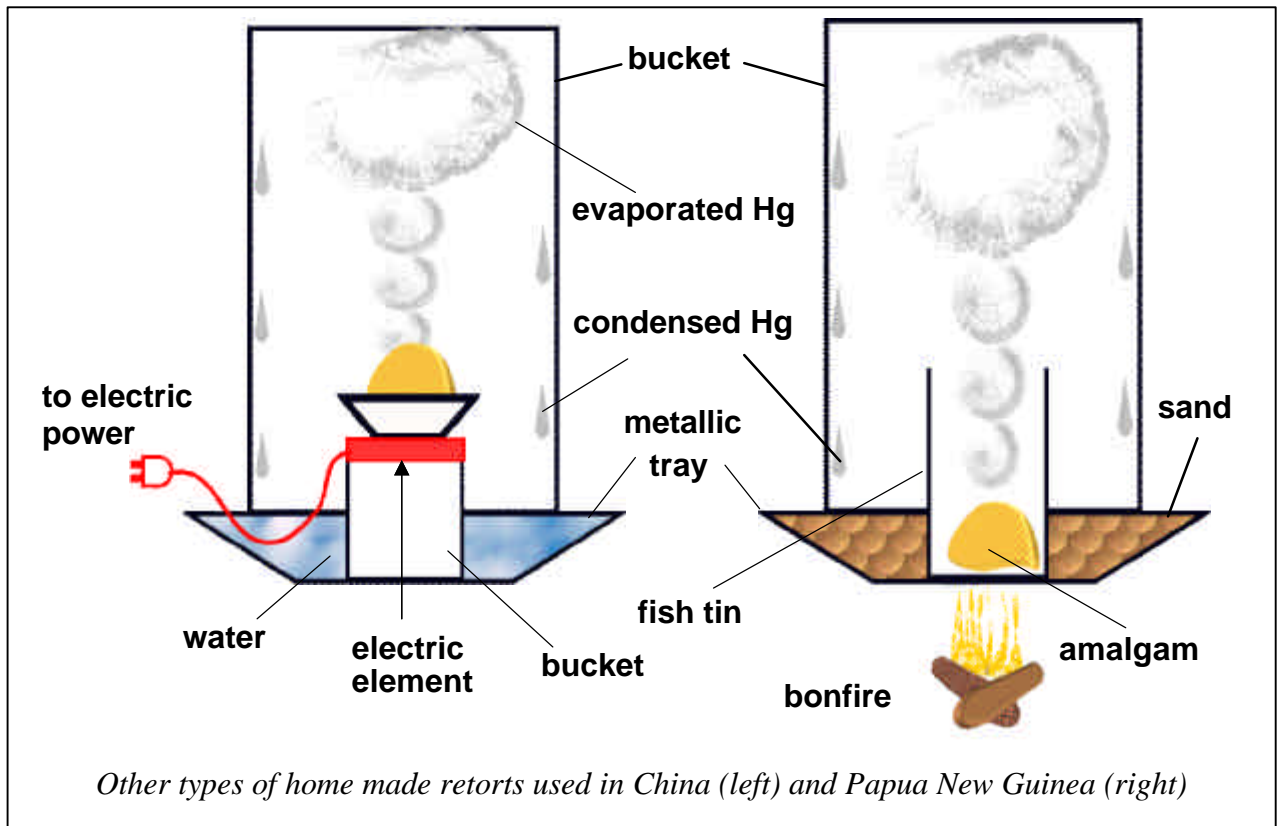
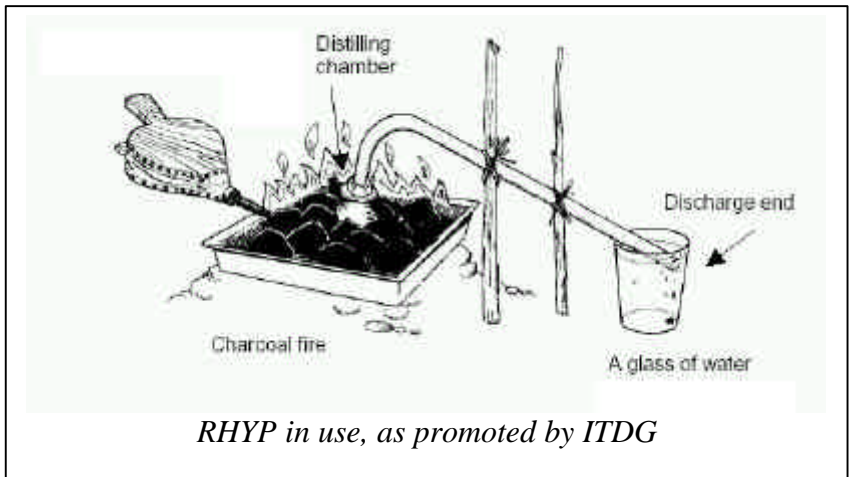
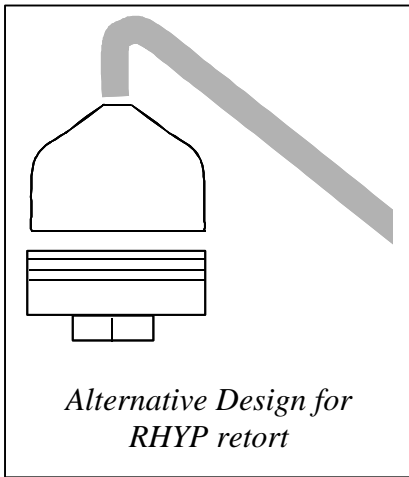
different designs of the RHYP retorts are available. The main drawback is that the pipes are made of galvanized steel and when mercury condenses, it sticks to the cooling pipe creating an amalgam with zinc. With the use of the retort, eventually, the accumulate mercury comes off, but this can bring a bad impression for the miners. In a brochure made by the British NGO, Intermediate Technology Development Group (ITDG)<sup>7</sup>, there is the following note: *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.*



For an adequate operation, the zinc from all plumbing parts must be burned off. Zinc fumes are relatively toxic. This initial operation must be done in a fume hood. Mercury can also leak through the connections. For a better operation it is advisable to heat the entire retort body in a charcoal bed and preferentially using an air-blower to speed up the operation.

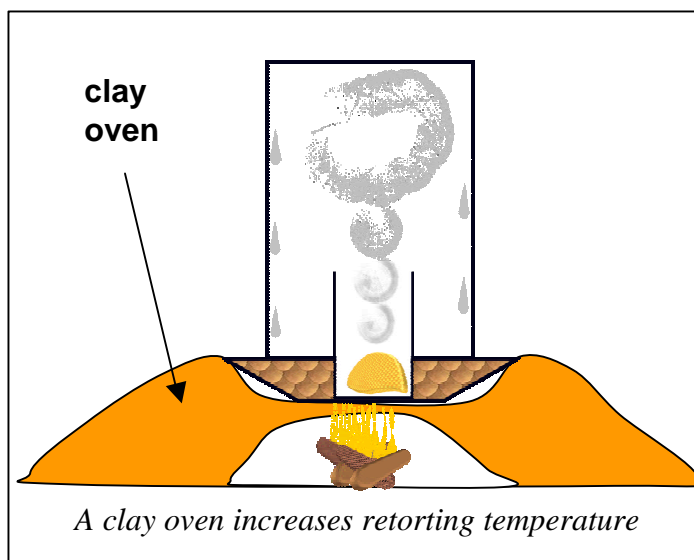
Home-made retorts can also be made of steel tins. An inexpensive option for retorting has been applied in Papua New Guinea and China. The Chinese two-bucket retort consists of a metallic bucket and a bowl filled with water. A larger bucket covers the first bucket containing the amalgam. The PNG "tin-fish-tin" retort employs the same concept, but uses fish tins and wet sand instead of water. In both cases, the amalgam is heated using wood, charcoal or electric element and mercury vapors condense on the cover-bucket walls.

<sup>7</sup> ITDG. A Simple Retort. [www.itdg.org/html/technical\\_enquiries/docs/mercury\\_retort.pdf](http://www.itdg.org/html/technical_enquiries/docs/mercury_retort.pdf)

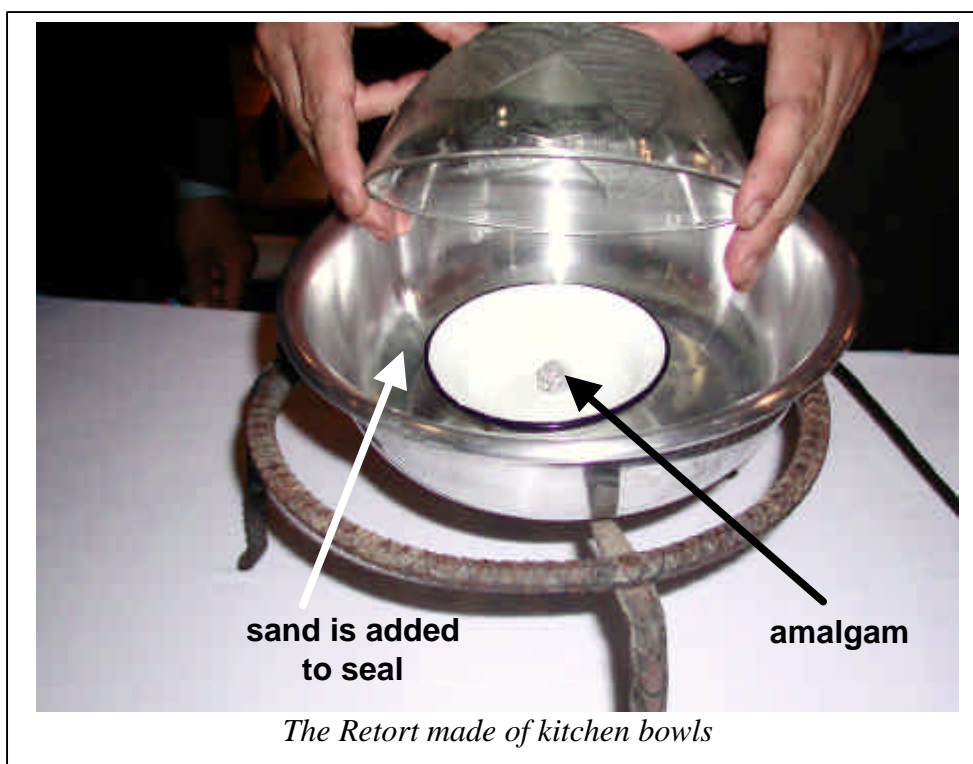




Using the same principle of the Papua New Guinea (“PNG retort”) fish-tin retort, UNIDO built some retorts using kitchen material for the ASM in Sudan. On a metallic support (locally used for cooking on bonfires), a small enameled steel tray with amalgam is placed inside another larger steel bowl, covered with a glass bowl and sealed with sand. The glass bowl allows the miners to see the amalgam decomposition, but this can be replaced with a metallic bowl. Mercury condenses on the bowl walls and drops into the sand. This retort took 10 to 15 minutes to eliminate most mercury from amalgam using a propane blowtorch or 30 minutes using a bonfire with air-blower. A serious inconvenient of this, is that sometimes miners remove the cover from the crucible while the retort is still hot. When this occurs, miners are exposed to mercury vapor. This retort cost less than US\$ 10 to be built. Miners can recover the condensed mercury panning the sand placed around the small tray.



Using a glazed-steel (enameled) bowl as crucible, yellow gold is obtained, increasing the acceptability of miners to the retorting process. The firing structure can also be built in clay as used in Western Africa for cooking. This process increases the temperature of the bonfire and concentrates the flames under the bowl.





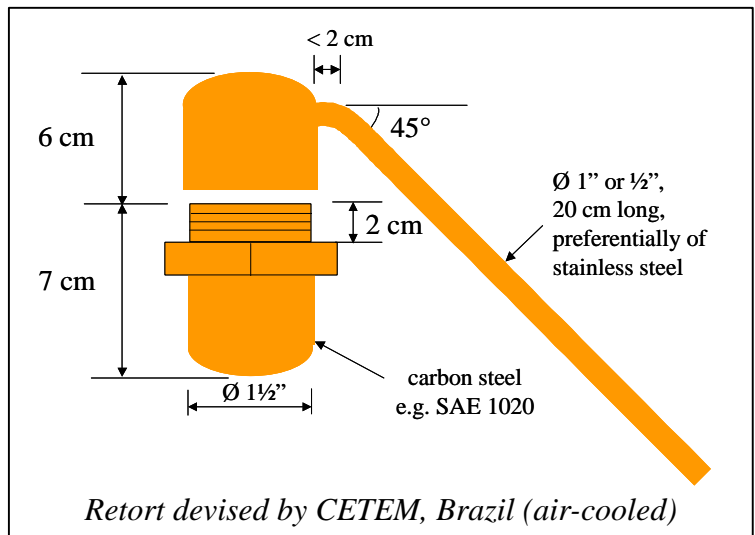
*Retort made of kitchen bowls in Sudan*



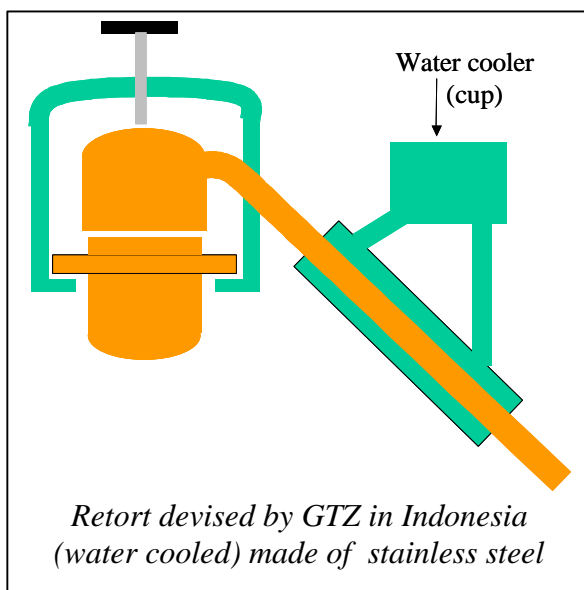
*Demonstrating in Sudan the principle of the kitchen-bowl retort*

### 3.4.3. Conventional Retorts

As mercury forms amalgam with almost all metals except iron and platinum, ordinary retorts are made of steel. Durable retorts can be made of steels that resist to corrosion and creep. Other characteristics to be observed are resistance to thermal expansion, structural stability and resistance to fatigue. In applications where the environment is not corrosive and the piece is not subjected to mechanical strength, carbon steels with low content of carbon (0.2 to 0.4%) work well. The strength of a low-carbon steel reduces from 43 kg/mm<sup>2</sup> (ambient temperature) to 25 kg/mm<sup>2</sup> at 540 °C. A simple and cheap air-cooled retort made of low-steel carbon was devised by CETEM (see diagram below). In order to increase the mechanical properties at temperatures above 500 °C addition of 0.45 to 0.65% Mo and 0.3 to 0.6% Mn to a 0.2% C steel increases its strength at 540 °C to 35 kg/mm<sup>2</sup>. Creep resistance doubles with small amounts of Mo and Mn in the steel. Addition of 5 to 6% Cr increases two or three fold the strength of low carbon steels. The main commercial Cr steel is the 410 AISI with 0.15% C.



*Retort devised by CETEM, Brazil (air-cooled)*



*Retort devised by GTZ in Indonesia (water cooled) made of stainless steel*

Retorts can also be made of Cr-Ni austenitic steels such as AISI 304 (0.08% C, 18-20% Cr, 8-11%Ni) or 310 (0.25% C, 24-25% Cr, 19-22%Ni). These steels combine high heat resistance with corrosion resistance up to temperatures around 900 °C. Stainless steels are much more costly than C-steels but the retorts are more durable. The aspect of durability must be discussed and cost/benefits must be presented to miners for their decision.

The advantage of having stainless steel cooling pipes is that mercury does not stick on the pipe wall when it cools down. Water-cooled retorts are slightly more efficient in Hg condensation than air-cooled. GTZ designed a 1½” water-cooled retort, used in Indonesia, in which no water circulation is needed. The price of these retorts made in Indonesia of stainless steel was around US\$ 100 to 120.

A creative idea used in Colombia<sup>8</sup> is the encapsulation of a stainless steel (AISI 304) retort using a cylindrical refractory cement, like a furnace. The capacity of this retort (known as “still”), as originally designed, is for as much as 400 g of amalgam. The cooling pipe is steep to minimize mercury sticking on the pipe walls and it crosses a 7.8 water-tank. With liquid-propane gas burner about 95% of mercury was recovered in 8 minutes of operation and 9 g of gas was burned per minute. While using gasoline burners, the burning time increases to 20 min consuming 0.015 L/min. The same heating system is used to melt gold in a graphite crucible. This retort can be manufactured in Sudan using a propane-gas burner. The retort can be made using either CETEM’s or GTZ’s retorts designs but in stainless steel. The idea of having a refractory insulation around a retort heating unit is very good and a clay-made oven can be tested for this purpose.

#### 3.4.4. Glass Retort



*Glass retort is useful to demonstrate the retorting principle*

A glass retort (Thermex) has been manufactured by the Munich-based company Metall-Technic. The high-silica-containing crucible resists up to 700 °C. The cooling pipe and connections are made of stainless steel. A water glass cools down the recipient receiving the condensed mercury. Miners can inspect the condensation process. This innovative approach has been very useful to demonstrate to miners the entire amalgam retorting cycle. As miners can observe mercury being released from the amalgam and condensed, they trust that all gold is recovered in the process.

UNIDO has distributed a number of these Germany-manufactured glass retorts in Ghana, Tanzania and the Philippines. Due to the low capacity (<30 g of amalgam), high cost (~ 1 oz gold), breakability and lack of spare parts, this cannot be used as a permanent retort but for demonstration purpose only. The refractory character of the silica crucible also makes the retorting time longer than when a steel retort is used but the amalgam color transformation, from silvery to golden, is quickly observed on the amalgam surface in less than 5 minutes of retorting with a blowtorch. With longer use, the crucible becomes opaque (silicon oxide formation) and becomes difficult to see the amalgam inside. It is important to demonstrate together with Themex that steel retorts employ the same principle and work similarly.

#### 3.4.5. Comparing Retorts

It is recommended to demonstrate as many different types of retorts as possible and build some along with the miners during the training step. This will be useful to highlight the cost and benefit of the various types of retorts. It is also important to work with miners to develop “new” types of retorts. This will make them more comfortable with their own inventions.

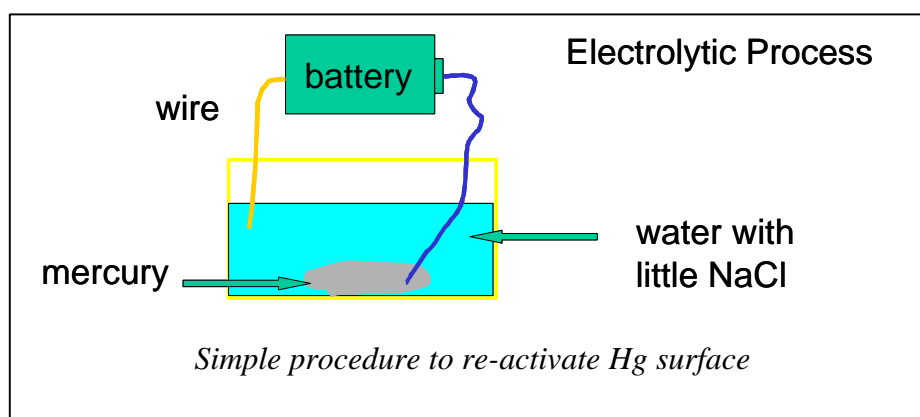
<sup>8</sup> Pinzón, J.M.; Contreas, R.; Bernardy, C., 2003. A new still for the prevention of mercury poisoning in small-scale gold mining by amalgam extraction. *Geofísica Internacional*, v.42, n.4, p.641-644.

**Table 3.10 – Different Types of Retorts to be Demonstrated to Miners**

	<b>RHYP</b>	<b>PNG</b>	<b>CETEM</b>	<b>Colombian</b>	<b>GTZ</b>	<b>Thermex</b>
crucible material	Galvanized steel	C-steel	Low C-steel	Stainless steel	Stainless steel	High silica glass
durability	Low	Low	Medium	High	High	Low
price (US\$)	5-20	5-20	20-50	80-90	100-200	400-500
possibility of local (Africa) manufacturing	High	High	Medium	Medium	Medium	None
retorting time (min) with blowtorch	15-20	10-15	15-20	10-20	15-20	20-30

### 3.4.6. Recovering Mercury Coalescence

Mercury recovered by retorting often does not have the same amalgamating properties as new mercury. In many South America countries, miners simply discharge retorted mercury. The most efficient way to reactivate the surface of mercury is by using an ultrasonic bath, such those used by dentists, wherein mercury droplets coalesce in seconds. However this is an expensive equipment (~US\$400) and not frequently accessible to miners. A much less expensive method<sup>9</sup> involves electrolytic activation using table salt and a simple battery to clean mercury surface. A process to retain the contaminated liquid effluent should accompany any activation method. For example, the effluent can be filtered through a pipe filled with lateritic material or activated charcoal. Despite the small amount of effluent, some soluble mercury could be transformed into more toxic forms once discharged into the environment. This equipment should definitely be demonstrated to miners using a simple steel or glass can and a radio battery with some copper wires.



### 3.4.7. Filter for Gold Shops

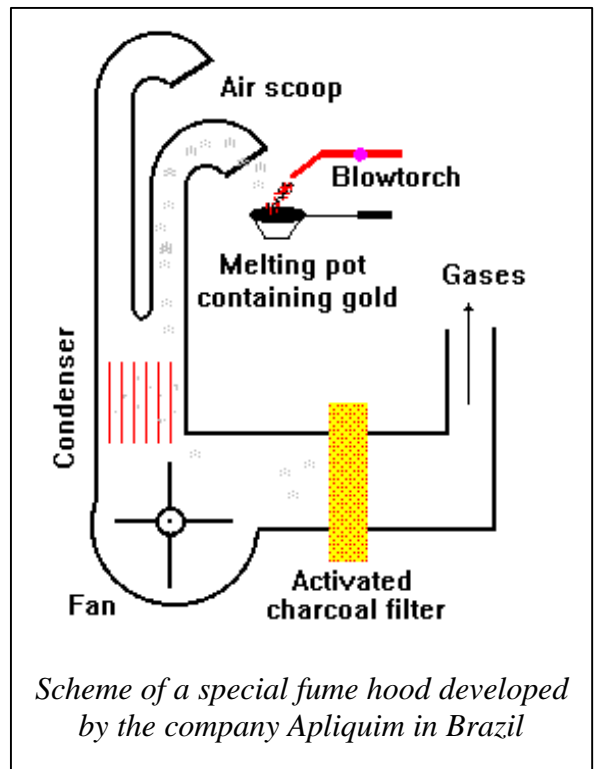
Usually gold *doré* is sold to gold shops in the villages or to dealers who come to the mines. The buyers often pay less for the bullion according to the quality of the gold from each region. Gold *doré* is then melted with some amount of borax and nitro to remove impurities and, sometimes, to make jewelry. As the *doré* still has residual mercury this is released during the melting operation. The residual mercury ranges from 1%, when retorting is well done to 20%, when amalgam is roughly burned in bonfires, as in Sudan. The fume hoods used by gold shops are usually very rudimentary comprising just a fan that blows out the mercury vapor into the urban atmosphere. In the interior of these shops Hg levels in air can reach 300  $\mu\text{g}/\text{m}^3$ . The residual mercury is lost. Gold shop employees and citizens living around the shops are exposed to high levels of mercury vapor and develop neurological problems. The most dramatic case was documented in the BBC movie

<sup>9</sup> Pantoja, F. and Alvarez, R., 2001, Techniques to Reduce Mercury Emissions in Gold Mining in Latin America, Book of Abstracts from the 6<sup>th</sup> International Conference on Mercury as a Global Pollutant, Minimata, Japan, October, 2001, p. 215.

“Price of Gold”. A citizen in Brazil lost his walking and speech abilities after living for eight years above a gold shop.

In 1989, a Brazilian company, Apliquim, developed a mercury condensing fume-hood consisting of a series of condensing plates coupled with iodide impregnated activated charcoal filters. This equipment reduces mercury emissions by more than 99.9%. Less than  $1 \mu\text{g}/\text{m}^3$  (WHO limit for public exposure) of mercury was detected in the exhausting gases of this fume hood.

Gold buyers are usually much more capitalized than miners, but the demonstration of a whole special fume hood for gold melting is very expensive to be included as a major component of the demonstration unit. It is suggested to include in the unit some components of an air filtering system to demonstrate to gold dealers in Omdurman and Khartoum. This can be simple condensers (even a simple water trap) and activated charcoals (impregnated with potassium iodide) filters.





## 4. Capital Cost of a Demonstration Unit

The capital cost for manufacture the Transportable Demonstration Unit (TDU) includes the costs of equipment, supporting structure (truck bed or container), all ancillaries (wires, pipes, etc.), the tent to be used as classroom and dormitory, power generator, and all labour, supervision and field expenses for first transportation, installation, start-up and short training.

There are a number of tents in the American market that are used as portable classrooms. Shelter Systems offer a dome-tent with diameter of 30' (9m) and it is 11' (3.3m) high weighing 190lb (86 kg) 706 square feet (65.6 m<sup>2</sup>). According to the manufacturer, the tent can be set up by one person in 30 minutes without tools and taken down in 5 minutes. The price is around \$2000. The tent is to be used as classroom as well as to show videos and slides to miners. In Zimbabwe, Taylors Canvas offers a 6x6m tent with galvanized steel and PVC cover that can easily accommodate 30 people in 3-seat benches. The walls roll up and more people can attend the lecture. Tent manufacturers in Sudan were not identified but they must exist.

Audio-visual equipment for training and awareness campaign is also considered. This consists of a lap-top computer plus a data projector and a screen. A turn-key contract with an engineering company is recommended to manufacture, install and start-up the unit. Some pieces of equipment do not necessarily operate on the truck bed. They must be installed on the ground in a way to be easily dismounted and removed. A drop-side container is much more secure than a flat bed platform.

All the prices were approximately quoted in Harare with Small Mining Supplies Ltd. The transportation cost of the pieces of equipment to Gugub can increase the quoted price.

**Table 4.1 – Capital Cost of a Transportable Demonstration Unit**

Equipment	# units	Price US\$ (Geita)
Small jaw crusher (6"x3")	1	5000
Small ball mill (Ø48 x 60 cm)	1	8340
3-set portable screening system with 200l plastic container and replaceable screens	1	500
Sluice boxes: A52 Keene (25 x 129cm)	2	400
Carpets and vinyl mats for sluice boxes	2	100
Cleangold (60x50cm) and structure	4	2000
SMS elliptical amalgamation barrel (Ø30 cm)	1	2000
Special amalgamating plates (40x30cm) Goldtech (with box)	4	1500
Spiral pan (Ø40 cm)	1	500
Centrifuge to remove excess Hg (food processor)	1	1000
Stand with clamps to support retorts	3	150
Retorts: RHYP	10	200
Retorts: PNG retort	10	400
Retorts: CETEM retort (c-steel)	5	400
Retort: Colombian still (stainless steel) with burner	1	500
Retorts: Thermex retort	3	1500
Burner (camping stove with propane or butane gas tank)	2	100
Air blower	1	200
Filter for gold shops (activated charcoal with KI)	1	300
Pulp scale	1	300
200-kg scale	1	100

Gold scale (20 g to 1 mg), portable and battery operated: PP-2060-D Digital Acculab Pocket Scales	1	400
Platform/container to transport all pieces of equipment	1	3000
A&V equipment (computer + beamer + screen)	1	5000
Power generator (27 kVA)	1	8000
Canvas tent (6x6 m)	1	2000
Portable folding plastic chairs	30	850
<b>SUBTOTAL</b>		<b>44740</b>
Miscellaneous (gloves, masks, safety equipment, glassware, bowls, buckets, small instruments, etc.) + spare parts (10%)		4474
Contingencies (10%)		4474
Transportation + installation + start-up + training (10 days)		6000
<b>TOTAL</b>		<b>59688</b>

## 5. Operating Cost of a Demonstration Unit

The TDU must be operated by trainers which include a local mining and mineral processing expert and a technician. It is also recommended to hire one or two local miners to help the unit operation and promote the training activities. These trainers must be trained and this cost is not included herein. Eventually, some other experts (see invited experts) in a specific field related to mercury pollution (e.g. health) can be invited to go the TDU for a sequence of lectures. In principle, the TDU will move just three times per annum, staying in each site for 4 months. The truck to transport the unit must be rented. The platform or container containing all pieces of equipment to be transported can have some legs to facilitate the loading process.

The Government must be committed with the operation of this demonstration unit and keep it working at different sites after the UNIDO project life.

A mechanic and/or an electrician are listed as an expected expense to repair any type of equipment in the unit.

The operating time of the demonstration plant is calculated based on a use of 50% of the demonstration plant, since other 50% of the operators' time is used for classes, training, analysis, maintenance, etc. The operating hours of the plant is calculated as follow:

$$8 \text{ hours/day} \times 22 \text{ days/month} \times 12 \text{ months/annum} \times 50\% \text{ of operation} = 1056 \text{ hours/a}$$

The cost of power was estimated using a power generator but when electric power is locally available, this can be rented from the milling center. In this case, a power meter must be installed on the line in order to pay the right energy cost to the miller. When using a diesel generator it is estimated the use of 0.2 L of diesel/HP-hour or 0.27 L/kWh. Considering a total power of 15 kW and an operating time of 1056 hours/a then the total energy consumed by the unit is around 15840 kWh/a or 4277 L of diesel per annum or 356 L/month. Considering the cost of US\$ 0.85/L, then about US\$ 303/month of diesel is expected.

The tailings generated by the demonstration unit must be safely disposed before the unit moves to another site. This must be done by hiring a truck and disposing the tailings in a landfill, preferentially re-vegetating the site. Water to be used in the TDU comes from local suppliers that in many cases are the milling centers. The use of water from natural streams should not be the first option. The water management item includes the cost in reclaim the water from the ponds an/or any type of expense related to fees to be paid to millers.

The most feasible way to operate the demonstration unit is through a sub-contract with a Government institution (e.g. GRAS) that provides trainers and technicians, and it will be in charge of the unit maintenance. Ideally this institution should own the TDU.

The operating costs must be discussed with the local demonstration unit operators and a more accurate list must be obtained.

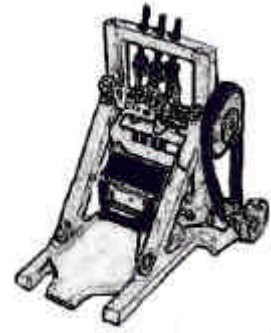
**Table 5.1 – Operating Cost of a Transportable Demonstration Unit**

<b>Item</b>	<b>US\$ (monthly)</b>	<b>US\$ (annually)</b>
Direct Labor		
• local expert (6 months)	1000	6000
• technician (12 months)	500	6000
• one miner (helper) (12 months)	250	3000
• invited expert (lump sum) (2 month/a)	2000	4000
Mechanic + electrician		1000
Repair parts (5% of the capital cost)		3500
Lubricants (1% capital cost)		700
Power (diesel oil) or electric power when available	303	3632
Power generator maintenance (20% of the generator price/a)		1600
Truck rental (3 times/a): 3 x 700		2100
Rental of the Custom Milling (50% of the time)	385	4620
Water management	100	1200
Tailing management	100	1200
Carpets replacement		200
Retort replacements	100	1200
Reagents (NaOH, Hg, etc.)	50	600
Living expenses for 3 people	3 x 400	14400
Meals + coffee for the course attendants (10 days/month)	450	5400
Travel expenses for 3 people	100	1200
Fuel for cars		1000
Office and promotional material	100	1200
<b>Subtotal</b>		<b>63752</b>
Contingencies + administration (10%)		6375
<b>TOTAL</b>		<b>70127</b>



# Small Mining Supplies (Pvt) Ltd

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email: satmark@zol.co.zw



3 November 2003

Dr. Marcello Veiga,  
UNIDO  
Global Mercury Project  
Vienna International Centre

Per email: [M.Veiga@unido.org](mailto:M.Veiga@unido.org)

## **GLOBAL MERCURY PROJECT – DEMONSTRATION UNIT – ZIMBABWE**

Dear Dr Veiga,

We would like to thank you for consulting our company in respect of the above, and for the useful discussions we held in Zimbabwe and Ghana.

To refresh your memory, I shall start with a brief outline of our company, and then move on to how we believe we can be of assistance to you:

### **SMS Company Outline**

Small Mining Supplies (Pvt) Ltd (SMS) was formed 2 years ago with the express intent of providing expertise and equipment to the Zimbabwean artisanal and small mining community, which as you have seen is relatively sophisticated. Despite this sophistication, this sector suffers from a lack of finance, and thus inability to establish privately-owned process plants. As such the artisanal sector is at the mercy of custom mill operators, and the small-worker sector, whilst frequently operating privately-owned mills, often suffers from a lack of cutting-edge technology and finance to make technological capital improvements.

At SMS we felt that there was an opportunity here to provide both expertise and equipment, on a scale and cost level suitable for the ASM sector. Expertise is borrowed largely from the experience and ongoing R&D programs of our sister company, Peacocke, Simpson & Associates (Pvt) Ltd (PS&A). This company has provided extensive minerals dressing services to the region and internationally since 1985, and relies upon the skills of a number of Zimbabwean key players:

Kevin Peacocke, BSc, C Eng – Director

Peter Simpson, BSc, C Eng – Director

Barnabas Moyo, C Eng – R&D Manager

Stanley Makonde, Dip Acc – Sales & Procurement Manager

Patrick Chiropa – Laboratory Manager

The staff of Peacocke, Simpson & Associates (Pvt) Ltd have combined experience in excess of 100 years, heavily biased towards the Zimbabwean small mining sector, which is a model industry in Africa. Messrs Peacocke & Simpson sit on the board of SMS, which also draws upon the skills of the other key players in the company. Both Messrs Peacocke & Simpson are strongly associated to Knelson Concentrators and have traveled extensively for this company in Africa and beyond. Their

particular forté is gravity processing and optimizing of processes and recoveries without the need for chemicals.

The third board member of the SMS board is Mr Kevin Woods, also a Zimbabwean by birth, who has some 20 years of experience in the Zimbabwean mining industry. Mr Woods' background has been predominantly in the sourcing, refurbishment and supply of used or new small mining equipment in Zimbabwe. Over the years, Mr Woods has dealt with nearly all of the more important players in the Zimbabwean industry, as well as numerous lesser players, and he has very strong relationships with various indigenous small-mining associations.

Although SMS is only 2 years old, therefore, it draws upon a huge expertise & experience resource, and has made significant strides in the industry. The company has developed a small single-stamp mill aimed at artisanal and cooperative miners, rubble scrubbers, amalgam barrels, etc., and is presently developing a low-priced centrifugal concentrator. The bias here is towards providing medium/high technology which is both appropriate in terms of both price and operator skill level. All internal equipment lines are continuously improved and updated with feedback from the industry and according to R&D investigations at PS&A.

Moving beyond the borders of Zimbabwe, SMS has an existing joint venture with Mulittech Services of Ghana for small mining equipment supply in West Africa, and is actively seeking JV partners in other African countries. Outside the continent, we have excellent relations worldwide with a number of mining equipment supply companies, generally through the worldwide Knelson network. Most of these companies have been allied to Knelson for many years, and have tried-and-tested track records.

K H Woods, P T Simpson, K G Peacocke  
Directors of SMS