PERU: FOURTH INTERNATIONAL GOLD SYMPOSIUM

Advances in the Implementation of Clean Technologies in Bolivian Small Scale Mining to Mitigate Mercury Emissions, Liquid and Solid Waste

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ABSTRACT

The "Integrated Environmental Management in Small Scale Mining Programme" (MEDMIN) in conjunction with the Ministry of Sustainable Development and Planning (MDSP) of Bolivia have been working on prevention and control of environmental mining problems.

The main objective of this Programme is to reduce the pollution caused by the mining activities from small mines and cooperatives, through the enforcement of the new environmental and mining regulations, in close cooperation with public and private organizations promoting a small scale mining environmentally sustainable. Important issues are the appropiate use of mercury during the amalgamation process, the correct final disposal of solid residues (tailings) and the introduccion of new non expensive clean technologies environmentally sound.

To achieve this objective both MEDMIN and the MDSP are doing lots of efforts sending technicians some times even to remote areas, to talk about the current regulations, promote capacity development in environmental issues and implementation of clean technologies. The Programme offers mainly technical assistance. However, when its possible some economical assistance can be also provided.

As a result of this coordinated work, at present approximately 10 tons of mercury per year are not longer emitted into the environment (air, water and soil). As for the tailings discharge, few implementation tasks have already been executed but still remain many things to be done.

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INTRODUCTION

From the approximately 7 millions inhabitants in Bolivia, about 400,000 depend on small scale mining. This activity, that in many cases seems archaic, is the cause of serious environmental problems, which not only affect miners themselves and their families, but also the population who live nearby. In Bolivia, mining pollution problems are associated to:

- Mercury emission and discharge produced by gold mining
- Water pollution produced by flotation plants, mainly due to solids discharge
- Acid mine drainage from current and abandoned mines
- Siltation of rivers produced by alluvial mining
- Destruction of landscape produced by alluvial mining

The Program “Integrated Environmental Management in Small Scale Mining” (MEDMIN) in Bolivia, is a Programme of environment protection in small scale mining in Bolivia. The Programme has been mainly financed by the Swiss Agency for Development and Cooperation (SDC) and executed by Projekt-Consult GmbH. The Ministry of Sustainable Development and Planning (MDSP) was the Bolivian counterpart of MEDMIN. It started its activities in April 1994 untill December 1999, when the Programme has turned into a Foundation.

This paper presents the advances made in the implementation of clean technologies to mitigate mercury emissions in primary gold mining in La Paz Department and at the Brazilian border in Beni Department (San Simón). The implementation of Lamella thickener as an alternative for tailings dams in small concentration plants to clarify silty effluents and the planification of a common tailings dam to collect tailings from 40 flotation concentration plants in Potosi City are also briefly described.

IMPLEMENTATION OF CLEAN TECHNOLOGIES IN PRIMARY GOLD MINING

Small scale mining of gold-quartz veins has gained more and more importance in Bolivia in the last 10 years. Only in La Paz Department there are about 100 mining cooperatives and small private mines operating in this sector, the majority of them located in the Eastern Cordillera region. There exists a great variety in the technology employed and the throughput achieved, from manual and artisanal mines to semi-mechanized mines and processing plants with capacities up to 20 tpd. Altogether, the production of small scale primary gold mining can be estimated to reach 5 tpy of gold, which represents a very important economic factor for Bolivia. An estimated number of 10,000 miners and their families dedicate themselves to this activity. This mining activity goes hand in hand with sizable environmental impact in the mining areas, which mainly comprises the contamination of the rivers with sulphides and their siltation with finely ground host rock, besides the problem of mercury emissions.

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Currently processing techniques used in the Bolivian small scale primary gold mining sector show a great variety of individual methods which specially depend on the financial situation of the miners and their technical knowledge. The gap in technology reaches from primitive "stone age" methods (stone mills), to methods which can be found in Agricola's "De Re Metallica" (strakes, hand jigs), to quite modern equipment which shows no difference from the one used in more sophisticated mining (shaking tables, spirals, etc.).

Performance and environmental impact

Generally, gold recovery in the processing plants is low. This is partly due to a portion of the gold not being recovered by gravimetric means or amalgamation. Yet, free gold is also lost to the tailings, specially fine gold or flaky gold (flattened by the milling process), and part of the gold is lost because of insufficient liberation. The combination of milling and amalgamation causes high losses of small gold particles trapped in *floured mercury* or in the form of gold-amalgam-flocs, which often contain air bubbles or enclose water. These flocs have a relatively low specific gravity and a large surface, and are easily washed to the tailings.

The accompanying sulphides (pyrite, arsenopyrite, etc.), which represent a very interesting byproduct with their gold content of 40-200 gpt, generally fail to be recovered systematically and are lost in the tailings.

The tailings are commonly flushed into the vicinity of the processing plants or into the next river. In some mines, coarse tailings are retained within sedimentation tanks and piled up for further, future treatment, while their portion of slime goes with the overflow water into the river. The siltation of the rivers leads - more so than contamination with mercury or sulphides- to a strong decline of the aquatic fauna and to confrontations with peasants living downstreams who consume river fish.

The emission of ground sulphides into the river systems or their unsaved deposition in form of tailing piles causes, due to the oxidation of the sulphides, a lowering of the pH in the effluent waters and a leaching of heavy metals (Fe, As, Zn, Cd, etc.) in these effluents, metals which are clearly detectable in the rivers of the gold mining areas.

The emissions of mercury in the atmosphere through the burning of the amalgam represents not only an environmental problem but also a problem of industrial safety. Normally, about 500 g - 1000 g of mercury per kilogram of gold are evaporated, which in turn condense and sediment, for the most part, very close to the direct burning area.

Miners constantly inhale mercury vapor, a fact which leads only to very few cases of acute mercury poisoning. In some medical investigations, high mercury concentrations in the blood of miners and their family members have been detected. The harsh living conditions of the miners (poor nutrition, lack of hygiene, no medical attention, high alcohol consumption, etc.) make it difficult to establish a clear relation between the use of mercury and health problems. It is yet far more difficult to make the miners understand that their easy use of mercury could be a health risk for the populations downstream.

The most serious environmental problem is the use of mercury in an open circuit. Added to the mill, the mercury is ground finely into small spheres (20-50 µm), or so-called *floured mercury*. The substances in the feed material such as fats, oil and others such as aluminum and copper from detonators and cables, minerals like talcum, etc. contaminate the mercury in such a way so that it looses its ability to combine to bigger mercury pearls and its amalgamating strength is lowered. A large part of the added mercury turns into floured mercury, which cannot be recovered sufficiently with any gravity separation method (like mercury traps, etc.). Normally, when comminution and amalgamation are combined, 5-10 kg. of mercury are lost in the open circuit, per kilogram of recovered gold. This is several times the amount lost when burning the amalgam. Other mercury emissions result from the unsaved tailing deposition from amalgamation drums. Table 1 shows emissions, causes and possible solutions. Until now, cyanide leaching is not used in small scale gold mining in Bolivia.

Table 1: Emission, cause and possible solutions in small scale primary gold mining in Bolivia

Emission	**Cause**	**Solution**
mercury	use of Hg in open circuit in the mill	eliminate the combination of milling and amalgamation through the improvement of gravity concentration methods
	burning of amalgam at open air	use retorts
	unsave deposition of amalgamation tailings	construct safe disposals or sell the tailings to leaching plants
sulphides	use of inapropiate gravity concentration	improve traditional gravity concentration methods; proper sulphide disposal
coarse and fine solids	lack of apropiate tailings disposal and water treatment	construct small tailing dams and decantation devices for slimes
acid drainage from tailings	oxidation of sulphides	recover of sulphides, see above
heavy metals	natural leaching processes of mineral tailings	recover of sulphides, use of precipitation plants and or artificial wetlands

Improved Techniques

In the first two years, the later described methods and equipment were tested in practice together with the miners in several mineral processing plants. At the same time, the construction in local workshops was started and the quality of the equipment was controlled. During the third year of the project, a systematic divulgation of the improved techniques was started as well as their installation in a number of mines (see Table 2), while continuing the testwork to solve still existing technical problems. The introduction and divulgation of the clean techniques was accompanied by seminars for the miners, teaching videos, brochures, etc.

The main emphasis was laid on avoiding the use of mercury in an open circuit, as this currently represents the most severe environmental problem, and to recover the accompanying sulphides. At this point, gravity concentration processes were optimized to enable a good recovery without combining amalgamation and comminution.

The starting point for the work with the gravity concentration methods was the low recovery of the traditional methods, despite their use of mercury in an open circuit. Another point of interest for the miners was the reduction of high mercury consumption, which represents not only an economic loss, but often also a problem of acquisition in the sometimes very remote areas. It could be seen now, that most miners in fact are open to change their working system and to introduce clean techniques, if this means higher recovery (income) or less costs for them.

The traditional widespread sluices or strakes were improved and shaking tables, jigs and spiral concentrators were implemented. Small additional equipment, such as amalgamation drums, upward current sorters for the separation of amalgams and sulphides, and mercury retorts for the distillation of mercury in a closed circuit complete the processing methods promoted by the project.

Until now MEDMIN has mitigated approximately 10 t of mercury per year which are no longer emitted to the ecosystem. The divulgation of these clean technologies will be continued, so it could be expected that mercury emissions due to small scale gold mining will be mainly controlled in the near future.

Concerning the metalurgical balances, there exists an average of a 20% higher recovery rates in the modernized and changed concentration plants. The small miners are much more interested in this economic advantage than in the positive environmental impact.

Lamella Thickener

In Bolivia, one of the many impacts due to the small scale primary gold mining is the siltation of the water basins with fine slimes and coloidal particles (silica and sulphides) coming from mineral processing plants, which threats clearly people´s health living down stream of these basins.

The natural settling velocity of these particles is too low, so it is difficult to achieve an effective natural clarification by using small tailing dams or ponds. Aditionally, the highland topopraphy area where those processing plants are located, do not offer neither areas nor ppropiate conditions for the safety construction of tailings dams or settling ponds.

The previous considerations led to MEDMIN to study and test other replacing alternatives. One of them is the use of floculants to accelerate the sedimentation process assisted by a plate thickener of ¨Lamella¨ type, for the retention and removing of fine coagulated slimes. This combination is an effective system for the clarification of silty water.

Floculants are polyacrilamides of high molecular weight which allow the colloidal particles to get aglomerated forming flocs able to settle down quickler.

The Lamella clarifier alllows the retention of these flocs and it is basically composed for a package of leaned parallel plates placed in a tank, which reduce the settling height and increase the effective settling area. The effective area used by the Lamella clarifier is only 5% of that one required by a conventional round thickener. The leaned plates allow the gravitational settlement and the movement of coagulated solids to a collector tank at the bottom. The area between the plates is for the clarification, whereas the lower collector tank underneath the plates is for thickenning. There are different types of Lamella, with a few differences between each other. They are mainly related with the type of packing of the plates and with the tank geometry.

The **main operating parameters** of the clarification system are:

- silty water inlet flowrate
- inlet flowrate and consistency of the floculant solution
- floculant addition point (s)
- Lamella´s thickened sludge discharge frequency

The **main advantages** offered by the utilization of a Lamella clarifier are the following:

- efficient clarification of silty water
- low investment capital cost
- easy operation
- continuous discharge of clear water and tickened sludge
- visual follow up of the clarification process

- low energy requirement (only for the floculant preparation)
- the unit can be stop, drained and re-started, with out requiring stabilization periods
- the effective area occupied by the Lamella clarifier is only 5% of that one required by a conventional thickener.

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Table 2: Summary of the equipment and techniques implemented by MEDMIN in diferent small scale gold mining operations

(please insert Table 2) Exel file attached

mine/ cooperative	La Suerte		Yani		25 de Julio		LIBeRTAd		15 de Agosto		10 de Febrero		Virgen del Rosario		Il Huayna Sunchulli		Cotapata		Fortaleza de S. Vicente		Zongo		Union Ideal		[illegible]
equipment																									
jawcrusher	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
ball mill	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
chilean mill	X				X								X		X								X		
quimbalete									X		X														
toloka (stone mill)					X				X																
rustic sluice (tojlla)			X		X		X						X		X		X		X		X		X		X
sluice with carpets				X		X		X		X		X		X		X						X		X	
tromel (exit mill)	X			X		X	X	X		X		X		X	X	X	X	X	X			X		X	
spiral clasificator	X	X																		X					
hydraulic clasificator		X								X								X		X	X	X			
pan (for preconcentrate)									X		X														
jig		X								X								X		X	X	X			

shaking table	X	X	X	X														X	X	X					
amalgamating plate	X		X		X																X		X		
spiral				X														X						X	
amalgamating drum	X	X		X		X				X		X		X				X	X	X	X	X		X	
pan to separate amalgam	X		X		X		X	X	X				X		X	X	X		X		X		X		X
hydroseparator for amalgam		X		X		X				X		X		X				X		X		X		X	
retort	X	X		X		X		X		X		X		X		X		X		X		X		X	
process																									
comminution	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
milling	X	X		X		X	X	X		X	X	X		X		X	X	X	X	X	X	X	X	X	X
comminution with Hg (open circuit)	X		X		X				X				X		X				X		X		X		
milling circuit with conc.		X		X		X		X										X		X					
amalgamating with plates	X				X																X		X		
conc. grav. with rustic sluice			X		X		X						X		X		X		X		X		X		X
conc. grav. with optimized sluice				X		X		X		X		X		X		X						X		X	
conc. grav. with jig		X								X								X		X	X	X			
conc. grav. with tables	X	X	X	X														X	X	X					
conc. grav. with spiral				X														X		X				X	
other processes with conc. grav.																			X*						
manual amalgamation of concentrates			X		X		X	X			X		X		X	X	X						X		X
mecanized amalgamation of concentrates	X	X		X		X				X		X		X				X	X	X	X	X		X	
amalgamation with toloka					X				X																
open air burning			X		X		X		X				X		X		X		X		X		X		X
retort burning	X	X		X		X		X		X		X	X	X		X		X		X		X		X	
systematic recovery of gold bearing sulphides		X		X		(X)				(X)		(X)		(X)		(X)		X		X		X		X	
systematic deposition of coarse tailings	X	X		X		(X)	X	X		(X)				X		X				X					

former process (shaded) | new process | (X) parcial | *Knelson

Figure 1 : Flowsheet of the improved concentration plant of La Suerte Cooperative

(Not available)

At the moment, a Lamella clarifier is operating at ¨La Suerte¨ Gold Mining Cooperative, located on the mountainous region of Yani, La Paz-Bolivia. The attached diagram (Figure 1) shows the location of this Lamella unit within the mineral processing circuit.

San Simon Project

In the Bolivian Lowlands, in San Simón in Beni Department, near to the Brazilian border, 350 small scale miners are working in the concession of an international exploration company. These miners have an agreement with the company. The extracted raw ore is concentrated in about 18 small gold concentration plants (hammer mill, amalgamating plate, rustic sluice). Mercury is used directly in the mills, which produces incredible high amounts of mercury losses. Taking into acount the installed capacity of the mills (30tph), working 8 hours per day, 20 days per month, using at least 500 g of mercury per ton of raw ore, there is a minimum use of 2,400 kg of mercury per month. The recovery rate of mercury is less than 10%. This means that we have more than 20 t of mercury emissions per year. Concerning the metallurgical balance, the gold recovery rates of these plants are less than 50%.

Concerned about this alarming reality MEDMIN installed ad hoc a parallel sluice system without using mercury in an open circuit to compare metallurgical data with the traditional concentration system. The results are shown in Table 3.

Table 3: Simple comparison of the traditional and a sluice concentration plant (milling the same raw ore):

	MEDMIN-System	San Simón System
Mill	Hammer H2	Hammer H2
Raw Material	3 tons	3 tons
Milling grade	- 2mm	- 2mm
Recovering system	Sluice/carpets	Mercury in mill, plates
Mercury used	50 g*	2 kg
Mercury recovered	50 g	100g
Gold recovered	28.8 g	28 g

** only for the final concentrate*

Figure 2 : Flowsheet of the implemented Pilot Plant in San Simón

(not available)

This first pilot testing shows that it is feasible from the technical point of view to improve quiet easily the concentration plants economically (higher recovery) and environmentally (to reduce mercury emissions at least about 95%). In the meantime, MEDMIN installed a more sophisticated pilot plant (hammer mill, concentration spiral, sluices, amalgamating drum, retort, see Flowsheet Fig. 2), which is currently in test operation. Ajusting the milling grade to the optimal liberation grade of the gold, first tests have shown an improved recovery of at least 30-40%. Mercury is only used to amalgamate the concentrate in a closed circuit, so mercury losses are minimium. This fact presents also a cost reduction for the miners. Taking into acount the data in Table 3, the losses of 2 kg of mercury (1 kg mercury cost 3 g of gold at the local market) represent an operating cost of 6 g of gold, which are more than 25% of the produced 28 g of gold.

SAN ANTONIO TAILINGS DAM IN POTOSI CITY

MEDMIN commissioned Golder Associates (UK) Ltd. (GAUK) to undertake a feasibility study for a tailings storage facility near to the city of Potosí, Bolivia. In and around Potosí there are around fourty small scale mineral concentration plants either operational, idle or under construction. They receive lead, zinc, tin and silver ore from Cerro Rico to the south of the city, and from other mines in the region. At present, the tailings slurry from the concentrator plants (ca. 1,000 tons per day!!) is discharged directly to the Rio de la Ribera, Rio Huaynamayu, Rio Korimayu and the Rio Alja Mayu. These rivers also receive raw sewage from the city, Acid Rock Drainage (ARD) from various sources and seepage from old tailings dumps and waste rock piles. These rivers eventually become the Rio Tarapaya which is used by communities downstream as a source for crop irrigation. The Rio Tarapaya which is a tributary of the Rio Pilcomayu contributes significantly to its contamination. The Pilcomayu river (670 km) very well known in South America for its “sábalo fish”, flows through Potosí, Chuquisaca and Tarija Departments on Bolivian territory to then reach Argentina and Paraguay. This water pollutin results in a source of conflict between the downstream departments of Chuquisaca and Tarija and the governments of Argentina and Paraguay with Bolivia.

Background to the Project

The most evident form of contamination of the river resulting from the tailings is a characteristic dark grey coloration as a result of high amounts of suspended solids in the stream flow, which can be seen many kilometers downstream (in the dry season more than 200 km). The river water is also contaminated by milling reagents such as frothers and collectors, lime, cyanide, metal ions and complexes.

In 1997 an environmental regulation for the mining sector has been enacted by the Bolivian government to complete the existent general environmental law and regulation. The water quality standards that are applied to a water course depend upon its end use. For the purpose of the feasibility study it has been assumed that the rivers in and around Potosí are Class D (restricted to navigation and industrial uses).

Principal Design Considerations

One of MEDMIN's fundamental objectives is to introduce cost effective means of minimizing environmental impacts due to small scale mining activities. The primary purpose of the project is to remove tailings solids from the rivers downstream of Potosí. However, removing the high pH tailings discharge from the rivers would cause the pH of the rivers to decrease, resulting in an increased ARD and associated heavy metal loading. It is therefore proposed to collect the main sources of ARD and divert them to the tailings dam. This will not cause the pH of the rivers to decrease whichever decant strategy is adopted, and should cause it to increase if the decant water is recycled or treated and discharged at near neutral pH.

The requirement to protect groundwater and surface water from pollution by contaminated seepage flows is a fundamental design consideration. This dictates the containment design, operational characteristics and closure plan of the dam. At Potosí the groundwater is already contaminated primarily by sources of ARD and this is unlikely to change in the long term. While this should be taken into account, the design of the tailings dam should not result in a deterioration of the situation. The tailings at Potosí contain up to 40% pyrite, which is one of the main sources of ARD, and will generate acid upon oxidation, with subsequent leaching of metals.

Once the tailings solids have been removed from the rivers it is likely that communities downstream will perceive that the river is much less contaminated. However the bacterial loading from sewage discharges will remain. A comprehensive educational programme for communities downstream will need to be implemented prior to commissioning of the tailings dam.

The tailings would be transported to the tailings dam through a dedicated tailings collection system. An efficient slurry transport system requires tailings flow that does not vary significantly in flow rate or pulp density.

Four disposal sites were identified at La Palca (Site A), Rio de la Ribera (Site B), San Antonio (Site C) and Cantumarca (Site D). Initial assessment of the catchment area, likely foundation conditions and storage to construction volume ratios led to Site C (San Antonio) being selected as the preferred alternative.

Feasibility Studies

Studies were carried out to :

i) determine ground conditions in the areas of the proposed tailings dam.

ii) locate suitable materials for dam construction

iii) determine groundwater and surface water conditions in the area.

iv) assess the properties of the tailings to be stored in the dam.

v) assess the practicalities of the tailings collection and recycled water distribution.

Design

The main features of the proposed tailings disposal scheme are :

- Construction of an earthfill starter dam at the chosen site.
- Raising of stack walls with tailings to the elevation necessary to provide a life of around 15 years at a tailings production of 1,000 tpd.
- Control of the phreatic surface within the stack wall by limiting the tailings pond size and allowing seepage through the starter dam.
- Decanting of tailings pond water via a system of concrete penstock towers and decant culvert.
- Rationalisation of tailings transport by provision of make-up water from a central thickener and the tailings dam allowing plants to discharge slurry at lower pulp densities.
- Collection of permanent ARD sources and transportation of these to the tailings facility.
- Passive treatment of tailings dam seepage by means of an anoxic limestone drain (ALD), settling pond and acid wetland downstream of the tailings dam.
- Minimization of infiltration of rainfall after closure by provision of a low permeability capping layer.

Costs

An assessment of capital costs, operating costs and closure costs has been made for the project as designed. However, there are some uncertainties associated with some of the quantities and some of the prices. Where uncertainty with respect to quantity or price exists for an item, upper and lower limits have been applied, the choice of which depended upon judgement. A Monte Carlo simulation of values between the upper and lower limits was run in order to arrive at a final most likely cost. Minimum and maximum costs were also calculated. The Capital, Operating and Closure Cost estimates (in millions of US $) derived using this approach are presented below. Costs per tonne of tailings stored are in US $.

COST	**CAPITAL**	**OPERATING**	**CLOSURE**	**Cost Per Ton**
Mean	2.30	5.46	1.44	1.61
Minimum	2.18	5.19	1.32	1.52
Maximum	2.41	5.73	1.55	1.70

The German Financial Cooperation (KfW) is financing an integrated water project in Potosí (approximately US $ Mio 18), which includes the final design and construction of the San Antonio Tailings Dam, a sewage canal system, and a sewage water treatment plant, so that the water pollution problem in Potosí will be almost solved in an integrated manner. MEDMIN is still involved in the project and last year elaborated an integrated concept (financial, intitucional, administrative and economic) for the tailings dam to complete the technical and economic feasibility study. Moreover, international donors within the environmental sector are actively supporting the remediation and control of environmental problems.

Conclusions

- As a result of a coordinated work between public and private organizations (authorities, miners and MEDMIN) it has been possible to reduce the pollution caused by the mining activities from small mines and cooperatives in some mining areas of Bolivia.
- At present approximately 10 tons of mercury per year are not longer emitted into the environment (air, water and soil). As for the tailings discharge, few implementation tasks (final disposal and storing) have already been executed but still remain many things to be done.

- Although it has been possible to achieve some enforcement of the new environmental and mining regulations, still remain lot of monitoring and work to be done in order to guarantee the current mining and environmental sound practices.
- The introduccion of some capital for new non expensive clean technologies and for environmental issues, have helped the miners to improved the efficiency of their operations. It has shown them a number of benefits instead of constraints.
- Talks about the current mining, environment and sectoral regulations have helped to promote capacity development, so that the projects should be self sustainable.
- Nowadays, MEDMIN FOUNDATION is a highly recognized organization among the mining industry, which is providing payed consultancy but still free assistance to the most poorest and needed mining cooperatives.

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