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Reducing global mercury pollution with simultaneous gold recovery from small-scale mining tailings

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The increasing population on planet Earth has many impacts—one is a strong influence on the amount of mercury released to the environment. The worst influence stems from the rapidly increasing number of small-scale gold miners in Asia, Africa, Central and South America, who presently provide food on the table for tens of millions of households. Small-scale gold miners use vast amounts of mercury to capture the gold, and much of this mercury is released directly to the environment. A large part evaporates to the atmosphere and the rest is transported downstream in rivers ending up in the oceans. The amount of mercury released is phenomenal: an estimated 3000 tons of mercury is released annually by small-scale gold miners alone, a staggering 37 % of global mercury pollution. A vast proportion enters the food chain in fish and sea mammals, as well as in rice polluted by spillage waters which enters irrigation pathways. Human consumption of polluted fish and/or rice already today has a crippling impact on human health in some countries, and this will have even more severe consequences if the current situation is not changed radically and rapidly. It is of particular concern if mercury-intoxicated women become pregnant, because the foetus extracts mercury from the mother. The human foetus is much more sensitive to mercury intoxication and thus has a high risk of being born with brain damage as well as physical disabilities. Over just one generation this will cause reduced intelligence for exposed children. Through such organisations as the United Nations Environment Programme (UNEP), the World community has become acutely aware of the rapidly increasing global mercury pollution. The treaty designed to protect human health and nature, the "Minamata Convention" has today been signed by the majority of world countries. Signatory countries are hereby obliged to start initiatives to reduce and even stop mercury use. This grim outlook has prompted a group of international concerned researchers and small-scale gold miners from Philippines to start teaching small-scale gold miners to work without the use of mercury and simultaneously to find ways to clean mercury-polluted gold mining tailings, which are one of the main polluting agents. This latter will have an immediate positive economic effect for the communities involved, which should be a significant motivation to change to non-mercury recovery processes. We here describe the specific technological drive to be able to go mercury free.

Keywords: mercury flour, mercury pollution, gold loss, cleaning tailings, small-scale mining, artisanal mining, state batteries

Introduction

Mercury pollution has become a serious problem for life on planet Earth. Through such organisations as the United Nations Environment Programme (UNEP), the World community has become acutely aware of the rapidly increasing global mercury pollution. The treaty designed to protect human health and nature, the "Minamata Convention" has today been signed by the majority of world countries. Signatory countries are hereby obliged to start initiatives to reduce and even stop mercury use. Small-scale gold mining accounts for 37 % of global mercury pollution. Millions of poor people resort to this type of mining as the only way of sustaining their families. A large part of the mercury used in the final step of gold extraction ends up as mm-sized droplets in dumps (tailings) from which mercury slowly evaporates to the atmosphere. These droplets make up what is referred to as *mercury flour*, which is a main contributor to the global mercury pollution. The flour also contains large amounts of gold. This paper describes a road map to clean up mercury from tailings with dual benefit: environmental and economic. The gold in the mercury flour, will cover most, if not all, cleaning-up costs and may even provide a handsome profit in addition. Possible ways of safe long-time storage of the recovered mercury are also outlined below.

Background

Global mercury pollution is a fundamental problem for life on Planet Earth since, in addition to causing other serious health problems, it affects foetal brain development.[1] This creates major learning problems for generations to come all over the World. The global mercury pollution affects millions of poor people in Southeast Asia, Africa, Central and South America who, in order to provide a livelihood, resort to gold mining using primitive equipment and low tech approaches. The final step in the gold extraction process is relying on mercury to capture the numerous small gold grains in pulverised hard rock or river sediments. Carried out for hundreds of years in the past, this type of local gold mining earlier only caused relatively minor mercury pollution to the planet. However, the dramatic population increase during the last century has caused a massive increase of this pollution. While we cannot easily provide immediate alternative sources of income for millions of small-scale gold miners, we **can** influence the prevalent way of thinking about how to extract gold in an equally efficient, mercury-free approach and, furthermore, simultaneously be able to show an avenue to clean up the hundreds of thousands of heavily polluted mining dumps that litter Planet Earth.

Small-scale gold mining

Small-scale gold mining, also termed artisanal gold mining,[2] is often caricatured as "three men and a wheel barrow". In Africa, Southeast Asia, Central and South

America, it is driven by the abject poverty of millions of people, and there are inherent advantages as well as disadvantages. On the one hand, small-scale mining reduces urbanisation and provides food for millions of families in rural areas, but on the other, it creates massive mercury pollution with extremely serious consequences for humankind in generations to come.

Gold occurs in mineralised hard rock as µm to mm-sized grains, either as pure grains but more often enclosed in other minerals, and as free gold in river sediments, in *placer deposits*.[3]

Small-scale gold mining is carried out from pits, shafts or tunnels. The ore is crushed and further milled down to mm-sized powder in order to *liberate* the gold grains from their host minerals. This is a difficult process if the goal is for it to go to completion, but usually a certain fraction of liberated gold is acceptable enough at this minimum technology level. Depending on country, milling is performed in many different ways. In Southeast Asia and parts of Africa, metal drums filled with hard metal rods or balls are frequently used (Figure 1), whereas in Central America other methods are often in use. In Nicaragua, for example, four big stones slowly churn around in a cement cavity whereby the crushed ore is milled (Figure 2).

Figure 1. Efficient artisanal processing plant (Sudan) with mill and gravitational processing of pulverised gold ore. The ore is milled in the drum in the background, after which the fine-grained ore is passed through a system of sluices, which concentrates the heavy minerals, including gold.

The next step is to *concentrate* the heavy minerals, among these, gold. The gravitational methods used vary greatly from simple to complex. The former, such as panning, are the most common, but more complex methods generally result in higher yields. The outcome is a mineral concentrate comprising a variety of heavy minerals including gold.

The following step is to *separate* gold from the other heavy minerals. This is more often than not done by adding mercury to the concentrate (Figure 3). Mercury has the capacity to *amalgamate* elements such as gold, silver and copper into an *alloy*. The key next step is to burn off the amalgam so that mercury evaporates and gold is left behind. This simple process does not require much investment in equipment, but it is extremely toxic because of a total lack of suitable protection technology; for artisanal mining there is absolutely not the economic ability to even contemplate introducing such protection. Increased awareness is one of the objectives for the drive described in this communication.

A slightly more advanced method consists in the miners adding mercury at the milling stage. This saves time and work, since this also takes care of good mixing of mercury with the pulverising gold ore, thereby creating the desired gold amalgam very efficiently. When the amalgam is heated mercury evaporates, thus being released to and polluting the environment, leaving the gold behind (Figure 4).[4] The waste, called tailings, is simply dumped. This procedure is used by millions of artisanal miners.

Figure 2. Low tech milling (rastra) with mercury addition (Nicaragua). The boulders mill around slowly for a couple of hours. When milling is complete, the cavity is cleaned of milled ore and mercury amalgamated with gold. The flour floats away.

Besides the very serious atmospheric mercury pollution, from the point of view of the extraction technology itself there is also a serious disadvantage in the form of so-called "mercury flour", a product of the mixing which is discussed more in the following section.

Mercury flour

During milling and hand mixing, part of the mercury is transformed into mm-sized droplets referred to as mercury flour (Figure 5). This can float on water because the individual droplets are very small. Many of the droplets may float close together but they never coalesce, neither do they coalesce when dispersed in milled gold ore. Mercury flour disperses into the environment and so is lost for the miners. The remaining flour is scattered in the tailings and is therefore, likewise, unattainable to the miners.

Mercury flour is one of the main contributors to global mercury pollution. It constitutes one of the most severe threats to the environment and to the health of us all on Planet Earth. Mercury flour in the tailings gradually evaporates. Through wind, the vapour is actually incrementally spread all over Planet Earth. Rain brings the atmospheric mercury to the surface of the earth where it enters the drainage system. In the rivers and in the soil metallic mercury is changed into methylated mercury, which

Figure 3. Hand-mixing mercury with milled gold ore (Tanzania).

Figure 4. Gold has been concentrated and smelted to a small bead.

Figure 5. Mercury flour (droplets) in a spoonful of tailings (Philippines).

enters the food chain. The mercury is thus not only a health risk in the countries where small scale gold miners release it to the atmosphere, but it very quickly creates a global problem.

"Interestingly" (see further below) this is not the only issue associated with mercury flour. Another, a potentially positive issue, is that it contains large amounts of gold. Such gold, if realised, has such a high value that this could provide quite a substantial lift to the miners' livelihood. Reaping this gold amounts to a win–win achievement for all.

A prime question is why droplets of mercury flour formed during gold extraction do not coalesce as they otherwise normally do? Per Møller, professor in metallurgy at the Danish Technical University in Copenhagen, through a series of dedicated tests, has shown that flour droplets are coated with an oxide film during milling and stirring. It is this thin coating that inhibits droplet coalescence. Furthermore, it was also found that by adding small amounts of a certain non-toxic organic compound, the droplets lose their mercury oxide coating and so again coalesce more easily.[5] This organic compound is aptly named "DETOX"; Professor Møller's process is currently being patented.

Capturing mercury flour

At first sight, it would seem an insurmountable task to recover the immense number of very fine droplets scattered throughout all the innumerable local artisanal tailings from small-scale gold mining, on several continents; the logistics appear completely overwhelming. There is a way, however, ….

The first attempt at this was carried out in 1894 by the Australian Government during the major gold rush in Western Australia.[6] The Australians termed the new facilities "State Batteries", but they apparently soon went out of use. The next attempt was in 2011 where a research group supported by the Benguet Federation of small-scale miners in the Philippines, the Sumitomo Foundation (Japan) and the Geological Survey of Denmark and Greenland (Denmark) improved the working processes inherent in the State Batteries.[7] The resultant facility is now known under the name "Peter Plates", a name coined by the Benguet Federation of small-scale gold miners.

"Peter Plates"

"Peter Plates" consist of a number of copper plates stacked at an inclined angle, one plate on top of the next in a continuous flow train (Figure 6). Before use, the plates are thoroughly cleaned with nitric acid, after which they are treated with metallic mercury, which forms a thin coating of copper amalgam. Tailings with mercury flour are now slowly flushed down the plates. On contact with the copper amalgam, the flour sticks to the plate and is so *captured*. If the first plate does not retain all droplets, subsequent plates come into play in a classic cascade process. When the plates are at capacity, the amalgam is scraped off and the process can easily be repeated.

After processing, the amalgam is heated and the vapour captured in a cold trap. Testing carried out in the Philippines in 2010 and 2011 proved that this method can extract up to 60 % mercury from tailings.[7] Although this is promising by itself,

Figure 6. Prototype of "Peter Plates" in action (Philippines). Tailing slurry from the tub is passed over the plates in succession.

Figure 7. Mercury Recovery Plant (MRP) being loaded by tailings (Nicaragua).

reflecting a capacity of only about 100 kg tailings processed per hour, when considering the millions of tons of polluted dumps that today wait to be cleaned, a long-term viable solution still would appear far away.

Large-scale recovery

Thus, the efficiency of "Peter Plates" to capture mercury is promising, but their capacity is currently not at a level to make a significant quantitative contribution to the clean-up that is needed in order to reduce the many tons of tailings in existence already.

As a signatory of the Minamata convention, the Danish Government feel obliged to make an effort to contribute to reducing the global mercury pollution. Consequently, in 2015 and 2016 the Ministry of Environment and Food awarded a group funding for two tests to explore if more efficient ways to clean-up mercury-polluted tailings from small-scale gold mining. A consortium—composed of two Danish companies, Elplatek A/S and AppelGlobal, together with Oro Industries, California—obtained funding for a two-year feasibility project aimed at *increasing the capacity* of mercury recovery from tailings. The first work was carried out in Northern Nicaragua in 2015 and 2016.[5] Further work, but on a smaller scale, carried out in Peru was financed by the US Department of State. Future test work on a larger scale is planned for cleaning the River Naboc in Mindanao, Philippines. This river has drained a rich gold occurrence (Diwalwal), which has been mined by small-scale miners using mercury for well over 50 years.

A mobile, high-capacity processing station

In 2013, the Californian company Oro Industries invented a Mercury Recovery Plant (MRP; Figure 7). It is a large mobile machine on wheels, towable by truck and thus suitable for reaching tailing dumps spread across large geographical areas. It processes heavy mineral concentrates through a series of cyclones with the concentrate from each cyclone directed on to the next. The concentrates from the two first cyclones are directed into a centrifuge, and the concentrate here from is finally directed into the last cyclone. The process is described in detail in Reference 5. One MRP unit has a capacity of 15–20 tons per hour. Based on this, each plant produces a concentrate in the order of 10–20 kg heavy minerals per hour, including mercury and gold. A combination of MRP and Peter Plates increases efficiency significantly; the latter hooked on the MRP outlet, extracts mercury flour and gold from the heavy mineral concentrate as shown in (Figure 8).

The capacity of the combined MRP and Peter Plates can extract auriferous mercury from 20 tons per hour, 24/7. A rough estimate of the total tonnage of current tailings produced per day will require in the order of 5000 processing plants to travel Africa, South and Central America and South-east Asia to just to keep up with the daily production. It will thus require many more processing stations if the target is to clean the tailings produced previously. However, the thrust of the present communication is that the necessary dual-purpose technology is at hand, and that the still impressive clean-up intensity, can in fact be tackled—it is simply a matter of scaling-by-numbers of the combined MRP-Peter Plates units.

Sampling—a critical success factor

In order to benchmark the combined MRP–Peter Plates process, it is necessary to assess the efficiency, and how much mercury and gold in total can be extracted from a set of selected test tailings by the developed processing system. For this it

Figure 8. Mercury Recovery Plant (MRP) hooked up with Peter Plates (Nicaragua).

is necessary to get a reliable assessment of the overall mercury and gold content *before* processing. The specific sampling issues involved are far from standard. How does one obtain a reliable figure for mercury and gold content in a typical, say, 10-ton tailings stock, in which both elements are very irregularly distributed? In fact the average tailing concentration is at the extreme low end of trace levels for both elements. Due to this extreme heterogeneity, there are fewer more challenging sampling scenarios, when almost all levels of sampling technology and equipment is virtually absent. "Barefoot sampling" was what was needed,[8] but with the exact same stringent objective—obtaining a *reliable* estimate of the concentration levels present in the seven test piles selected. Tailings for this test were collected from a number of different small-scale mining sites where the gold ore varied significantly both w.r.t. ore type, mineralogy and contents; thus, a wide span of target lots could be expected.

Under such difficult field conditions the best way to achieve this sampling goal is by so-called incremental *composite sampling*, a technique developed at research institutes and private companies over many years. The specific approach used during the phases of this project, carefully crafted to comply 100 % with the demands of the Theory of Sampling (TOS). The critical primary sampling procedure is comprised of ~2000 increments (each ~100 g) from each test tailing (ranging from 4 ton to 21 ton in weight), which, when aggregated, resulted in primary composite samples of the order of 200 kg. After these documented representative samples were collected in the field, they were subsequently further mass-reduced both in the field (field site, Nicaragua) as well as in the laboratory (GEUS, Denmark), in order to arrive at reasonably sized aliquots for analysis for mercury and gold, which was subsequently carried out in a commercial laboratory (Actlabs Canada). The full "from-lot-to-aliquot" sampling pathway is described in detail by Esbensen and Appel,[8] together with a complete reference curriculum.

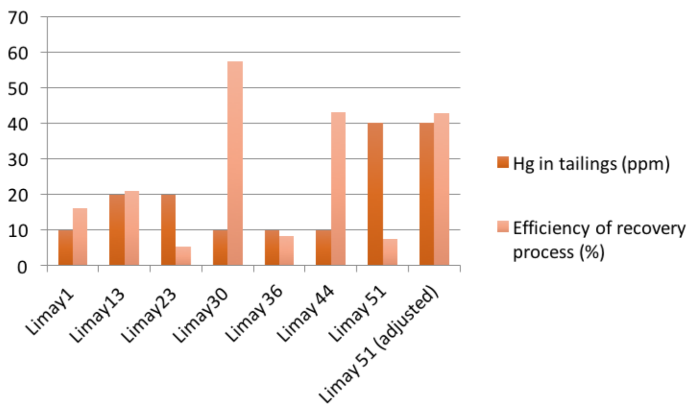
MRP-Peter Plates efficiency testing

Seven test tailings were sampled in full TOS-compliance from lot-to-aliquot, and the resulting analytical results are presented in Tables 1 and 2. The overall average content of mercury ranged from 0 ppm per ton to 40 ppm per ton, and for gold the range was from 1.15 g per ton to 13 g per ton. These tailings were subsequently processed by the local experimental MRP-Peter Plates setup in a feasibility study.[8] The recovered amalgam and mercury (Figure 9) was scraped off the plates and weighed. The amalgam and mercury were distilled, and the condensed mercury weighed together with the gold. This allowed estimation of the efficiency of the MRP + Peter Plates combination, which is listed in Table 1.

Gold recovery varies widely from one tailings pile to the next, with no immediate observable pattern. A likely reason is that part of the gold is free gold in some samples, and so is easy to recover by the Peter Plates, whereas in other samples gold is still found embedded in other minerals.

Table 1. First feasibility results: mercury recovery efficiency ranges from 5 % to 57 %.

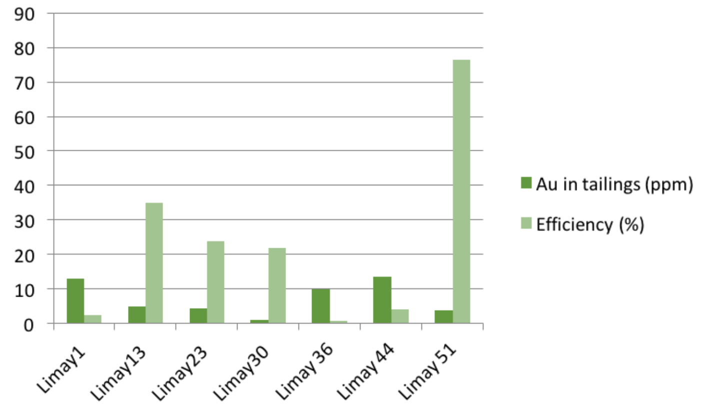
	Municipality	Location	Hg in tailings (g/tonne)	Hg recovery (g/tonne)	Efficiency (%)
Limay 1	San Fransisco	El Nancital Rastra #1	10	1.6	16
Limay 13	San Fransisco	Rastra las Agua	20	4.23	21.1
Limay 23	San Juan De Limay	El Portillo	20	1.05	5.2
Limay 30	San Juan De Limay	El Morcillo	10	5.74	57.4
Limay 36	San Fransisco	El Nacital Rastra #2	10	0.84	8.4
Limay 44	San Fransisco	El Nacital Rastra #3	10	4.317	43.2
Limay 51	San Fransisco	Rastra las Agua	40	2.99	7.5
Limay 51 (adjusted)[a]	San Fransisco	Rastra las Agua	40	16.99	42.8



[a]It proved difficult to purchase DETOX in Nicaragua at short notice. Therefore, enough for one test was shipped to Managua from Copenhagen. The heavy mineral concentrate from sample Limay 51, which previously had passed over the Peter Plates, was soaked overnight in a solution of the organic compound. When passed over the Peter Plates again, the results were very promising; the efficiency of mercury recovery increased from 7.5 % to 42.8 % (see Table 1). This demonstrates the potential of adding DETOX to future operations.

Table 2. First feasibility results: gold recovery efficiency ranges from 1% to 76%.

	Municipality	Location	Au in tailings (g/tonne)	Au recovery (g/tonne)	Efficiency (%)
Limay1	San Fransisco	El Nancital Rastra #1	13	0.32	2.4
Limay13	San Fransisco	Rastra las Agua	4.99	1.75	35.1
Limay23	San Juan De Limay	El Portillo	4.41	0.36	23.8
Limay30	San Juan De Limay	El Morcillo	1.15	0.25	21.9
Limay 36	San Fransisco	El Nacital Rastra #2	9.87	0.09	0.9
Limay 44	San Fransisco	El Nacital Rastra #3	13.5	0.57	4.2
Limay 51	San Fransisco	Rastra las Agua	3.95	3.02	76.5



Such gold is unrecoverable although it features in the chemical analyses of the tailings, undoubtedly contributing significantly to the very wide recovery efficiency range observed. At present the relevant mineralogical information is not available for the first test tailings made available for the present project. As always when dealing with gold ore mining and processing, there is a critical need for detailed mineralogical characterisation of the samples and subsamples in addition to the *in toto* chemical and amalgam-capturing data.[9] While lamentable, this uncertainty was unavoidable with the kind of funding and budgets available for the present pre-feasibility survey. However, the layout for a fully comprehensive feasibility study is now available. This is the other important take-home message from these scanty, but very promising first results.

Fate of recovered mercury

When the combination MRP + Peter Plates goes into production across three continents, the amount of mercury recovered will reach many tons per year. This raises the important question about the destiny of this mercury. Fortunately, there are several research groups currently working on this problem, which is not only pertinent with respect to gold mine tailings but also for cleaning up other sites with large mercury spills. Two of these are:

i) Nomura Kohsan Co. of Japan (www.nkcl.jp) which has constructed a solidification system which provides safe, long-term storage of mercury. The company has expressed interest in constructing a *portable* processing plant that can follow the MRP + Peter Plates activities.
ii) Batrec Group in Switzerland (www.batrec.ch) has to date solidified more than 600 tons of metallic mercury into the naturally occurring cinnabar (HgS). The cinnabar is stored in German salt mines.

Conclusions

These first foray studies have shown that the *combination* of MRP + Peter Plates is able to recover substantial amounts of mercury from the numerous tailings from small-scale gold mining that litter Southeast Asia, Africa, Central and South America; the present results point to that crushing and milling efficiency is a critical success factor for increasing the fraction of gold ultimately recoverable. As MRP-Peter Plates units go into production, re-processing of tailings will increase recovery substantially. Minor technical improvements may likely be added as well in the future.

It is clear that local adjustments will be needed in order to be able to characterise local tailing compositions more comprehensibly to be able to compensate for differences in mineral composition of the tailings from one area to the next, especially regarding the degree of liberation of the most prominent amounts of gold. It would be highly advantegeous to be able to use fast "barefoot" mineralogical assessment methods to assess gold particle liberation, i.e. allowing artisanal miners definite information as to whether the tailing gold has been sufficiently crushed to allow complete liberation. While the gold liberation issue has been the target of an enormous R&D effort in the mining industry for numerous decades, an easy approach has not yet emerged. Should not the gold mining industry be able to divert just a minute fraction of its enormous revenues to this low-tech challenge, and thereby help millions of starkly impoverished artisanal mining communities in addition to contributing towards the Minamata convention goals as well? It will also likely be important to observe and compensate appropriately for the characteristics of local climatic conditions regarding whether the climate is humid or dry.

Fully comprehensive feasibility study

The major remaining question concerns *why* some tailings are more amenable to

Figure 9. Large amount of mercury captured on Peter Plate (Nicaragua). The plate is about 20 cm wide.

mercury extraction than others? First generation mineralogical investigations have not provided a clear answer,[4] but to date it has not yet been possible to carry out more comprehensive studies due to lack of appropriate funding. The specific comminution/crushing/milling approach further developed, and attendant problem-dependent processing times, will likely also play an important role in increasing the degree of recovery.

It is hoped the present report and its companion[8] will provide a fully satisfactory foundation for future funding. What is clear already is that the amount of gold recovered together with mercury will more than likely cover the costs of the clean-up operations.

Legal problems are also likely to arise. As of now, ownership of old and highly polluted tailings is not particularly obvious, and there is understandably a certain lack of willingness to claim ownership. One expectation is that when the MRP + Peter Plates clean-up system begins to take effect, and so demonstrates an efficient way of recovering gold and thus to make money from what was before a hopeless prospect, the situation will likely change with declarations from many potential owners. There may, therefore, paradoxically turn out to be significant potentially troublesome legal issues surrounding this aspect.

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