

**FLOWSHEET AND LEACHING  
ALTERNATIVES FOR THE  
ROSIA MONTANA PROJECT**

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## 1 INTRODUCTION

There are a number of flowsheet options available for the processing of auriferous ores. Many of these options are applicable only to certain ore types and specific sets of conditions. Such conditions are dependent on ore characteristics, location, environmental, social issues, infrastructure, economic considerations and risk.

The selection of the most relevant flowsheet for processing of the Rosia Montana ore types has given consideration to numerous options. Many of these options, whilst practical in the sense that they would provide a recovery of gold and silver from the Rosia Montana ore, are impractical when the other considerations are applied.

The actual extraction of gold and silver from the ore to provide a metal product requires a level of chemical separation. This can be achieved by smelting, which is cost prohibitive unless the gold and silver are by-products of another process. Alternatively this separation can be achieved by leaching.

Leaching is by far the most common process with over 90% of the world's gold production over the last 20 years being provided by cyanidation.

Cyanidation is the most common leaching alternative for gold and silver. There are several other chemical processes which leach gold and silver, but they are typically impractical, dangerous or prohibitively expensive. Some do not recover silver at all and most have never been practised at a commercial scale.

This document:

- Summarises the flowsheet options considered practical for the Rosia Montana ores.
- Provides a ranking for the options and presents the fiscal risk associated with the most likely alternatives.
- Discusses the leaching alternatives (alternative lixivants).
- Presents a toxicological assessment of the alternatives.
- Provides the supporting dialogue presenting cyanide leaching as the best available technique (BAT) for processing the Rosia Montana ores.

## 2 FLOWSHEET OPTIONS

### 2.1 Flowsheet Optimisation and Selection

By no means the only consideration, but still a key aspect of flowsheet selection is management of economic risk. Whilst a particular flowsheet may be identified that provides the maximum revenue under a set of prevailing economic conditions, this same flowsheet may be overly complex, require high entry capital or may quickly become uneconomic under certain new and different economic conditions. A decision may be taken to use what is considered a more robust flowsheet option and not necessarily the most profitable on the day the decision is taken.

Flowsheet selection must consider the possibilities of differing economic conditions and the longevity of the project to ensure sustainability and full utilisation of the resource.

### 2.2 Facts Specific to Rosia Montana Ore

There are a number of hard facts relevant to the Rosia Montana case. These facts directly influence the flowsheets that are applicable for the processing of the ore. They include:

- The Rosia Montana ores are low grade. The high grade zones have been mined over the last 2,000 years leaving the altered halo. The revenue available per tonne of ore is therefore low and the processing techniques used must be low in operating cost.
- The Rosia Montana deposit is large as well as low grade. The processing technique needs to be capable of high tonnage rates to provide suitable economic returns and a robust project that will not be sensitive to fluctuating economic conditions.
- The Rosia Montana ores contain significant silver in addition to the gold. The selected flowsheet must be applicable to silver recovery.
- The Rosia Montana ores contain sulphides – predominantly pyrite. Processes that are not applicable to ores which contain sulphides cannot be applied.
- The Rosia Montana ores contain gold and silver values associated with both sulphides and with the non-sulphide host rocks. A process specific to treating only the host rocks (silicates) or only the sulphides will result in low recoveries and poor exploitation of the resource. The process needs to address both types of gold and silver host mineralisation.

These points suggest a number of flowsheet options and leaching alternatives will suffer serious disadvantages and are unlikely to be applicable without having to undertake any testwork or economic studies. For example:

- Processes with high operating costs such as whole of ore pressure oxidation and similar complex high temperature and high pressure processes will not be applicable.
- Halide leaching alternatives (bromide, chloride, iodide) will not recover silver. Apart from the issues of cost, toxicity and difficulty in detoxification of tailings, such leaching alternatives would result in zero silver extractions and a loss of this significant and valuable resource to tailings. Halides also react with sulphides in the ore which will re-precipitate gold and result in prohibitive reagent consumptions.
- Flotation or other sulphide recovery processes will be expected to recover gold and silver however much of the non-sulphide associated precious metal will be lost to the flotation tailings. If the flotation tailings are not also processed, significant losses of gold and silver to tailings will result.
- Whole of ore processing (WOO) is likely to be required to support project economics and continued operation in harder economic times.
- Whole of ore processing is required to maximise the rational exploitation of the Rosia Montana resource.

Whilst these outcomes can be drawn simply by looking at the Rosia Montana ore characteristics, various flowsheet options that were suspected to be unfavourable were still evaluated as part of the flowsheet selection processes conducted by the various international engineering companies that have been involved in the project development. The following section summarises these flowsheets and ranks them accordingly.

### 2.3 Flowsheet Alternatives

Twelve flowsheet options have been evaluated for processing of the Rosia Montana ores. Block diagrams are attached as Appendix 1. The flowsheets assessed for the Rosia Montana ore can be summarised as follows:

**1. CIL processing of whole of ore (WOO).** This is the proposed Rosia Montana flowsheet and all others should be compared to this option. The whole ore is cyanided for gold and silver extraction at a grind size of 150  $\mu\text{m}$ .

**2. Flotation of concentrate and cyanide leach of concentrate at 150  $\mu\text{m}$  grind.** This is a sulphide recovery and free gold and silver recovery option. Gold and silver associated with silicates will not be recovered. The sulphide concentrate is leached with cyanide to recover the contained gold and silver. This option is attractive in that it provides for a reduced tonnage of leached material that needs to be detoxified and a smaller storage volume of leached tailings.

There is also a possibility of reduced total cyanide consumption. It should be noted however that the species present in ores such as Rosia Montana that react and consume the cyanide are often similarly concentrated into the sulphide concentrate. So, if 5% of the feed mass reports to the concentrate, it does not mean the cyanide consumption will now only be 5% of the whole ore leaching consumption. It is usually much higher by proportion.

Flotation cannot be carried out effectively at high pH or with cyanide present as these conditions depress the sulphide and retard their flotation. As a consequence, the recirculation of process water at elevated pH and particularly cyanide must be controlled. This means the cyanide saving practise of recirculating tailings thickener overflow and the contained cyanide to the milling circuit cannot be employed. This actually adds to the cyanide consumption as no cyanide credit is obtained.

This flowsheet is effectively employed at a number of mine sites world wide but requires almost all gold and silver to respond to the flotation step for high recoveries to occur. This flowsheet is similar to that proposed for the Certej project currently under development in Romania.

**3. Flotation of concentrate and leach of concentrate at 10  $\mu\text{m}$  re-grind.** This is a sulphide recovery and free gold and silver recovery option. Gold and silver associated with silicates will not be recovered. Effectively the same as Option 2 above however the concentrate is ground to 10  $\mu\text{m}$  to increase the contained gold and silver exposure to cyanide to increase the leach recoveries. This additional step typically increases the cyanide consumption as the cyanide reactive species in the concentrate have more surface area and will consume more cyanide. It is common to find the cyanide consumption increases to levels greater than if the whole of the ore was leached.

**4. Flotation of concentrate and leach of concentrate at 150 µm grind and leach of flotation tail (WOO).** This is a sulphide recovery and free gold and silver recovery option. Gold and silver associated with silicates will be recovered however as the flotation tailing is leached with cyanide as well as the concentrate. This option may provide an increase in extraction when the sulphides are leached separately as the leaching conditions can be manipulated. In the Rosia Montana case, no benefit was identified and the extraction is the same as Option 1.

**5. Flotation of concentrate and leach of concentrate at 10 µm re-grind and leach of flotation tail (WOO).** Similar to Option 4 except the concentrate is again fine ground to provide additional extraction from the sulphides.

**6. Flotation of concentrate Pressure Oxidation and leach of concentrate at 150 µm grind.** This option again produces a sulphide concentrate with free gold and silver. The flotation tailings are sent to the TMF without extraction of the contained gold and silver resulting in an anticipated loss of metal values. Pressure oxidation is used on the small tonnage but high grade concentrate to destroy the sulphides and thereby liberate almost all of the contained gold and silver values. This results in very high leach extractions when the oxidised concentrate is leached with cyanide.

**7. Flotation of concentrate Pressure Oxidation and leach of concentrate and leach of flotation tail (WOO).** This option is the same as Option 6 however the flotation tailing is leached to recover the gold and silver values that remain with the flotation tail. This option gives very high overall extraction as all components are leached and the gold and silver in the sulphide concentrate is liberated and available for cyanide attack.

**8. Gravity, intensive cyanide of gravity conc at 50 µm and leach of gravity tail (whole of ore (WOO)).** This option considers the use of gravity to produce a concentrate having the high specific gravity particles such as the sulphides and free gold and silver. Again, gold and silver associated with the gravity tailings do not report to the concentrate however they are recovered by leaching the gravity tailings with cyanide. This is a whole of ore process similar to Option 1.

It is similar to the flotation options in that it produces a concentrate but uses gravity devices in place of the flotation process to generate the concentrate. This is simpler and does not have the issues associated with recirculation of high pH water and cyanide which suppress flotation recoveries (refer to Option 2 for discussion).

The gravity concentrate is ground in an attempt to liberate contained gold and silver values and increase extraction. This option also has the advantage of capturing coarse gold values before they report to the whole of ore leaching step.

**9. Gravity, intensive cyanide of gravity conc at 10 µm and leach of gravity tail (whole of ore (WOO)).** Similar to Option 8 however the concentrate is ground finer to increase the liberation of gold and silver in an attempt to provide higher extraction when leached with cyanide.

**10. Heap leach of WOO.** Heap leaching involves stacking of the crushed ore on an impermeable membrane and irrigating the heap with cyanide solution to dissolve gold and silver. This is a low capital cost option, and because there is little size reduction undertaken, the operating costs are also low. The heap can be detoxified after leaching.

The issue with heap leaching is that the process is slow and typically the extractions are often much lower than achieved by grinding and agitation leaching. A loss of metal values therefore results and the resource is not fully utilised.

These first 10 options all utilise cyanidation to extract the gold and silver values from the respective concentrates and/or ore. One of the major issues associated with the development of the Rosia Montana project is with the use of cyanide because of its toxicity. This aspect of cyanide use is discussed in more detail below however the possibility of two flowsheet options that do not use cyanide *in country* have been investigated at high level. One option looks at selling a flotation concentrate whilst the other considers use of an alternative lixiviant to cyanide. It should be realised both of these options are in effect theoretical as a number of assumptions have been made.

**11. Flotation of concentrate and freight concentrate to third party out of country.** This option looks at production of a flotation concentrate which will contain sulphide associated gold and silver plus some of the free gold and silver. Losses of gold and silver to the flotation tailing results as is similar to Options 2, 3 and 6. Instead of processing the concentrate on site by leaching with cyanide, it is assumed the concentrate can be sold to a third party.

Sale of concentrates results in handling and freight costs. These have been considered. Similarly the buyer will charge a treatment cost and a refining cost as is typical of concentrate processing contracts. Often, the first 1/g/t of concentrate gold grade is also paid to the buyer as a profit margin for the buyer. These costs too have been considered.

As the concentrate is basically a pyrite concentrate, it will have to be blended if used as a smelter feed as a fuel. It is not known if this option is practical and it is doubtful that it would be. The tonnage of concentrate would be substantial and therefore difficult for a smelter to successfully blend in with say base metal concentrates.

The grade of the concentrate will be low – of the order of 20 to 30 g/t gold. Such a low grade of concentrate without additional revenue from say copper, lead or zinc, would be uneconomic to process based on typical and historic comparisons.

The local RosiaMin operation, recently shut down due to being uneconomical, unsuccessfully utilised this flowsheet.

Obviously the final metal product would be produced and sold out of Romania.

**12. Alternative lixiviant (thiosulphate, filtration, copper precipitation or similar).** Of all the alternative lixivants to cyanide, the one considered by world experts as the most likely replacement is thiosulphate. This is discussed further in Section 3 of this report, which covers alternative lixivants and their applicability to Rosia Montana ores. Option 12 is in all likelihood impractical and this comparison to the other options merely academic. However it has been prepared based on literature review of likely flowsheets and discussion with recognised experts in the field.

It is also important to note that no flowsheet has been fully developed or implemented for thiosulphate leaching on such an ore and certainly not at the scale required for Rosia Montana.

Thiosulphate typically gives lower extractions than cyanidation. Reasons for this are known and are explained in Section 3 below. Suffice to say, a loss of what would be recoverable metal results when employing thiosulphate as a lixiviant over cyanide.

There are a number of other flowsheet alternatives that have not been explored as they simply will not be suitable for processing the Rosia Montana ores, their capital and operating costs will be high or they offer no advantage over cyanidation with regard to toxicology, environmental or social aspects.

Examples are:

**Amalgamation** – This process uses mercury to collect free gold particles by wetting them and making them adhere to either the resulting amalgam or alternatively metallic copper amalgam plates. This process, whilst effective for free gold, is not suited to ores with high sulphide contents as the sulphides “sicken” the amalgam, effectively rendering it ineffective. In addition, and most importantly, mercury is a heavy metal that accumulates and can poison humans and animals. Whilst it can be collected and retained, it cannot be detoxified but must be bound as a stable compound or contained as the metal. It is not biodegradable. Use of amalgamation is not considered as a safe or practical alternative.

**Bacterial Leaching** – Bacterial leaching processes use bacteria (thiobacillus ferro-oxidans or similar) to break down sulphide minerals in a flotation concentrate thereby releasing the contained gold and silver values. The process can be likened to the pressure oxidation alternatives presented above, Options 6 and 7, except bacteria are used to replace the pressure oxidation step.

Bacterial oxidation is conducted at mildly elevated temperatures in an acid environment. It is a slow process and requires long residence times in large temperature controlled tanks. After the bacterial oxidation, the slurry has to be neutralised and is then leached to solubilise the gold and silver. Bacterial leaching does not extract the gold and silver, it merely exposes it so that cyanide can access the metals and high extractions result.

Bacterial oxidation would still result in the use of cyanide and would also require whole of ore processing to recover gold and silver values in the silicates.

### 2.4 Assessment of Options

The various flowsheets were simulated by testwork to establish the metallurgical performance and the extractions were estimated. The capital cost of each option was estimated on a relative scale and the operating costs estimated to a level of accuracy suitable to allow comparison. The revenue of each flowsheet option was calculated and the net present value (NPV) at a discount of 5% over ten years applied.

A number of basic criteria are then applied to each option to establish if it can be taken forward as a sensible and practical option. These criteria are summarised in Table 2.1 below and discussed as follows.

**Criteria 1** Is the option economically feasible at current metal prices as would be applied to the project in order to establish viability?

Whilst economics are not the only consideration in selecting the flowsheet, obviously the project as to make a return to be implemented and ensure sustainability. To assess this, a gold price of \$600/oz and a silver price of \$10/oz are applied and all options are found to be viable except the production and sale of flotation concentrate to a third party, Option 11.

**Criteria 2** Is the option economically feasible at lower metal prices, prices similar to those experienced in the recent past?

Responsible development requires the flowsheet is robust and can tolerate fluctuations in the metal prices. If this is not achieved the project is obviously not as attractive economically but importantly, the resource will not be fully utilised and the sustainability aspects of the project will not be fully realised. To assess this aspect, a gold price of \$450/oz and a silver price of \$8/oz are applied. Options 3, 4 10 11 and 12 are all found to be revenue negative and application of these flowsheets would suggest closure of the project. These flowsheets are not considered responsible selections and this alone would be reason enough not to consider them any further.

An important point to note here is that the use of an alternative lixiviant, even if the flowsheet could be proven and financiers could be found to take on the risk of such a venture, would not provide a robust alternative to cyanidation. Selection of such a flowsheet would be irresponsible with regard to sustainability, rational exploitation of the resource and income to the people of Romania.

Similarly, the production and a sale of a flotation concentrate to a third party would fail at the prices assessed.

Criteria 2 alone shows that the only robust flowsheets for the Rosia Montana ore can be seen to be those that involve effective leaching with proven cyanidation techniques.

**Criteria 3** Has the process been proven at a commercial level?

The only processes that can realistically be applied to the Rosia Montana project are those that have a proven track record.

All of the options investigated except for Option 12 comply with this criteria. It is not only a technical consideration, but one that is considered by project financiers due to increased risk of failure if using commercially unproven technologies. Similarly, new processes almost always suffer from delayed start-ups and additional costs due to the fact that further modification and development are required at full-scale production.

**Criteria 4** Does the option provide for rational exploitation of the resource, or, does it result in losses of valuable metals to the tailing facility?

When the characteristics of the Rosia Montana ore are investigated, significant precious metal values reside in both the sulphide component and the silica components. Flowsheets that only process sulphides and free gold ore components will result in substantial losses of gold and silver to the tailings. This is also why these options are not as economically robust – revenue is not being made available due to the magnitude of metal losses.

Options 3, 4 6 and 11 all fail in this regard.

**Criteria 5** Is the flowsheet simple and reliable compared to typical gold processing techniques?

The only justification for a more complex flowsheet is that it provides benefits in some form or another, be it social, environmental or economic. Options 6 and 7 utilise high pressure autoclaves and specialist equipment. These processes are applied successfully around the world for treating refractory ores however the plant is much more complex and costly to both build and operate.

Option 12 is more complex than a conventional gold leaching facility and of course, has a question with regard to reliability as the process is not proven.

For Criteria 5 to be ignored in option selection, considerable benefit in other areas would have to be realised.

**FLWSHEET AND LEACHING ALTERNATIVES FOR THE ROSIA MONTANA FLWSHEET**

**Table 2.1. Selection Criteria for Flowsheet Options**

Flowsheet Option	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Can the flowsheet be considered applicable to Rosia Montana as a result of Criteria 1 to 5?	Does the flowsheet utilise cyanide on site for gold and silver extraction?	Ranking of Option by NPV at a discount of 5%	Ranking of Option based on all five criteria
	Is option profitable at \$600/oz gold and \$10/oz silver price?	Is option profitable at \$450/oz gold and \$8/oz silver price?	Has option been proven at commercial level?	Does option recover silicate associated gold and silver (whole of ore process)?	Is the flowsheet simple/reliable compared to typical gold processing?				
Option 1 CIL	Yes	Yes	Yes	Yes	Yes	Yes	Yes	1	1
Option 2 Float con leach	Yes	Yes	Yes	Yes	Yes	Yes	Yes	10	5
Option 3 Float con leach at 10 µm	Yes	No	Yes	No	Yes	No	Yes	11	
Option 4 Float con leach tail leach	Yes	No	Yes	No	Yes	No	Yes	5	
Option 5 Float con leach at 10 µm tail leach	Yes	Yes	Yes	Yes	Yes	Yes	Yes	6	4
Option 6 Float POX leach con	Yes	Yes	Yes	No	No	No	Yes	7	
Option 7 Float POX leach con tail leach	Yes	Yes	Yes	Yes	No	No	Yes	4	
Option 8 Gravity con leach 50 µm tail leach	Yes	Yes	Yes	Yes	Yes	Yes	Yes	2	2
Option 9 Gravity con leach 10 µm tail leach	Yes	Yes	Yes	Yes	Yes	Yes	Yes	3	3
Option 10 Heap Leach	Yes	No	Yes	Yes	Yes	No	Yes	8	
Option 11 Float con and sell to third party	No	No	Yes	No	Yes	No	No	12	
Option 12 Use alternative lixiviant	Yes	No	No	Yes	No	No	No	9	

## 2.5 Selected Option

Application of the various criteria described above results in the deletion of Options 3, 4, 6, 7, 10, 11 and 12. The remaining options are all “whole of ore” flowsheets and similarly *all utilise cyanide* leaching. This is not surprising given the specifics of the Rosia Montana ores as were highlighted in preceding sections of this document.

The remaining flowsheet options are comparable on issues of social, environmental and safety aspects. The final option decision can then be made on economic grounds.

Table 2.1 presents the economic ranking of all options at an NPV of 5% over 10 years. If Options 3, 4, 6, 7, 10, 11 and 12 are ignored due to their unsuitability, the economic ranking for the remaining options can be found and are presented in the last column of Table 2.1.

The outcome is the application of CIL (cyanidation) processing is most suited to the treatment of the Rosia Montana ores.

## 3 ALTERNATIVE LIXIVIANTS TO CYANIDE

### 3.1 Introduction to Cyanide and Alternative Lixiviants

The development of the Rosia Montana project is planned to involve the use of cyanidation of the ground ore followed by storage of the detoxified tailings in a tailings management facility (TMF).

Whilst the project is recognised as providing significant economic benefit to the people of Romania in addition to providing a means of addressing the disgraceful environmental legacy of previous mining, there is resistance to the development of the project.

It would be fair to comment that the strongest resistance is due to the use of cyanide for leaching and the use of a storage of tailings in a dam structure. Cyanide being an issue due to toxicity and the TMF due to failures of structures previously employed by others on other properties.

The following sections address the main issues associated with cyanide toxicity and the available alternatives.

In the last 25 to 30 years there has been a significant focus on identifying an alternative lixiviant to cyanide for gold and silver leaching. This has been driven by both economic forces in times of cyanide shortages and more recently, environmental and safety reasons due to the toxicity of cyanide.

There is no doubt cyanide is toxic to certain life forms. There is however considerable mis-information with regard to its *relative* toxicity and worse, the often inaccurate suggestions that various alternatives to cyanide are substantially safer. In addition, cyanide has a certain stigma associated with it from years of being portrayed as the poison of choice both in fiction and sadly, in historical real life events.

Cyanide use is common and not just by the mining industry. Hydrogen cyanide is the basic form from which most major cyanide compounds are derived. It has been produced worldwide for many years using basic chemicals such as ammonia and natural gas.

About three million tonnes of hydrogen cyanide are produced annually worldwide, of which about 8% is converted into sodium cyanide and used in the metals industries (mining and metal plating). The remaining 94% of the hydrogen cyanide is used in the production of a wide range of industrial and consumer items as follows:

#### Uses of Hydrogen Cyanide (2001)

- Sodium Cyanide for Mining & Plating, 8% (as would be used at Rosia Montana)
- Speciality Chemicals, 12%
- Plastics and Resins, 13%
- Nylon, 47%
- Amino Acid Health Supplements, 6%
- Surface Coatings, 6%
- Miscellaneous uses, 8%

It can be seen cyanide use is common, and whilst the majority of the worlds gold is produced with cyanide, mining is a minor consumer of the chemical on a global scale.

This data also shows that when “bans” of cyanide use for mining are proclaimed based on claims of the chemical toxicity, in essence such bans would influence a very minor percentage of the worlds cyanide use. Furthermore, the most easily handled and safest form of the reagent as sodium cyanide is targeted and not the HCN form as is more commonly used in industry.

With regard to alternatives to cyanide, the questions that need to be addressed are:

- Do practical alternatives to cyanide exist that are suited to the leaching of the Rosia Montana ores?
- Do alternatives exist that have been proven at a commercial scale as would be required for processing of the Rosia Montana ores?
- Do these alternatives actually offer an advantage compared to cyanide?
- 

### 3.2 Alternatives Available

Cyanide is an extremely good lixiviant for the dissolution of gold and silver for a number of reasons:

- The gold-cyanide and silver-cyanide bonds are strong making the leached complex stable.
- Cyanide can be detoxified readily and is bio-degradable. Its toxicological effects are well known, understood and documented.
- It only requires the use of oxygen (as air) to effect oxidation of the gold and silver and subsequent leaching. Other lixiviants require more aggressive oxidative reagents that have to be brought to site.
- It does not require additional toxic or difficult to handle reagents as a supplement or catalyst – a point often ignored when assessing alternatives.
- Whilst cyanide itself toxic it is in fact easy to transport, store mix and dose.
- Whilst a major operating cost component for an operating leach plant, it is a relatively cheap reagent.
- It is un-reactive towards most other ore components, and in the case of Rosia Montana specifically, it is un-reactive towards the sulphides present.
- It is used in an alkaline environment which is safer than an acidic environment and does not require specialist materials of construction and does not result in the mobilisation of heavy metal ions.
- Its use is common and industry standard for gold and silver leaching. The processes are well understood and proven.

Alternatives to cyanide must therefore compete on all these criteria to be deemed more appropriate than cyanide.

Should an alternative be identified that was not as effective as cyanide with regard to some of these criteria, but found to be significantly less toxic, then compromises would be able to be made for the sake of safety and the environment. Such a replacement would have to be practical and a proven technology however to justify such a change.

The identified alternative lixiviants are:

- Thiourea
- Bisulphide
- Sulphite
- Thiocyanate
- Ammonia
- Halogens (chloride, iodide, bromide)
- Thiosulphate

#### 3.2.1 Stability of Alternatives

The stability constant,  $\beta_2$ , is a standard method for representing stability of a reaction product, in this case, the gold complex resulting from leaching. For a gold complex it is defined as the ratio of the concentration of the complex divided by the product of the concentration of the reactants:

$$\beta_2 = [\text{Gold complex}] / [\text{Gold}] \times [\text{Lixiviant}]^2$$

Table 3.1 below presents the stability constants for the various lixiviants of gold. It can be seen the value of  $\log_{10}\beta_2$  for cyanide is 38.3 whilst for thiosulphate for example is 28.7. As this is a logarithmic scale, the thiosulphate complex is around 4000 million times less stable than the cyanide complex for gold.

Thiosulphate leaching requires a high level of chemical control to both effect leaching and to maintain the gold complex in solution once formed. The thiosulphate complex easily breaks down if the conditions are not maintained resulting in losses of dissolved metals due to re-precipitation. Similarly, thiosulphate gives lower extraction compared to cyanide, resulting in a loss of gold and silver values to tailings.

As the thiosulphate complex is less stable, chemical equilibria dictates high reagent dose to maintain the gold and silver complexes in solution. This requires additional transport to site of a much more expensive

reagent than would be the case with utilization of cyanide. It also adds to flowsheet complexity as a high recirculation of reagent is required to make the process cost effective.

These observations are a direct function of the lower stability of the complex and similarly, why cyanidation is such a robust process in comparison, the cyanide complex being much more stable.

Review of Table 3.1 shows that cyanide is by far the most stable complex.

**Table 3.1. Stability constants for Alternative Lixivants compared to Cyanide**

Lixiviant	Chemical Formula	Stability constant, log <sub>10</sub> β <sub>2</sub>	Operating pH range
Cyanide	CN-	38.3	9 – 10.5
Bisulphide	HS-	29.9	>10
Thiosulphate	S <sub>2</sub> O <sub>3</sub> <sup>2-</sup>	28.7	8 – 11
Ammonia	NH <sub>3</sub>	26.5	>9
Thiourea	CS(NH <sub>2</sub> ) <sub>2</sub>	23.3	<3
Iodide	I-	18.6	<4
Thiocyanate	SCN-	17.1	<3
Sulphite (laboratory)	SO <sub>3</sub> <sup>2-</sup>	15.4	<4
Bromide	Br-	12.0	<4
Chloride	Cl-	9.1	<4

### 3.3 Toxicity of the various Lixivants

To compare the toxicity of the various alternatives to cyanide, it is necessary to distinguish between the various toxicity measures which are described as follows:

- **LD50** is the single lethal dose for 50% of the animals tested. It is usually expressed as mg/kg of animal body weight.
- **LC50** is the concentration in air that will kill 50% of the animals tested with a single exposure (usually 1 to 4 hours) and is usually expressed as ppm or micro milligrams of material per cubic metre of air.
- **TLV** is the Threshold Limit Value and is the term used to express the airborne concentration of material to which nearly all persons can be exposed to day after day without adverse effect. This is appropriate to consider with regard to the possible work place exposure to the various lixivants.
- **WGK** is the water contaminant category (German Federal Water Management Act, Wassergefährdungskategorie) and is a measure of the negative influence of a substance on the physical, chemical or biological characteristics of water. Broad categories are 0 = not a contaminant, 1 = slight water contaminant, 2 = water contaminant, 3 = strong water contaminant.

An important aspect that need to be appreciated is that it is not only important to look at the toxicity of the actual lixiviant itself, but also of the carrier ions and other reactants required to effect the leaching.

The lixiviant itself is always an anion, gold and silver being cations. The lixiviant when transported or introduced to the leach must have an associated cation to be stable. This is often the benign sodium ion, as is the case with cyanide, however it can also be ammonium. This can change the perspective of the toxicity assessment as will be seen in the case of thiosulphate leaching.

#### 3.3.1 Thiourea

Thiourea is the only alternative lixiviant that has found some specialist commercial application (Australia, China and France) on ore components in recent times. However it has been categorised as a suspected carcinogen compound and a water contaminant (WGK = 2).

If the oxidation potential of the leach is not maintained, ammonium ion is produced in addition to release of hydrogen sulphide and cyanamide as a result of the many side reactions of this acidic and difficult to control process.

As the reagent consumption is high for thiourea due to its reactivity and lower complex stability, plus ferric ion is required as an oxidant and sulphuric acid for pH control, detoxification costs are very high.

Thiourea's toxicity profile is not considered any better than cyanide when these considerations are made (Gos and Rubo, 2000). With the threat of it being carcinogenic, is not a practical alternative to cyanide even though thiourea itself (not its reaction products) has seemingly low LD50 and LC50 values.

### **3.3.2 Thiosulphate**

Thiosulphate is considered by many to be the only likely alternative to cyanidation, although the process has not been developed commercially. Thiosulphate is a common and commercially available reagent, however consumptions are typically five times that of cyanide for the same ore. The price of sodium thiosulphate is approximately double that of ammonium thiosulphate, and economics will drive selection of the ammonium thiosulphate as the successful reagent.

Thiosulphate is often compared to cyanide as a safe, non-toxic alternative. Thiosulphate itself is considered “non-toxic” having high LD50 and LC 50 values. However, thiosulphate spontaneously decomposes to sulphide and bisulphide, both of which are highly toxic (see section below on bisulphide). Thiosulphate is also a reducing agent, and is capable of reducing the oxygen content of waterways should a substantial spill occur. Combined with breakdown to bisulphide depending on pH, the ecotoxicity limits for aquatic forms of life can be exceeded. Again, note this is not for thiosulphate itself, but its breakdown products and the depletion of oxygen.

German drinking water regulations limit the concentration of thiosulphate in drinking water to less than 2.8 mg/L.

If ammonium thiosulphate is used, which is considered in many cases a necessity to retain project economics (this is case by case specific), the issue with ammonia and ammonium compounds needs to be considered. This is covered in the section on ammonia toxicity below.

### **3.3.3 Thiocyanate**

Toxicologically, thiocyanate is considered safe having a high LD50 value and no apparent releases of gas and is only classified as a slight water contaminant (WGK = 1). However, if the reagent were to be used as the form ammonium thiocyanate, the issues of ammonium compounds and ammonia itself would need to be considered.

Whilst toxicologically this lixiviant appears suitable, it has not had commercial application for other reasons described below.

### **3.3.4 Bisulphide**

Bisulphide requires the presence of sulphate to effect regeneration of the lixiviant, and so it is not suited to all ore types. It has not found commercial application

Bisulphide detoxification costs would be high due a high chemical demand for oxygen to produce a sulphate. Bisulphide is categorised as a water contaminant (WGK=2).

Bisulphide leaching results in generation of H<sub>2</sub>S, which has a TLV very similar to that of HCN at 15 mg/m<sup>3</sup>. Gas control measures and the volatility of H<sub>2</sub>S suggest it would be more difficult to control emissions from such a circuit than HCN emissions from a cyanidation circuit.

### **3.3.5 Ammonia**

Ammonia leaching requires high pressures (1.7 to 7.9 bar) and elevated temperatures (100 to 300 Celsius). Ammonia would need to be re-cycled to prevent emissions of volatile ammonia (closed system).

Ammonia has a TLV of 14 mg/m<sup>3</sup> and is therefore similar to HCN. However, given the operating conditions and the volatility compared to HCN under gold leaching conditions, it is considered more of an issue to manage and more dangerous.

The ammonium ion itself is classified as a slight water contaminant (WGK = 1) and ammonia a water contaminant (WGK = 2).

Ammonia can be broken down to nitrate, however this is a slow process and recirculation of the majority of the ammonia is preferred for both toxicity issues and issues of operating costs.

### **3.3.6 Halogens**

The halogens bromide, chloride and iodide are well known lixiviants for gold, being used before the introduction of and replacement by cyanide. They are applicable to a number of ore types however they are reactive towards sulphides and do not leach silver. Their applicability for Rosia Montana is therefore compromised.

As the halides are ions, they cannot be detoxified and would have to be recycled or subjected to electrical oxidation.

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The TLV for Cl<sub>2</sub> and Br<sub>2</sub> are 1.5 and 0.66 mg/m<sup>3</sup> respectively, both significantly lower than for HCN. Iodine is classified at 1.1 mg/m<sup>3</sup>, also higher than HCN. Br<sub>2</sub> is classified as a strong water contaminant (WGK = 3) and Cl<sub>2</sub> is a water contaminant (WGK = 2). I<sub>2</sub> and I are classified as slight water contaminants (WGK = 1).

The oxidants required for leaching are typically the halogen of the halide itself. It is also possible for these to form halogenated compounds that all have TLV values lower than that of HCN. They can also form halogenated organic compounds which are usually very toxic even at very low concentrations.

### 3.3.7 Summary

As has been presented, many of the alternative lixivants have toxicity issues themselves, and do not necessarily make for a better alternative than cyanide on a toxicity basis. Of note, is that only the options of thiourea (suspected carcinogen), thiocyanate, and thiosulphate are appreciably better than cyanide when it comes to work place exposure (TLV values).

If ammonium thiosulphates are used, the issues of ammonia are raised which again brings this lixiviant into similar territory as cyanides with regard to workplace exposures.

Table 3.2 summaries the toxicity data for the various lixivants.

**Table 3.2. Toxicity Data for the Various Lixivants**

Lixiviant	Toxicity - dose	TLV (or MAK, German equivalent)	Toxicity - concentration	WGK value
Thiourea	LD50 125 mg/kg (carcinogen)	-	LC50 >100 g/L	2
Thiocyanate	LD50 764 mg/kg	-	-	1
Thiosulphate (ammonium)	LD50 2890 mg/kg	-	Consider ammonia	1
Bisulphide (based on H <sub>2</sub> S)	LC50 1500 mg/m <sup>3</sup> /14 minutes (rat)	15 mg/m <sup>3</sup>	LC50 1500 mg/m <sup>3</sup> /7 min (fly)	2
Ammonia	LD50 350 mg/kg	14 mg/m <sup>3</sup>	LC50 0.53 mg/L/96 h	2
Bromine	LD10 14 mg/kg	0.6 mg/m <sup>3</sup>	LC100 10 mg/L/10h	3
Chlorine	LC50 293 ppm/h	1.5 mg/m <sup>3</sup>	LC10 0.05 mg/L/96h	2
Iodine	LD50 14000 mg/kg	1.1 mg/m <sup>3</sup>	LC50 0.16 mg/L	1
Cyanide, sodium	LD50 6.4 mg/kg	5 mg/m <sup>3</sup> as CN, approx 10 mg/m <sup>3</sup> as sodium cyanide equivalent	LC50 0.083 mg/L/96h	3
Cyanide, hydrogen	LD50 3.7 mg/kg	5 mg/m <sup>3</sup> as CN	LC50 2.29 mg/L/96h	3

### 3.4 Suitability to Leaching Rosia Montana Ores

Preceding sections have investigated the issues of stability of alternative lixiviant complexes and toxicity aspects. These investigations provide direction in establishing if an alternative lixiviant applicable to Rosia Montana can be identified.

In addition to these aspects, are the basic criteria of practicality, proven commercial application and the benefits of cyanidation as presented above.

Table 3.3 below has been prepared to summarise the advantages and disadvantages of each of the various lixivants in direct comparison to cyanide.

Of relevance is that none of the alternative lixivants have been utilised at a commercial scale except thiourea and the halides. This is a fatal flaw for each of them with regard to application at Rosia Montana.

In the case of thiourea, it has been recognised as a possible carcinogen, with one reference actually stating it as a carcinogen. It would be very difficult to justify the use of thiourea over cyanide as a result. In addition, the commercial application of thiourea has been for the treatment of certain high value materials that

cannot be economically cyanided due to the cyanide reacting with the material in question. It is not used as a general lixiviant.

The halides, whilst commercially applied, are again used for specialist applications. They react with sulphides and do not leach silver. They are just as toxic as cyanide, if not more so, and cannot be detoxified as they are ions. They are not a practical replacement for cyanide.

Thiosulphate is the reagent that may believe offers the best opportunity to replace cyanidation. It is alkaline, in the most part non-toxic although it can have issues associated with ammonium carriers and catalysts, and relatively abundant making it relatively low cost. Whilst it does not offer the same level of metal recovery, the potential to replace cyanide due to the perceived toxicity benefits make it worthy of investigation.

Detailed and high level investigations into the use of thiosulphate to replace cyanide have been underway since the early 1970's. The major mining houses have all investigated the use of this lixiviant as a replacement for cyanide. Newmont (20% owner of Gabriel Resources) have spent many years trying to perfect the process without success. Unfortunately, thiosulphate has not been able to be proven as a practical alternative to cyanide in this time.

The outcome of all this is that cyanidation, toxicity issues included, continues to present as the best available technique for the treatment of ores such as that at Rosia Montana.

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**Table 3.3. Summary of Alternative Lixiviant Applicability to Rosia Montana**

Query	Thiourea	Thiocyanate	Bisulphide	Sulphite	Ammonia	Thiosulphate	Halides	Cyanide
1 Suspected carcinogen?	Yes. One reference lists actually as a carcinogen.	No	No	No	No	No	No	No
2 Easily detoxified?	No	Yes	No	No	No	No (NH <sub>3</sub> )	No	Yes
3 Toxic decomposition products?	Yes	No	Yes	No	No	No	Yes	No
4 Requires off gas control and recirculation?	Yes	No	Yes	No	Yes	Yes	Yes	No
5 Less toxic than cyanide?	Yes (excluding carcinogen aspects)	Yes	No (H <sub>2</sub> S)	Yes	No	Yes	No	Not applicable
6 Acidic (heavy metal mobilisation and exotic materials of construction)	Yes	Yes	Yes	Yes	No	No	Yes	No
7 Leaches gold?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8 Leaches silver?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
9 Reactive towards pyrite (sulphides)?	No	No	No	No	No	No	Yes	No
10 Reagent consumption high?	Yes	Yes	No data	No data	Yes	Yes	Yes	No
11 Requires elevated temperature or pressures?	No	Yes	Yes	No	Yes	No	No	No

**FLWSHEET AND LEACHING ALTERNATIVES FOR THE ROSIA MONTANA FLWSHEET**

**Table 3.3. Continued**

Query	Thiourea	Thiocyanate	Bisulphide	Sulphite	Ammonia	Thiosulphate	Halides	Cyanide	
12	Commercially proven?	Yes, cyanide soluble concentrate leaching.	No	No	No	No	Pilot scale only	Yes, specialist leaching only, small scale.	Yes, dominant technology
13	Leached complex of high stability?	Yes	No	Yes	No	Yes	Yes	No	Yes
14	Require specialist oxidant apart from air (oxygen) and additional reagent freighting?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
15	Any current commercial applications on ores similar to Rosia Montana?	No. High cost so used for specialist leaching.	No.	No, suited to bacterial leached residues.	No. Laboratory only.	No.	No. Piloted or specialist leaching (chloride roaster product)	No	Yes
16	Capital cost of plant expected to be greater than cyanidation?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Lowest
17	Operating cost of plant expected to be greater than cyanidation?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Lowest
18	Higher extraction than cyanidation?	No	No	No	No	No	No	No	Highest
19	Considered to have fatal flaw with regard to applying to Rosia Montana.	Yes Query 1, 15	Yes Query 11, 12, 13	Yes Query 11, 12, 15	Yes Query 12, 13, 15	Yes Query 5, 11, 12, 15	Yes Query 12, 15	Yes Query 3, 4, 8, 9, 12, 13, 15	No

### 3.5 Selection of Most Suitable Lixiviant for Rosia Montana

It is apparent from the assessment conducted that cyanide is the most appropriate lixiviant for the processing of the Rosia Montana ores. All other lixiviants have fatal flaws with regard to their use and the most likely cyanide replacement, thiosulphate, is as yet unproven. Even if it could be utilised, the assessment of costs associated with its use and the reduced extraction that will result make it high risk economically – should metal prices drop the project could become uneconomic. It would be irresponsible to utilise such a lixiviant when the perceived issues with cyanide are manageable.

## 4 CONCLUSIONS

### 4.1 Flowsheet and Lixiviant Alternatives

Every production-scale low grade gold ore leaching operation in the world today employs sodium cyanide as a lixiviant at some stage of the process. It is a proven process with known risks and known measures for risk management, minimisation and mitigation. Some 90% of the gold produced in the world in the last 20 years has been recovered using cyanide.

Although research continues, there are no realistic alternatives to the use of cyanide for recovery of gold from low grade ores at the present time. Nor does research indicate any technologies that could be developed to a full-scale operation in the near future.

Financial assessment of flowsheet options show that for a robust project, the use of whole ore leaching with cyanide is the preferred flowsheet. The non-cyanide options of sale of a flotation concentrate or use of an alternative lixiviant are uneconomic at gold and silver prices similar to those that have been experienced by the international market in the last two to three years.

Non-cyanide options are simply not practical for Rosia Montana due to the inherent characteristics of the ore including grade, existence of sulphides and gold and silver department.

Cyanidation is the most effective flowsheet with regard to cost effectively maximising the value of the Rosia Montana resources. Other flowsheet options or lixiviants result in reduced extractions and poor utilisation of the Rosia Montana resource.

In addition to the discussion provided above, the cyanidation process offers:

- Minimal power and water consumption compared to most alternatives.
- Smaller footprint compared to other processes that can provide the same level of extraction.
- The most robust process both economically but also physically easier to operate and manage.
- It is the typical technology applied to gold and silver ore processing.

CIL processing of the Rosia Montana ores is considered the best available technique and the process of choice.

### References

1. “The Relevance of Alternative Lixiviants with Regard to Technical Aspects, Work Safety and Environmental Safety”, Stephen Gos and Andreas Rubo, 2000.
2. “Flowsheet Selection Case Study” Appendix 6.14, Feasibility Study, Minproc Engineers, March 2001.
3. “Are there Realistic Alternatives to Cyanide as a Lixiviant for Gold at the Present time?”, I M Ritchie, M J Nicol and W P Staunton.
4. Gold Processing Technology Course – Alternative Lixiviants to Cyanide, April 2006.
5. “Review of Alternative Lixiviants for Rosia Montana”, Havilah Consulting Pty Ltd, June 2007.
6. “Processing Alternatives and Flowsheet Selection for the Rosia Montana Flowsheet”, Aurifex Pty Ltd, March 2006.