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## State-of-the-art environmental technologies for the utilization and reprocessing of mineral industry wastes

### Report of the Secretary-General

*Summary*

The present report has been prepared in response to Economic and Social Council decision 1996/306. The report describes the utilization and reprocessing of mineral wastes within the larger context of the increasing uptake of source reduction technologies. Emphasis has been placed on solid wastes arising from the extraction and processing of base and precious metal ores since such wastes are responsible for some of the most intransigent and persistent environmental impacts. However, where relevant, examples from other mineral industry sub-sectors are also presented. Although the report focuses on mineral industry wastes, some of the technologies and practices reviewed may also be applicable to contaminated soils and other metal-bearing solids.

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# I. Introduction

1. The availability of rich geological resources in tandem with market conditions largely outside the control of the metal-producing enterprises have resulted in a sector characterized by a low level of technological innovation. However, the emphasis has now altered: after a period of limited technological change, a spur to technology development in the minerals industry has been applied by public concern over adverse environmental effects and the design of environmental regulation that obliges firms to mitigate or prevent such effects. The dominance of "waste management" as opposed to "pollution prevention" at the present time is perhaps a reflection of the prevailing attitude towards closure, namely that a civil engineering-style remedial approach is sufficient to properly decommission a site and avoid possible liability in the future. But although that may have been true 20 years ago, technology, legislation and the expectations of stakeholders have changed since then, and if there is a generic thread that links current waste management approaches, it is the possibility of future litigation and liability associated with what might be considered short-term (but relatively cheap) solutions to long-term environmental problems.

# II. Waste production in the mineral industry and related issues

2. Metals and other mineral resources are rarely found in a sufficiently pure state to be sold in an "as-mined" form. Metals are often found in chemical combination with oxygen (as oxides), sulphur (as sulphides) or other elements (chlorides, carbonates, arsenates, phosphates etc.). Non-metal mineral resources (coal, industrial minerals) also normally contain physically or chemically entrained impurities in their undisturbed state.

3. Although any unit operation within the life cycle of a mining operation has the potential to produce an environmental effect or impact, typically the potential arises from the deliberate (regulated) and accidental (non-regulated) discharge of solid, liquid and gaseous waste products. The characteristics of such discharges, the nature of the receiving environment and the distance over which the discharges are transported are major factors in determining the magnitude of their effect or impact. Societal values and preferences also play a significant role in determining how certain discharges are viewed by various stakeholder groups: this more subjective adjunct to the quantifiable and measurable discharge and receiving environment characteristics therefore sets, in part, the site-specific environmental "footprint" of an operation.

4. Increasingly, based on a more thorough understanding of the potential impacts, the pressure for environmental protection may outweigh the justification for exploiting particular mineral reserves (Hodges, 1995). The industry as a whole, in partnership with the broadest possible spectrum of stakeholders, must strive towards ever higher levels of performance in control and management of the mining process throughout the life cycle of an operation. This includes moving to an improved level of efficiency in resource utilization.

5. The major source of solid waste from mining and subsequent processing is "gangue" (valueless or sub-economic minerals associated with the target or economic mineral(s)). Depending on the point at which they are rejected from the process, gangue may be disposed of in an as-mined state (waste rock), as tailings (following mineral processing), as slags (after smelting) or as other waste products (dusts, sludges from water treatment, spent ore from leaching etc.). These various wastes may also contain significant quantities of the target mineral or metal due to inefficient processing, technological limitations or mineralogical factors.

6. There is also a trade-off between grade (the concentration of metal(s) in the final or intermediate product) and recovery (percentage of the total valuable metal(s) contained in the feed to the processing plant resulting in saleable product). It is possible to maintain a very high grade by rejecting a significant fraction of the input material (i.e., by accepting low recovery) or a very high recovery by excessively diluting concentrates with lower grade material. However, neither of these two extremes is normally the optimum economic solution. In simple terms, this is gauged by comparing the revenues generated by additional recovery of metal(s) against the capital and operating costs of doing so, within the greater context of technical feasibility. Without exception, some part of the target metal(s) will end up as waste, along with the gangue minerals.

7. In non-ferrous metal mining, gangue is normally the major component of an ore body. Nowhere is this more apparent than in the case of gold, where the concentration of valuable material is so low – normally 5 grams or less per ton – that effectively all of the mined ore is disposed of as waste in some form unless other valuable components, such as base metals, are also present. Other mineral resources may have less gangue relative to the target mineral, but disposal of gangue-related wastes normally remains a significant issue, and many mining operations are as much about waste disposal as they are about resource extraction.

8. Evidently, the process of waste disposal related to mining activity is a significant source of potentially harmful elements in the natural environment. However, inputs do not necessarily result in damage to the environment; many mitigating factors may exist, some related to the process such as the chemical and physical characteristics of wastes, and others related to the external environment, such as climate, topography or ecosystem characteristics.

# III. Utilization and reprocessing

9. Utilization and reprocessing are two of a range of "end-of-pipe" or "remedial" techniques for addressing the environmental issues associated with waste production in the mining industry. Historically, low-tech end-of-pipe approaches have dominated in the mining sector, but more recently these solutions have become increasingly sophisticated, against a background of the increasing application of "source reduction" technologies.

10. In the waste management "hierarchy" for dealing with wastes, utilization and reprocessing are less desirable than source reduction (pollution prevention) but a better environmental option than treatment or disposal (Allen and Rosselot, 1997).

11. Utilization normally entails the use of waste in an untreated form (although the physical form of the material may be adjusted); in the case of mineral industry wastes, utilization may be more feasible after reprocessing to remove or reduce the concentration of environmentally significant contaminants and target metal(s). Only those wastes that are sufficiently "clean" should be used, particularly off-site, since the major issue with waste utilization is the potential of dispersing environmentally harmful contaminants over a much wider spatial area. Generally, as the degree of contamination increases, so the potential for utilization decreases. Given those constraints, utilization may be equally attractive for current operations and for older or abandoned wastes.

12. The opposite could be said to hold for reprocessing, in that as the level of target metal(s) increases so the potential for reprocessing may increase. The concept of reprocessing to recover one or more valuable products (metal, metal salts, minerals) has a greater application in older waste outputs from the mining industry. There are two main reasons for this: in the past, ore grades were generally higher than those today and technology was less efficient.

13. Reprocessing may not necessarily result in environmental improvement, for example in cases where the residual waste (after reprocessing) still contains significant concentrations of other contaminants, such as non-target minerals. However, in many regulatory frameworks, reprocessing may be linked to safe disposal of the final waste (e.g., at an engineered disposal site) where this was not the case prior to reprocessing activity.

# IV. Drivers affecting waste utilization and reprocessing

14. There are many "positive" drivers motivating innovative approaches to the remediation of contaminated mining sites, such as waste utilization and reprocessing. There are also many impediments ("negative" drivers) to the increased uptake of such approaches. Key positive drivers include technological advances; increasing metal prices; commodity scarcity; changes in strategic uses of certain commodities; maximization of resource utilization; Agenda 21; sustainability; the necessity of decoupling economic growth and environmental impacts; the polluter-pays principle; legal obligations/liabilities and bonding requirements; and other diffuse stakeholder pressures.

15. The perception of the general public that current approaches may be neither optimal or environmentally acceptable in the medium and long terms may also be significant, although that driver is probably felt less keenly in the mining industry than some other industrial sectors. Nevertheless at the local and regional levels it may still be significant.

16. Other drivers include regulatory frameworks that promote innovation in technology and resource management, and industry initiatives to develop more effective and lower-cost solutions to existing and future environmental issues (Kovalick, 1993; Ayen, 1994).

# V. Mining (extraction) and potential wastes

17. In broad terms, there are three types of mining: surface, underground and *in situ* (solution mining). The latter is somewhat limited in its application, although it is sometimes used to exploit residual mineralization as grades drop at surface or underground mines. Surface mining is dominated by open pit (base and precious metal ore extraction) or open cast (coal operations) methods. Irrespective of the method employed, mining is always accompanied by processing of some description. For relatively pure or homogeneous

materials, processing may be limited to crushing and sizing (some natural zeolite extraction, quarried rock) or physical washing (some coal operations).Such simple processing options are only possible where the target minerals form the majority of the material extracted. In those cases, the main environmental releases, effects and impacts are associated primarily with the mining itself rather than with subsequent processing.

18. The two major releases from surface and underground mining relevant to reprocessing and utilization are mineral wastes (overburden and waste rock) and contaminated waters (acidic, metal-laden discharges from waste disposal sites and workings). The latter is also of importance at *in situ* mining operations, although the added chemical(s) by which the process of metal leaching takes place can also contribute to water contamination and pollution.

# VI. Mineral processing and potential waste generation

19. Mineral processing is defined as the physical processing of minerals. It does not result in any chemical changes to the mineral components of the ore but is a means of achieving the physical separation (and concentration) of different mineral phases, such as the separation of target minerals from gangue minerals or of one valuable mineral from another (Hayes, 1993). For non-metal mineral resources, mineral processing can produce a final product, but in the case of metals it is an intermediate stage since it does not affect the chemical combination of the metal with oxygen, sulphur and so on. Mineral processing is normally an intermediate stage between mining and extractive metallurgy, although there are exceptions, such as heap and dump leaching of as-mined ore. The outputs from mineral processing (concentrates) form the inputs to extractive metallurgy (either hydrometallurgical or pyrometallurgical processes, see paras. 24-31 below).

20. Mineral processing methods can be divided into two groups: size reduction and separation of mineral phases. Crushing and grinding (in tandem with sizing) are used to liberate economic and non-economic minerals from one another, thereby producing suitable feeds for subsequent processes in which separate mineral phases can be generated. However, grinding does not normally produce a completely liberated mineral product, and some particles may be a mixture of two or more mineral species, with physical or chemical characteristics representative of that mixture. This can result in target minerals being disposed of with gangue minerals, or the dilution of the mineral concentrate by gangue minerals.

21. Size reduction is undertaken using “crushers” (jaw, gyratory and cone crushers) and “grinding mills” (rod, ball, hammer and impact mills). Crushing is used to reduce incoming ore from boulder-size down to a diameter of 25 millimetres or less. This material may then pass to grinding mills or may be processed directly if the valuable mineral is sufficiently liberated. Grinding reduces particle size down to a lower limit of about 10 microns.[1] In contrast to crushing, which is carried out on run-of-mine ore, grinding is almost always done wet and the output from grinding is a “slurry”, a suspension of fine particles in water.

22. Mineral separation can be achieved by employing differences in mineral characteristics based on particle size, particle density, magnetic properties, electrical properties or surface chemistry (flotation).

23. The separation technique of choice is based upon a number of site-specific factors, including the size of the operation, the particle size at which minerals are sufficiently liberated, mineralogy, the overall processing circuit (from mining to extractive metallurgy) and so on. Ultimately, each process produces a “concentrate” (rich in the target mineral or minerals), “tailings” (containing mainly sub-economic or non-economic minerals) and “middlings” (particles in which target and gangue minerals have not been fully liberated). Middlings are normally reground or sent to an alternative process to liberate or otherwise recover the valuable mineral, while tailings are disposed of as waste. Of the various separation processes, flotation is now the dominant method for the production of mineral concentrates, particularly from sulphide ores, and is the major source of tailings. Other unit operations within mineral processing are of limited interest in terms of their potential to impact the external environment because they mainly operate within what are effectively closed circuits, i.e., many unit operations pass 100 per cent of their input to the next process. Flotation is often the final unit operation and the stage at which wastes (tailings) are generated and transferred to the external environment. Tailings generated during flotation are mainly composed of fine particles of gangue minerals, within which are contained varying amounts of the target mineral(s), depending on process economics, process efficiency and mineralogical constraints.

# VII. Extractive metallurgy and potential waste generation

24. Extractive metallurgy can be subdivided into two major disciplines, “hydrometallurgy” and “pyrometallurgy”. A third discipline, “electrometallurgy” is not considered here in depth because its use is more limited in the mining sector (mainly for the production of aluminium and some zinc).

## A. Hydrometallurgy

25. Hydrometallurgical methods of ore treatment are most commonly used for gold, uranium, copper and aluminium, and to a lesser extent zinc and nickel. In particular, ores containing oxide material (about 10 per cent of non-ferrous ores) are treated by leaching. Ore is first processed according to the requirements of the subsequent processes, and a leaching agent is then used to extract the valuable metal(s) in the form of a dilute, metal-laden solution. This solution then passes to the metal recovery stage, which may involve precipitation, solvent extraction (SX) or electrowinning (EW).

26. Leaching reagents and solvents commonly used include:

(a) “Acids” (hydrochloric acid, sulphuric acid) for oxidized copper minerals, such as azurite, malachite, tenorite and chrysocolla, and “oxidants” (ferric sulphate) for less oxidized copper minerals, such as chalcocite, bornite, covelite and chalcopyrite;

(b) “Alkalis” and “ammonia-based” reagents (sodium/ammonium hydroxide or carbonate) for certain copper minerals;

(c) “Bacterially mediated” leaching, using bacteria to cost-effectively generate acid and oxidants from sulphide minerals;

(d) “Cyanide” (as a sodium or potassium cyanide solution) to dissolve gold;

(e) “Mercury” as an amalgamating reagent in the recovery of gold; it is widely applied at small-scale mining operations, principally in developing countries.

27. The methods used to deploy the above-mentioned leaching reagents include:

(a) “Dump leaching” of material on an unlined surface. The term derives from the practice of leaching materials that were initially deposited as waste rock; however, it is also applied to run-of-mine, low-grade sulphide or mixed-grade sulphide and oxide rock placed on unprepared ground specifically for leaching;

(b) “Heap leaching” of low-grade ore that has been deposited on a specially prepared, lined pad constructed using synthetic material, asphalt or compacted clay. In heap leaching, the ore is frequently pre-treated using size reduction (crushing) prior to placement on the pad;

(c) “Vat leaching” as a high-production rate alternative to heap and dump leaching, conducted in a system of vats or tanks using concentrated lixiviant solutions and run-of-mine ore/mineral concentrates.

28. The procedure for metal recovery varies with the metal, but often involves preferential cementation (copper or gold) SX/EW (copper).

29. Wastes generated during hydrometallurgical processes relevant to reprocessing and utilization include:

(a) “Spent ore/depleted concentrate”, containing residual process chemicals, target and non-target minerals/metals;

(b) “SX-EW sludge”, containing materials that can accumulate in solvent extraction/electrowinning tanks (particulates, emulsion of organic and aqueous phases);

(c) “Spent electrolyte” generated during electrowinning activities and laden with soluble impurities;

(d) “Mercury-contaminated wastes”, resulting from the use of mercury in amalgamation.

## B. Pyrometallurgy

30. Pyrometallurgical processes are currently the backbone of recovery for copper, zinc, nickel and lead from sulphide deposits. The process routes typically include mineral processing (normally flotation) to produce a concentrate, followed by smelting, which breaks down the crystalline structure of the minerals by heat-fuelled oxidation. The process for each metal or suite of metals is different. For example, copper smelting produces a “matte” (containing up to 40 per cent metal content), which in its molten form is converted and separated into “blister” (about 97-99 per cent pure) and an iron-silicate slag, which may have sufficient economic value to be worth further processing. Since blister metal is too impure for most industrial applications, refining is necessary. This is usually undertaken by a fire process (using a reverberatory furnace) if the feed has a low by-product content, or by electrolysis if additional metals are to be recovered. The resulting cathodes, which are usually about 99.8-99.9 per cent pure, are marketed directly to the semi-

fabricators or cast into shapes (wire bar). Lead, however, is produced via a route based on sintering, reduction of the sinter in a blast-furnace and pyro- or hydrometallurgical refining of the bullion.

31. Pyrometallurgical processes give rise to five potentially polluting products: waste gas, fugitive gas, effluents, smelter dust and slags, of which the latter two are of greatest significance in relation to reprocessing and utilization.

# VIII. State of the art in mineral waste utilization

## A. Constraints in mineral waste utilization

32. There are relatively few examples of mineral waste utilization in the base and precious metals mining industry. There are two main reasons. First, a constraint is placed on utilization by the presence of minerals (metals) that have the potential to cause environmental damage. Utilization in these cases can be viewed as a dispersion pathway and causative agent in wider environmental contamination and pollution. The second constraint is the high place value of the mineral wastes, even if "free" of contaminants. Transport costs outside a relatively limited area are likely in most cases to far exceed the saleable value of the waste itself. An additional constraint is the relatively low cost of primary materials with which the wastes compete (primary and secondary aggregates, other fill material etc.).

## B. On-site utilization

33. The first and second constraints outlined above can be circumvented to a large extent by developing on-site uses for the wastes. This is already done to a large extent at most mining sites, and wastes are used in such applications as bunding, road building and maintenance, and in geotechnical applications. However, the largest potential on-site use of waste is as backfill, particularly for underground mines. Once again, however, the issue of contaminants and possible dispersion once the waste is in place arises, and it is common to backfill the waste with Portland cement, pulverized fuel ash or other stabilizing agents (soluble silicates), both to improve its physical characteristics and to minimize the potential leaching of metals into groundwater. Backfill of wastes is widely used in shallow underground mining operations (coal, limestone).

34. Minor and probably site-specific applications in the future may include water treatment, such as the use of finely ground waste rock as an adsorption material for flotation collectors (Heiskanen and Yao, 1992) and the use of pyrite (recovered via reprocessing; see sect. IX below) to remove dissolved arsenic species by adsorption (Zouboulis et al., 1993).

## C. Off-site utilization

35. Toivola and Toivola (1997) have a patent for a method of producing a building material from a mixture of unscreened thermoplastic waste and mineral aggregate. Possible applications include paving slabs, bricks or concrete-style blocks. Aljaro (1991) reported the use of untreated tailings effluent as an agricultural water source, based on a study funded by the Corporación Nacional del Cobre de Chile in Chile. Untreated effluent has been used from the El Teniente copper-molybdenum mine to irrigate crops and water livestock. Crops that were tolerant of higher levels of copper, molybdenum, manganese and sulphates (and to local soil and water conditions) were identified and planted. Translocation of the metals to edible parts of the crops was limited and did not exceed allowable levels. However, due to the potential for build-up of metals in soil and groundwater, this use is likely to be very limited. Other uses that have been documented include large volumes of clean taconite tailings used as embankment, dam and highway materials in the United States of America, low volumes of clean taconite tailings used for ceramic, brick and tile production, and base and precious metal wastes used in dense calcium silicate bricks, aerated concrete, lightweight foamed building products, dry pressed bricks and glass (Mitchell, 1990).

# IX. Mineral waste reprocessing

## A. Reprocessing of wastes to recover acid generating sulphides

36. Partitioning of wastes into sulphide-rich and sulphide-depleted fractions offers the chance to expand waste management options for current operations, and to address environmental issues at sites where acid generation from non-segregated wastes is occurring. In both cases – theoretically – the low-volume sulphide-rich fraction can be disposed of at highly engineered disposal sites or isolated as buried "cells" within the bulk waste, while the high- volume

sulphide-depleted fraction can be disposed of as inert waste or utilized on- or off-site.

37. In a recent paper, Humber (1995) analysed the relationship between sulphide (pyrite and pyrrhotite) recovery, acid generation and operating/capital cost estimates for reprocessing. Several mineral-processing techniques were examined for their capacity to separate acid-generating sulphides from existing mill tailings and to generate a sulphide-depleted fraction and a low-volume sulphide-rich fraction. Methods examined included gravity separation (centrifugal concentrator, shaking table, spiral concentrator), flotation, magnetic separation and cyclone classification. These were tested on samples from three mines. The sulphide concentrates were also examined in terms of commercial value.[2] For each of the three samples, the sulphide minerals were well liberated and present at sufficiently low concentrations to produce (theoretically) a low-volume sulphide concentrate. None of the gravity methods attempted produced non-reactive (with no net capacity for acid generation) tailings. Flotation was more successful, although to a certain extent this appeared to reflect the simple nature of the mineralogy and the fine size distribution of the sulphides. Reprocessing via flotation not only reduced the capacity for acid generation in the depleted fraction but also reduced the concentration of other environmentally significant metals, such as cadmium, copper and zinc.

38. Based on the tests that generated wastes with the lowest potential for acid generation, operating and capital costs were estimated. Total capital costs ranged from $130,000 to $1,275,000. Operating cost estimates ranged from $0.50 per ton to $1.35 per ton. However, the work does not report existing operating or capital costs, and these additional costs cannot be fully placed in context. However, there are other examples of implementation at plant scale of this approach, albeit at operating sites rather than in the context of reworking older wastes. The Magma Copper Company has produced pyrite products at its Superior Mine operation by passing tailings from the copper circuit through an additional flotation circuit, thereby generating a less reactive tailings product, plus a fine, virtually pure pyrite product and a coarse pyrite concentrate (45-47 per cent iron, 48-50 per cent sulphur) (USEPA, 1994a). Approximately 500 tons per month of pyrite products were sold in 1994, representing 90-95 per cent of the United States market (USEPA, 1994b). However, in this case saleable pyrite products were generated because the ore (a) contained up to 25 per cent pyrite and (b) had few impurities. Those factors may make the deposit relatively unique, and thus the transfer of this approach to other operations may be more difficult than it might first appear. As noted above, the driver behind pyrite production was not strictly environmental (although the company did recognize the benefits accruing from reduced acid rock drainage generation) but rather demand for the product – when there was no demand, there was no recovery of pyrite. This emphasizes the difficulty of dealing with minerals, such as pyrite, which have little or no market niche or value.

## B. Reprocessing via bioleaching

39. Bacterially mediated leaching has been used to process refractory gold, hitherto unrecoverable due to its crystalline association with pyrite, which the bacteria can readily dissolve. Advances in biotechnology, combined with the environmental and economic advantages that bacterial leaching technologies appear to have over other larger-scale, more capital-intensive and more polluting traditional processes, may herald substantial changes in the structure of the minerals industry. In March 1994, Newmont Gold reported that field tests had confirmed the economic viability of a patented bioleaching process to recover gold from low-grade sulphide material that would not previously have been considered to be economic ore (Brewis, 1995). The system uses *Thiobacillus ferrooxidans* and *Leptospirillium ferrooxidans* to oxidize the gold-bearing sulphides on a heap leach pad, and then cyanide or ammonium thiosulphate leaching to remove the gold. Although the reaction kinetics are slow, this approach is economically viable due to the low cost of the biological systems used. To date, bioleaching has only been applied commercially to the recovery of gold, uranium, copper and nickel; its use has also been suggested for heap leaching of low-grade zinc ores.

## C. Alternatives to cyanide in gold recovery

40. Although cyanidation is the major route used for gold recovery at formal operations (100 per cent of formal gold production in South Africa) (Adams, 1997), cyanide is not the only lixiviant with the potential for use in gold recovery. Other potential alternatives to cyanide include thiocyanate (Adams, 1996) and halogen-based solvents, such as chlorine gas, sodium hypochlorite, iodine and bromine (Ramadorai, 1994). None of these could be considered a generic replacement for cyanide, but they may be useful in the treatment of specific ore types or gold-bearing wastes for which no economically or technically viable processing option exists at the time of disposal. Indications are that for non-refractory ores, halogen solvents are no more efficient or cost-effective than cyanide. Instead, halogen solvents may find more greater application in the treatment of refractory

ores and wastes, although this remains an area requiring further substantiation.

# X. Utilization, reprocessing and source reduction approaches

## A. Source reduction in mining, mineral processing and extractive metallurgy

41. Clean technology is an integral component of – and is often considered synonymous with – waste minimization and pollution prevention (source reduction), and has principally been used and indeed developed within the process industries. Ideally, in assessing the "cleanliness" of a technology, the environmental performance of upstream suppliers and downstream users and disposers of products should also be taken into account, although this is often difficult to determine and the boundaries of such evaluation are in practice restricted more closely to the process in question.

42. A number of generic or cross-sectoral strategies are adopted within an overarching management system to facilitate pollution prevention: (a) improved plant operations, (b) alterations to process technology, (c) recycling, recovery and reuse of waste products, (d) changing raw materials and (e) product reformulation.

43. In the context of base and precious metal mining and processing, strategies (a), (b) and (c) above have the most obvious applications, although the capacity does exist occasionally to change the nature of the process input (i.e., strategy (d)), for example by selective and more accurate ("right-in-space") mining practices (Almgren et al., 1996). Strategy (e) is of little direct relevance to the mining industry and is ignored here.

44. Where there are a number of competing clean technologies, they can be ranked according to the reduction in the hazards associated with their waste outputs, treatment/disposal costs, future liability, safety hazards and input material costs. The means of determining the cleanliness of a particular technology relies heavily on the assessment of resource usage and environmental impact using life cycle inventory and life cycle assessment (LCA) methodologies.

45. Although the benefits of waste minimization are wide-ranging, there are often institutional disincentives that may need to be overcome, such as management uncertainty due to unsure investment returns, the potential for production downtime, problems with product quality and loss of proprietary information to waste reduction consultants. The best way to circumvent those obstacles is to involve top and middle management, plant management and plant operators (i.e., the complete corporate structure) (Haas, 1995).

## B. From waste management to waste prevention and back again

46. The current trend in the mining sector towards source reduction is being undermined by such issues as those surrounding low-value but environmentally harmful minerals present in base and precious metal ore bodies, for example arsenic and pyrite. Arsenic is a particularly topical example of the problems and issues associated with the sub-economic and toxic contaminants commonly associated with valuable mineral assemblages. It is mainly produced as a by-product during the production of other more important metals, such as copper, lead, zinc, gold, silver and tin. Commercial grade arsenic trioxide is recovered from the smelting or roasting of non-ferrous metal ores or concentrates in at least 18 countries (Broad, 1997). Future market opportunities do not look promising for arsenic, with lead-arsenic alloys in batteries being replaced with lead-calcium equivalents and increasing pressure on low-tech uses, such as timber treatment.

47. Many of the treatment technologies that have been developed for the safe disposal of hazardous wastes do not apply to arsenic-contaminated mineral wastes. To compensate, other possible routes are under development, involving:

(a) "*Synthetic mineral immobilization technology* (SMITE)": SMITE treatment precipitates or converts metals into non-volatile forms and then adds appropriate "tailoring" chemicals so that during the conversion phase the desired synthetic mineral assemblage is formed (White and Toor, 1996). SMITE has been used for the stabilization of arsenic flue dust (containing arsenic trioxide) in the form of a low solubility apatite-type mineral ($Ca_5(AsO_4)_3F$);

(b) "*Ferric arsenates*": research on the high temperature precipitation of dissolved arsenic as stable, crystalline ferric arsenates has been under way for a number of years (see, for example, Swash and Monhemius, 1994, and references therein). Ferric arsenates are generated by the dissolution of the arsenic species (commonly arsenic trioxide (Van Weert and Droppert, 1994)), followed by conversion to crystalline scorodite ($FeAsO_4.2H_2O$) using iron-bearing acidic nitrate (or sulphate) solutions at temperatures ranging from 140°C to 160°C;

(c) "*Incorporation in silicate slags*": alternatives to the formation of low-solubility mineral phases include the incorporation of arsenic in silicate slags. Research has indicated that up to 10 per cent arsenic by weight can be incorporated into “glassy” silicate slags, with very low arsenic release during subsequent leaching (Machingawuta and Broadbent, 1994).

48. Despite these recent advances, the issue of arsenic recovery, treatment and disposal is one that has still to be resolved. The lack of markets for arsenic by-products removes the financial incentive for recovery (although recovery is often achieved incidentally during the processing operation), and the financial implications of liability are not sufficiently developed to act as an alternative driver. Where there is no market for a particular waste or by-product and the presence of the contaminant in the process feed is unavoidable, the development of a truly “clean” technological solution is impossible. The alternatives are to (a) not exploit ores containing problem metals and minerals for which there is no market, or (b) accept that the recovery, isolation and effective treatment of the problematic elements prior to disposal is the optimal option. Realistically, it is the latter case that will predominate, although there have been instances of proposed mining developments being rejected on the basis of generally unacceptable risk (New World Mine on the edge of Yellowstone National Park, United States), which may set a future precedent for restrictions on mining on or near “sensitive” sites not already “protected” from such activity. At the very least, the unpalatable nature of restrictions on mining may help to promote the recovery and predisposal treatment of non-target and non-economic metals and metalloids if that can be established as the best environmental option based on rigorous scientific studies.

# XI. Conclusions: optimizing source reduction, reprocessing and utilization

49. State-of-the-art technologies are difficult to describe in absolute terms since the supporting tools with which assessments are made, such as LCA, have not yet been fully developed. Neither are the ecotoxicological implications of utilization and reprocessing fully understood, although advances in site-specific ecotoxicological assessments have reduced uncertainty associated with some remedial actions at mining sites (Pascoe, 1994; Greene and Barich, 1994). There is, however, an increasing pressure on those involved with waste management to develop a sustainable approach and to integrate relevant strategies to engender the best practicable option for environmental protection (Barton et al., 1996). Realistically, there will always be a requirement for the parallel use of source reduction, reprocessing, utilization, treatment and low-tech remedial solutions in the mining sector. Each has a niche, and although the balance can be expected to change with time, none will be subsumed completely. Many potential agencies – government and private – that could potentially be involved in the remediation of mine sites (and by extension, reprocessing) are impeded by regulatory and institutional barriers, such as the question of liability. These not only impede the physical reclamation or remediation of sites but also tend to stifle capital investment in the development of innovative technologies (Durkin, 1995). The question, therefore, is how regulation can be used to promote the reprocessing and utilization of mining industry wastes more effectively than currently implemented approaches.

50. The remediation of existing mine sites represents a significant opportunity to develop new and innovative technologies for the reprocessing of mine wastes, and to develop policy and technical procedures to promote the utilization of secondary wastes rather than primary resources, where possible. Increasing constraints on the exploitation of primary resources have elevated wastes into potential resources themselves. Regulatory standards and quality standards may impede the use of innovative technologies, and there may also be technical barriers to the reprocessing of certain complex waste materials. Innovative technologies may also have limited cost and performance information, which in turn generates a lack of incentive to invest in innovative technologies. State-of-the-art technologies must also compete against a growing number of stabilization techniques (SMITE). While such technologies have disadvantages, such as lack of credibility and concerns about their long-term stability, they may, however, be the only practicable solution for minerals/metals with little or no market value.

*Notes*

[1] Below this size, particles become increasingly difficult to handle and/or separate.

[2] There has been a substitution of elemental sulphur for pyrite in the production of sulphuric acid (Berkowitz, 1988), indicating that the sale of pyrite might not be commercially viable.

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