Mining Non-ferrous Metals

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1 Introduction

The products of the extractive industries, both metals and minerals, are of pivotal importance to modern life-styles. This situation will continue for the foreseeable future in spite of the inroads made into some non-ferrous applications by plastics, ceramics, and composites. Some of the many applications illustrating this point are indicated in Table 1.

In this introductory review, emphasis is placed primarily on the environmental impacts arising from the mining and concentration of non-ferrous metal ores. Brief reference is made to the efficient management of emissions from non-ferrous smelting processes, recycling, and the environmental issues arising from the significant power requirements of the industries involved.

Unlike organic chemicals and plastics, metals generally cannot be degraded chemically or bacteriologically into simpler constituents, such as carbon dioxide and water, which are relatively neutral environmentally. Metals occur naturally in a wide range of economic concentrations in the ground from approximately 0.05% for uranium, through 0.5–1% for copper, to approximately 60%–70% for iron, and invariably occur in admixture with a wide range of minor and trace metals. Many non-ferrous metals occur naturally as sulfidic compounds. Thus, **metals use is essentially metals relocation** and requires:

(1) *Large energy inputs* to extract the ore and to separate the desired metal from undesired mineral substrates and minor metal impurities, *i.e.* concentration effects.
(2) *Consideration of the toxicity of metals* and associated impurities, *i.e.* their chemical type in extraction, purification, and use (*i.e.* toxicological effects).
(3) *Recycling after use* or, where this is impracticable, permanent disposal in an environmentally acceptable manner, *i.e.* collection and process technology issues.
(4) *Managing the effects of associated impurities*, including associated minor metals and sulfur.

This overall set of processes is summarized in Figure 1.

Table 1 Non-ferrous metals are essential to modern society

Housing
- Structural steel protected by galvanizing (zinc)
- Roofing (Architectural and Ancillaries) (lead, zinc, copper)
- Long life windows in aluminium or plastic protected by metallic stabilizers
- Electrical conductors, *etc.* in copper, aluminium

Quality of Life
- Domestic appliance/equipment components die-cast in zinc or aluminium alloys
- Portable tools and appliances powered by nickel/cadmium batteries
- Ornamental items in brass and copper

Transportation
- Automotive batteries (lead/sulfuric acid)
- Car body-shells protected by galvanizing (zinc and zinc–aluminium alloys)
- Electrical equipment (copper and aluminium)
- Stand-by power systems (nickel/cadmium)
- Alloy steels (nickel)

The production, use, and recycling of non-ferrous metals thus requires a complex series of technologies carried out by organizations of widely varying size and sophistication in many areas of the world exhibiting extremes of climate, development, and political outlook.

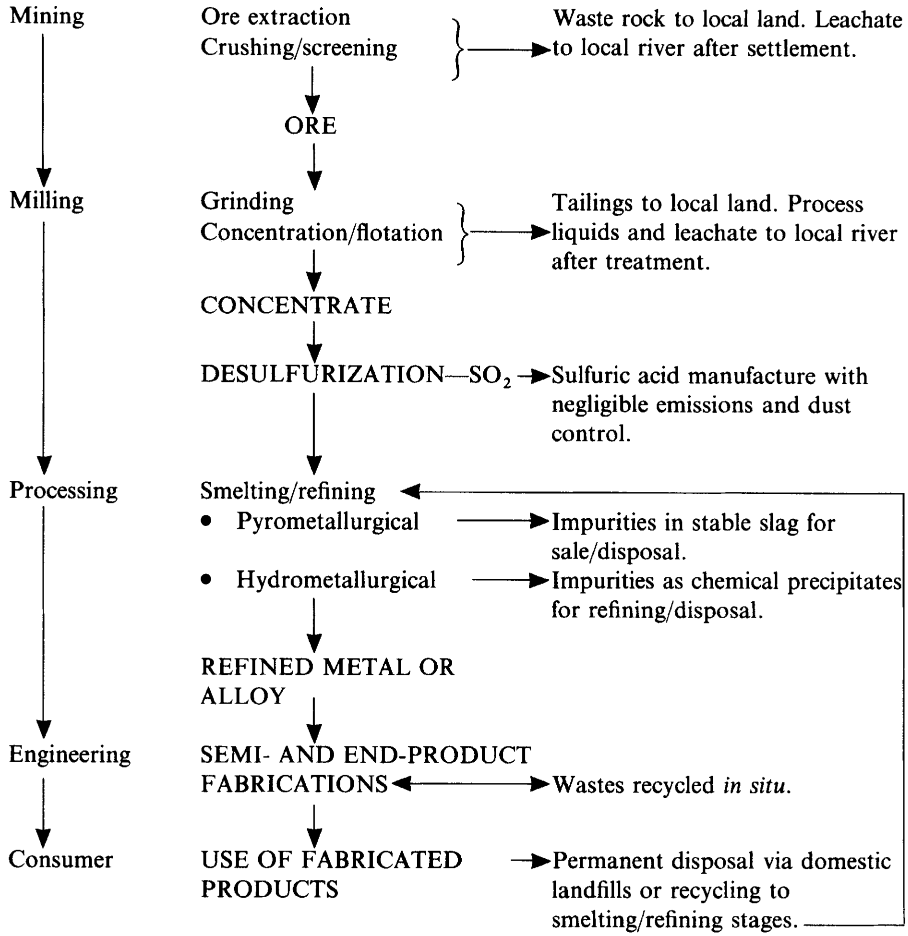
2 Environmental Background

The desire to protect the environment from the perceived effects of both the extraction and processing industries is strong in the so-called 'developed world' (*e.g.* North America, Europe, Japan, Oceania) and growing rapidly in the 'developing' countries, largely through the efforts of various United Nations agencies. Politicians and regulators express these public wishes through increasingly stringent regulations whose true costs are usually impossible to estimate accurately. Slogans such as the 'Polluter Pays Principle'—whereas the consumer usually eventually pays—are sometimes used to suggest that eventually the costs of building new plants to meet modern environmental standards will become so high that such plants will either not be built or will be constructed in 'developing' countries where standards are thought to be lower.

In general, this view is illusory for new construction and largely so for the upgrading of older plants to modern environmental standards provided an adequate time-scale is allowed; say 5–7 years. It is likely that increasing importance will be attached to environmentally acceptable disposal routes for consumer durable and other end-products. This could result in some market restrictions which would find grudging acceptance from producers and consumers of all environmental standpoints.

The non-ferrous metals industry, in common with its product competitors, has also to manage the impact of quite rapidly rising power costs. Technically, these

Figure 1 Metals use is metals relocation



increases are attributed mainly to the cost of developing low-sulfur basic sources of energy and the cost of neutralizing acidic emissions at power stations burning coal of relatively high sulfur content, to minimize 'Acid Rain'. The cost of safely decommissioning time-expired nuclear power stations will also become an increasing factor.

Environmental issues are often presented confrontationally—development or environmental devastation; compliance with criteria *versus* costs; industry *versus* the regulators or the 'Greens'—and, indeed, there is never complete congruence between these different viewpoints.

However, the confrontational approach does scant justice to the desires of most people to improve their material standards, not at any cost, but inevitably through industrial activities which provide employment and income as well as products. It also fails to reflect the increasingly general management view that operations must be designed, run, and maintained to the best professional standards, rather than to those which appear to be the most economic in a short-term view.

From a mining and processing standpoint, aspects of implementation of this policy are outlined in the following review. Though mineral extraction, processing, smelting, and refining can never be environmentally neutral, the overall areas of impact are generally quite small. A fully professional approach can achieve a high degree of amelioration provided it is applied consistently and continuously, on a long-term basis, from project initiation to final 'close-out' of the restored and remediated mine and/or refinery.

From the economic standpoint, the cost of meeting inevitably stricter environmental regulations—and the non-regulatory aspects of such disparate issues as accident prevention, including planning for disaster prevention and mitigation, occupational health, product safety, and 'environmental friendliness' in the ultimate end-product—should be judged on a **comparative** basis, relating one product's total cycle costs to those of its market-place competitors. Whilst the future situation *vis-à-vis* competition from plastic and composite materials is much more difficult to estimate with any accuracy, it seems likely that non-ferrous metals will retain many, though not all, applications dependent upon electrical conductivity, ease of repetitive manufacture, and the long-term maintenance of essential physical properties such as strength and relative absence of 'creep' and brittleness. The aesthetic properties of fabricated and well-finished metals will ensure that they are specified for a high proportion of prestige architectural and decorative applications.

Ease and practicability of recycling is already of increasing importance. Unlike metals, most current plastics cannot be recycled without some loss of their original physical properties and so find re-use in less demanding applications. Furthermore, most current plastics are not bio-degradable, *e.g.* in landfills, so that such materials as have to be disposed to landfill can present long-term environmental problems.

Bio-degradable plastics are being developed and, whilst relatively costly at present, plastics may in future be able to add 'environmental friendliness' to their current virtues of relatively easy availability and low finished-item production cost. However, it is virtually impossible to combine bio-degradability with long-term performance in an engineering plastic and, here, metals are likely always to have the advantage, particularly if their relatively easy reprocessing can be exploited in practice to provide higher levels of economic recycling.

General consideration will now be given to the environmental aspects of the separate stages in non-ferrous metals extraction and use.

3 Extraction and Concentration (Mining and Milling)

The production of non-ferrous concentrates can be depicted schematically as in Figure 2.

As noted earlier, natural concentrations of some non-ferrous metals are very low and invariably contain unwanted impurities. Hence, the tonnages of waste products in the form of tailings and overburden can be very large, amounting to many million tonnes per annum from an individual copper or uranium mine. Due to the in-ground concentration effect, tonnages moved and processed are often of the same order for large copper and iron mines. In relation to all foreseen needs, there are ample resources of all metals to be found in the top mile of the earth's crust. The limitations to winning these metals are the availability of cheap power

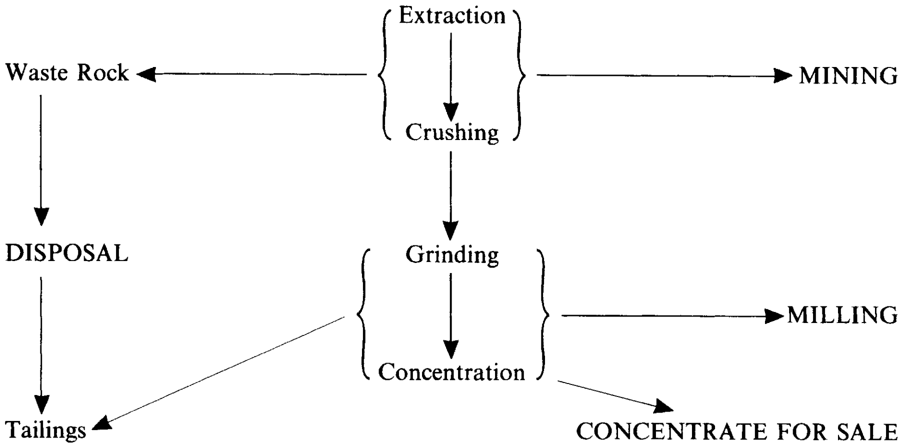


Figure 2 Major stages in the production of non-ferrous concentrates

and, to a lesser degree, practicable technology to isolate and extract deeply occurring metals.

Non-ferrous ores are extracted from both open-pit and underground mines, and occasionally from the two in combination. Where a choice is possible from technico/economic considerations, the balance has to be struck between ensuring the health and safety of the miners, usually easier in open-pit than underground mines, and the disposal of waste products, which is usually less intrusive in underground than open-pit mines which have the added problem of 'hiding the hole' at closure. Successful restoration of a worked-out underground mine is usually a simpler task than for an open-pit operation.

Environmental Impact Assessment

Codification and evaluation of all environmental impacts likely to arise from mining and minerals developed is now required in the form of detailed, independent Environmental Impact Assessments by almost all 'developed' and increasing numbers of 'developing' countries before the authorities will grant a licence to proceed. Some of the issues requiring detailed analysis and at least outline ameliorative or mitigation procedures are set out in the following sections.

Location and access. The location of the mine and its ancillaries is usually fixed by the nature of the deposit, though sometimes the mining plan can be modified to take account of particular features, a relatively common one being a feature of great historical or ethnic significance. The locations of the processing plants, intermediate and final product storages, and waste-rock dumps have to be studied with great care, taking account of the historical factors noted above, the restoration/revegetation plan which should be established in outline in the early planning stages, and the minimization of dust-blow from storage piles and conveyors. The areas selected for the deposition of waste rock must not encourage contamination of local streams by run-off nor hinder the restoration plan. The type and location of tailing areas will also justify a major study for all of the above reasons and additional ones, such as dump stability (particularly in seismic areas), rainfall run-off during storms, and dust-blows if high winds occur during arid seasons. The development of suitable and safe access routes to service the mine during both the construction and operational phases is always of vital importance from both the operational and aesthetic standpoints. All of the above factors become of enhanced importance if the operation is located near to significant residential areas or to areas of unusual scientific or ecological value.

Dust-blow. Total elimination of dust arising from blasting, transportation, handling, and storage is impracticable, particularly if the mine is located in an arid area subject to windy conditions. Neither is it practicable to eliminate completely all human activity from the areas generating and emitting dust. Thus many types of amelioration have to be applied, and these include: (1) dampening all areas of dust generation to the maximum practicable extent; (2) paving haul roads at the earliest practicable time, prior to which some chemical treatment or dressing with waste oil are useful temporarily; (3) providing respiratory protection for all exposed workers and ensuring its use; (4) providing mobile equipment operators with a supply of adequately filtered air; (5) ensuring that residential, office, school, and hospital areas are located as far away as possible in areas of minimum dust exposure; (6) covering permanently dumps, conveyors, *etc.* wherever practicable.

Processing operations, particularly crushing and conveying, require specific attention to the design of dust capture and arrestment systems to reduce in-plant dust levels to the relevant standard.

Mine safety. Physical safety standards are always a prime consideration in the design and construction of both open-pit and underground mines and, in most countries, are supervised by a specialist Safety Inspectorate. As in other areas, occupational health standards are correctly being tightened in the light of new information on the effects on health of exposure to contaminants encountered in non-ferrous mining generally; such exposures also include noise and vibration. In general terms, compliance represents a rather small additional cost and, somewhat paradoxically, infractions seem to receive less attention from groups external to the industry, than do environmental issues.

Erosion of Waste-rock Dumps. Unlike the chemical and metallurgical processing industries, mines have to be located where economic mineralization naturally occurs. Since large tonnages of extracted low-value materials have to be transported for upgrading, concentration plant associated with the mine also has to be located nearby. Extraction operations naturally break up the terrain and hence increase greatly the surface area of material exposed to rainfall which, in many parts of the world, falls as intense storms of relatively short duration, giving a high risk of flash flooding.

In these circumstances, 'wash-out' from waste-rock piles is inevitable. Fortunately, by definition, waste-rock contains low concentrations only of the desired elements, which are often relatively toxic, but the clays and silts eroded can cause local streams to become opalescent due to the high burden of suspended solids. Ameliorative measures of general applicability do not exist, though occasionally it is possible to channel run-off streams via the tailings impoundment. Fortunately, a corollary of 'spatey' rainfall is that there are often periods of several months of relatively dry weather when erosion is small and stream discoloration is much less marked. Practical problems arise only where streams subject to serious erosion are used for cattle watering. In these circumstances, provision of alternative supplies of water suitable for the purpose should be provided by the mine operators. This is usually not a particularly onerous requirement since the area of influence of even large, open-pit mining operations is usually quite small and clean supplies can be obtained by the provision of relatively small local impoundments either collecting rainfall or storing the water required for the operations of the milling and processing areas.

Run-off problems can be more serious where sulfidic (pyritic) deposits are being worked or where high-sulfur coal is being extracted. Acid is generated by oxidation reactions:

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4$$
$$4FeSO_4 + 2H_2SO_4 + O_2 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O$$
$$Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4$$

Many methods have been proposed for dealing with acidic run-off, including deep injection, neutralization with lime, and dilution. None are of general applicability; such treatments can only be applied where run-off follows well-defined channels, and, in any case, neutralization is both expensive and difficult to operate effectively. Reliance usually has to be placed on the natural absorptive powers of local streams and the ameliorative measures outlined in the preceding paragraph.

In assessing the impact of, and ameliorative measures for, acid generation the following factors would usually require analysis in the Environmental Impact Assessment: (1) location of waste-rock and tailings disposal areas; (2) contribution of each source to the total generated, *e.g.* waste-rock, tailings, mine, processing, *etc.*; (3) practicability of collection by interceptor drains followed by sedimentation, neutralization, *etc.* together with a disposal policy for the solids produced; (4) environmental effects and significance of a no-treatment policy.

Liquid Effluents from Milling. Milling is the comminution of the extracted ore into particles which can be subjected to a recovery process which separates the valuable materials (concentrate) from the valueless (gangue). The term is now usually used to cover the flotation process (or a chemical treatment process in the cases of alumina production from bauxite; gold; and uranium) which is now an essential part of all non-ferrous mining operations.

After primary and secondary crushing and screening, milling operations start with grinding in a multiplicity of ball and rod mills. After classification, the ground material passes to the flotation units where a variety of reagents may be used, depending on the chemical composition, density, *etc.* of the mineral being concentrated.

Froth flotation, by far the most widely used concentration method, is based on conferring hydrophobicity to the individual particles and hence assisting their attachment to air bubbles. Particles with higher mineral content then rise to the surface of a froth which is skimmed. The remaining barren particles become

Table 2 Flotation Reagents

Class	*Use*	*Compound*
(1) Collectors	To selectively coat particles with a water-repellent surface attractive to air bubbles	Water-soluble polar hydrocarbons, such as fatty acids, xanthates
(2) Modifiers		
(a) pH regulators	To change pH to promote flotation; either acidic or basic	NaOH, CaO, Na_2CO_3, H_2SO_4, H_2SO_3
(b) Activators and depressants	To selectively modify flotation response of minerals present in combination	Metallic ions, lime, sodium silicate, starch, tannin, phosphates
(3) Frothers	To act as flotation medium	Pine oil, propylene glycol, aliphatic alcohols, cresylic acid
(4) Oils	To modify froth and act as collectors	Kerosene, fuel oils, coal-tar oils

tailings. The flotation reagents used tend to be specific for particular processes. Some general examples are shown in Table 2.

Leaching is the concentration method favoured in some operations, sometimes in conjunction with flotation. The largest-scale example is the separation of alumina from bauxite by the Bayer process in which caustic soda is used to dissolve out the hydrated aluminium oxide; others are the use of sulfuric acid to acid-leach uranium oxide and some copper oxide ores, and the use of sodium cyanide in the extraction of gold.

By passage through a multiplicity of cyclones and thickeners, the end-product of the milling or leaching process is the concentrate of the desired metal or metals, together with a slurry containing the discarded process water, unwanted gangue, and the reagents, frothers, collectors, *etc.* added during the flotation stage. This slurry then passes to the tailings impoundment area, sometimes after chemical treatment, immediately after the flotation section to remove (by oxidation) organic reagents having high oxygen demand, and any cyanides which may be present. Overflow water from the thickeners *etc.*, is recycled back to process wherever possible.

Liquid Effluents from the Tailings Area. In most non-ferrous mining operations, tailings management is a subject of major environmental importance and it requires acceptable solutions to the following issues:

(1) *What is the optimum site for tailings disposal?* In addition to engineering, environmental, and aesthetic acceptability, the site must not infringe areas of historical or ethnic interest and value; nor must it affect the livelihoods of local inhabitants.

(2) *Dam stability and the method of design and construction*, including safe systems for handling exceptional rainfall during heavy storms.
(3) *Tailings stability in seismic areas.*
(4) *Purity of supernatant or run-off water and its disposal route either to recycle or to adjacent streams.*
(5) *The management of any adverse effects which supernatant water may have on adjacent streams and groundwater.*
(6) *The revegetation of tailings areas* to minimize windage losses and to improve aesthetic appearance.

Tailings are inhomogeneous, differing substantially in different non-ferrous mining operations in relation to particle size [slimes (< 200 mesh sieve) to sand(> 200 mesh sieve) ratio], specific gravity, physical characteristics, including abrasiveness, chemical composition, and pH.

The two first parameters influence strongly the flow, settlement, and—in seismic areas—liquefaction characteristics; the chemical aspects naturally have a major influence on the levels of toxicity of the tailings water and treatment methods to minimize its effects on receiving streams or other bodies of water. The details of tailings disposal systems are thus necessarily highly site-specific; the following general outline requires modification and interpretation to suit the details of particular operations in specific locations.

Tailings Disposal—Method and Location. Usually, in mining operations overall, the method and location for tailings disposal has alternative courses of action so that the 'best practicable environmental option' can be selected.

Unlike waste-rock, tailings can be transported as aqueous slurries, either being pumped or moving under the action of gravity through pipes or culverts. Settlement characteristics can be calculated with good accuracy and this is clearly very important for the avoidance of blockages and breakdowns in operation, as is the determination of the degree of abrasiveness on materials of construction likely to be encountered. Slurry transportation often provides a range of options for the economic disposal of tailings which is usually not available for waste rock disposal.

Some such choices which may become practical alternatives are:

(1) *Narrow, deep valleys* versus *disposal in shallow valleys or plain-land*
Narrow, deep valleys are usually easier to dam and do not disturb agricultural land, although they may obliterate ecologically valuable areas of tropical jungle, *etc*. They are usually visually unobtrusive, partly because they are exposed to the vision of few people. On the other hand, such valley locations are often relatively elevated, thus increasing pumping costs and often increasing hazard in seismic areas if tailings liquefaction ever caused break-out; land at lower elevations is usually more valuable agriculturally.

(2) *Location to minimize adverse environmental impact on adjacent streams, surface waters, and groundwaters*
For streams and surface waters, the choice of the best practicable environmental option (BPEO) involves weighing and balancing factors such as the degree of treatment (and its cost) required for tailings water disposal into a particular stream *versus* discharging the untreated tailings

into a more distant but environmentally and commercially unimportant stream.

Although now generally out of favour with regulatory authorities, tailings disposal to sea can be a preferred choice in cases where pumping and pipeline costs are not prohibitive. In general, deep outfalls to sea can utilize its enormous absorptive capacity for ions and, usually, the area of serious disturbance to benthic organisms is relatively small. BPEO studies should be made to assist choice between the various options on the basis of both detailed scientific baseline data of all relevant ecological aspects and economics. Although less visually apparent, any adverse effects on groundwater supplies and purity may be very important indeed. Consequently, BPEO studies, based on Environmental Impact Assessments, must include hydrogeologic assessment of seepage flows, *etc.* for the tailings impoundment area, including the dam, as well as the extraction site.

(3) *Location for safety*
The failure of a tailings dam could have disastrous consequences to both human beings and other activities located nearby. Although the design parameters for tailings dams are now well-developed and incorporate safety factors to accommodate predicted frequencies of earthquake and storm, it remains prudent to locate tailings impoundments away from people and human activity as far as possible. This is another clear benefit for sea disposal where it can be done acceptably from the environmental and regulatory standpoints.

Purity of Supernatant Water and Effects on Adjacent Streams. At most mine sites water is expensive and recycling of tailings effluent is practised wherever possible. At open-pit operations in arid areas, recycled water is frequently used to spray haul roads, broken rock prior to shovelling, *etc.* with the object of suppressing dust to the maximum extent possible.

As noted earlier, the aqueous component of tailings slurry from the mill usually contains very low concentrations of surface-active frothers and collectors and, where acid conditions are present in the flotation circuits, relatively high levels of cations such as iron, manganese, cadmium, mercury, copper, lead, and zinc in specific circumstances. Problems in the tailings area can also be found where pyritic deposits are being worked due to the development of acidity by oxidation in presence of water. When the impoundment is in active use it is usually saturated with water and air access is limited; but when the pond level falls, conditions for rapid development of acidity are present, perhaps posing serious problems with pyritic deposits after operations have formally ceased. Bacterial oxidation with *Thiobacillus ferrooxidans* is thought to be a dominant factor in the development of acidity from sulfur-containing tailings.

If cyanide has been used in the extraction circuit, as in most gold concentration processes, it may be necessary specifically to convert it to relatively innocuous cyanate by oxidation immediately upon leaving the flotation circuits.

It is clearly impractical in this short review to provide worldwide purity criteria for tailings effluent but attention has to be focused on the obvious parameters such as heavy metals (including arsenic) on chloride, sulfate, occasionally fluoride, and, increasingly, nitrate, on suspended solids, and on pH, together with the flow characteristics and uses of the receiving bodies of water. Dependence is usually placed on utilizing the dilution and absorptive powers of the receiving bodies of water. Conventional treatment, *e.g.* liming to precipitate heavy metals, pH adjustment, *etc.* is used where it is necessary to preserve existing uses of the receiving body.

However, in view of the very large volumes of water involved in most tailings operations, particularly where recycling of supernatant is not practised, sludges, *etc.* from treatment processes, usually have to be disposed of separately in small impervious impoundments; this is often not a preferred environmental option compared with dilution into streams as it creates a toxic 'hot-spot' which may be difficult to manage after general operations have ceased. Whatever disposal option is selected, adequate monitoring should be practised to ensure that any significant changes in the quality of the receiving body are quickly detected and assessed.

Revegetation of Tailings Areas and Waste-rock Deposits. During the operating life of the mine, the deposited tailings are normally largely covered by the supernatant mill effluent, leaving only the beaches exposed. This is important for minimizing wind erosion which can become a serious problem where prolonged dry seasons are encountered. At 'close out' or cessation of active operations, it is now becoming usual for regulations to require some permanent system for the management of tailings and waste-rock areas so that they are not a health hazard to either human beings or animals; windage nuisance is minimized, and continued contamination of water courses does not occur. Improvement of aesthetics should also be a significant objective—flat sandy areas can be visually very obtrusive in wooded or mountainous terrain.

Where tailings contain major proportions of slimes, the eventual total 'drying-out' process can be very prolonged and can be accelerated by transpiration from suitable tree plantations. When tailings areas have adequately dried it is often possible to establish vegetation on this barren and hostile substrate using techniques which have developed rapidly over the last 10–15 years. Control of pH by heavy liming is usually a first essential, followed by application of the plant nutrients nitrogen and phosphorus. Grasses, *etc.* indigenous to the area, are often the most promising candidates for successful vegetation. Once a limited natural humus cover has been established, legumes can also be incorporated. Where tailings or waste-rock is highly pyritic, revegetation is much more difficult due to the generation of acid noted earlier, but progress is being made. Of course, all such areas can be top-soiled before re-seeding, but such a procedure is usually inordinately expensive.

Planning for the Avoidance and Mitigation of Disasters. All extraction and processing operations require detailed emergency plans designed to mitigate the effects of major accidents on both the operating personnel and near-neighbours. Both open-pit and underground operations must implement fully all regulatory or professional requirements in relation to physical mine safety.

For neighbourhood protection, close and continuing attention must be paid to the stability of waste piles and tailings areas, particularly dams and retaining walls for tailings disposal areas. All practicable steps must be taken to remove stormwater at an adequate rate and seismic risk must be taken fully into consideration. In the location of tailings areas every effort must be made to choose a location with the minimum possible risk to downstream populations.

Explosives are usually stored in buildings of approved construction and location but it is also vitally important that fuels and chemical reagents are also stored in secure, professionally designed, and bonded (diked) units with written procedures fully implemented for safe loading and discharging from the stores.

Detailed, written emergency plans, including specific responsibilities for identified personnel, must be available and rehearsed thoroughly at regular intervals, normally twice annually.

Site Closure, Remediation, and Restoration. Progressive mine managements support those increasing number of administrations where Impact Assessments require outline closure and remediation plans, usually to be updated as extraction proceeds.

Fundamental to the issue is the optimum location of tailings and waste-rock disposal areas from the standpoint of minimizing environmental impact both during the lifetime of the mine and in the post-closure period. Disposal back into the worked-out pit or underground will generally be impracticable—though some regulatory authorities appear to be thinking in these terms—and so options for the pit itself are restricted to making it secure from trespass with the second option of encouraging or discouraging organized visitors through tourism, depending on the ultimate use of the closed-down operations.

Depending on the weather and hydrology of the area, it may be possible to allow the pit to fill with water, provided it is acceptable for recreational or fishing purposes and does not contaminate local surface or groundwaters. The minerals extraction industries have now developed many leisure complexes, thus providing community value from completed operations.

It is important to store and preserve local topsoil in a biologically active state so that it can be used as a final cover for the waste-rock and tailings areas as they become filled. Such areas will need to be assessed for shaping or 'sculpting' after use. Techniques for improving the aesthetic appearance of such areas by revegetation have made considerable progress in recent years and should always be attempted. Successive managements of UK coal mines and some extraction operations have demonstrated that, with careful planning and management, operational areas can be restored to effective agricultural use. Even if only a low level of vegetation can be persuaded to thrive, this is usually appealing visually and is an important factor in reducing dust-blow, particularly from tailings areas.

Unless a positive decision has been made to develop the worked-out mine as a tourist or educational attraction, the processing buildings, foundations, and contained equipment will have to be dismantled carefully and either sold or disposed of in an environmentally acceptable manner. The inevitable contamination of the plant areas with heavy metals and/or chemical reagents will have to be assessed by specialists and remediated according to their recommendations. A much larger issue, both physically and in terms of ultimate responsibility, concerns the disposal of the 'mining towns', some quite substantial, which have developed, with more or less company participation, near to most significant mining operations. It is outside the scope of this review to do other than note these restoration issues but they are major in scope and not always the subject of clear regulations, particularly as most mines pre-date the requirements of modern Environmental Impact Assessments.

Both public expectation and the professionalism of modern mine managers and operators force the positive conclusion that the local areas of dereliction and the continuing contamination of streams and rivers historically associated with the extraction industries are quite unacceptable today. Whilst the scale of major non-ferrous mining is such that some locally adverse environmental impacts are inevitable during active operations, these can be controlled by active foresight and planning to acceptable levels *for the lifetime of a mining operation*, typically 20–40 years. Techniques actively developed during the last 10–15 years offer considerable promise that long-term dereliction and contamination of river systems can be reduced substantially in the future.

4 Smelting, Refining, and Recycling—Regulatory Developments

Compared with extraction, a larger proportion of these phases of the non-ferrous metals production and use cycle is located in 'developed' countries such as the USA, Europe, Japan, Australia, and the former Soviet Union (FSU). The environmental issues are generally similar to those encountered in the chemical process industries and similar environmental management and control regimes are applied.

In recent years legislative criteria have developed worldwide on the basis of those provided by 'Best Available Technology' (BAT), sometimes, as in the United Kingdom, modified by economic and managerial factors to 'Best Available Technique Not Entailing Excessive Cost' (BATNEEC).

By way of illustration, the UK Environmental Protection Act, 1990, incorporates several new philosophies. Taken together, these will provide a comprehensive system for the control of all process emissions to the external environment to levels which have a rational basis and are as low as can be achieved when modern plants are efficiently operated and maintained. BATNEEC was first embodied in European Community Legislation to control sulfur dioxide emissions and will probably be the basis for future controls promulgated by the European Community. It is also likely to be required as the basis of future projects worldwide supported by international funding agencies such as the World Bank.

The Act will apply the principle of Integrated Pollution Control (IPC) to all processes judged to be of major polluting potential by HMIP (Her Majesty's Inspectorate of Pollution) in the UK. Integrated Pollution Control requires all wastes and emissions to be reduced to the practicable minimum by the use of BATNEEC. Such wastes and emissions as cannot be avoided will be disposed of, as far as possible, using the route causing minimum adverse environmental impact. This will be chosen after considering all options through BPEO studies. It is important to note the use of the word 'Technique' rather than 'Technology' in the UK definition of BATNEEC. 'Technique' includes design and all relevant managerial systems in addition to the technology of the process and its ancillaries.

These principles will be implemented, separately or together, by other regulatory agencies in the UK including the National Rivers Authority (NRA), which is responsible for regulating river quality and estuarial discharges; the Water Services Companies, having responsibility for regulating discharges to sewers; the Local Authority Environmental Health Departments, which deal with the relatively lower polluting-potential operations not regulated by HMIP; and the Local Authority Waste Disposal Units which handle the large tonnages of solid wastes, mainly domestic, which requires permanent disposal in secure landfills or by incineration.

The UK Government has announced that its future plans include the formation of an integrated Environmental Protection Agency from the main Agencies mentioned above to implement the Act and to avoid overlapping responsibilities wherever possible.

The main implications of BATNEEC for the non-ferrous metals smelting and refining operations—and to the major process industries generally—are: (1) the use of Best Available Technology (Technique in the UK) in new plants and the fixed emission criteria which its use implies; (2) the need to submit and obtain authorizations from the relevant Inspectorate. These may be regarded as licences to operate; they will be in the public domain; and will be reviewed regularly, probably at intervals of 3 to 4 years; (3) the upgrading of existing plants to meet current environmental criteria on a more extended timescale, typically 5–7 years; (4) performance monitoring and publication of results.

For the determination of Best Practicable Environmental Option the Inspectorate may require information on matters such as: (1) the process and its relationship with the locality; (2) all emissions leaving the site and the disposal routes that they take; (3) operational data; (4) monitoring information; (5) anticipated effects of significant emissions.

5 Treatment Technologies—Options to Meet Tighter Regulatory Criteria

As noted earlier, the smelting, refining, metal application, and the fabricating/engineering sectors of industry generate significantly different emissions in both type and volume, discharged to a range of media in many different parts of the world.

The metal concentrates produced by the extraction industries for smelting usually contain significant amounts of iron and minor, often toxic, impurities, which consequently have limited markets. For impurities such as cadmium, arsenic, and lead, these markets are reducing further as environmental and health concerns give rise to restrictive legislation and regulatory criteria. Tonnages are considerable, either as by-products from the basic process or arising from the purification of liquid effluents and emissions to atmosphere.

Pyrometallurgical smelters produce siliceous slags in the furnaces which are central to their operation; such slags encapsulate impurities in a form which leaches very slowly and is generally acceptable in well-designed landfills or other disposal areas. On the other hand, hydrometallurgical plants produce the greater part of their solid by-products and wastes in the form of chemical precipitates which are relatively pure and often leachable at a rate dependent upon their chemical and physical properties. Where such materials cannot be sold into the ever-declining markets for them, their ultimate disposal must be to well-designed sealed landfills which require long-term management to ensure environmental security and acceptability.

Lime treatment of liquid effluents produces considerable volumes of material in which metal values are very low. In some processes this material can be recycled for its lime value but, if this is impracticable, disposal to sealed pits is also necessary. Increasingly, 'polishing', using more sophisticated separation techniques, will be necessary to meet tighter criteria.

Platers, anodizers, engineering plants, tanneries, and other operations whose effluents contain non-ferrous metals will also be required to purify them to higher standards prior to discharge into sewer or river. In addition to reducing oxygen demand and adjusting pH, it is likely that processes based on electrolysis, ion-exchange, and reverse osmosis will increasingly be required.

6 Costs

The prolonged recession in developed countries world-wide has caused both industrial managements and some Governmental agencies to appreciate clearly the onerous cost implications of much of the environmental legislation formulated in the prosperous years preceding the recession.

Political slogans such as 'Pollution Prevention Pays', 'Cost–Benefit Analysis', and the 'Polluter Pays Principle' have been shown to be either spurious or of limited applicability. OFWAT, the regulator of the Water Industry in England and Wales, has preceded most other regulators in recognizing that only the consumer can, in the end, pay for the amelioration of pollution, whether it is generated by industry or by the consumption and other activities of consumers. Cost–benefit analysis is applicable to only a few issues and certainly not to the Global questions which are so important in current environmental thinking. 'Pollution Prevention Pays' in a few cases where economic recycling is practicable or where significant process efficiency improvements can be made. In general, however, it has to be recognized that environmental improvement has to be justified on a quality of life and resource basis.

My judgement is that there is no going back on the commitment to use BAT or BATNEEC to produce environmentally acceptable products from modern mines and plants which are designed, operated, and maintained to the best professional standards. Economics may require some delay in the time-scale to achieve BAT but there must be no change in the commitment to achieve the standards it requires.