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Mineral Sector Technologies: Policy Implications for Developing Countries

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FOREWORD

Much has been written about the causes of the unaccustomed economic uncertainty and instability that permeates the world today. Deep down, no single reason adequately explains what is driving these developments. However, one factor overshadows all else, and is setting the current period apart from all others: unprecedented and continual technological change. This development has thrust upon us a number of unresolved issues. Chief among them is the development of entirely new materials with changed and vastly enhanced new properties to reduce cost, improve strength, add flexibility, and alter where production takes place. "Old materials", like copper, tin, aluminum, even steel are increasingly faced with new competition and, some say, the loss of future markets.

It should thus come as no surprise that the notion has spread that the mining sector has become a "sunset industry", which has clung to old-fashioned exploitative practices and outmoded production processes with significant environmental implications. All this has contributed to a situation where governments have taken over in one way or another much of mining production activity in a wide range of developing countries.

Ironically enough, it is these very factors that have jolted the mining sector to become a much more dynamic contributor to development. The attached paper describes the fairly fundamental technological changes that have swept the sector, which has permitted mining companies to operate profitably in a much more competitive environment. Particularly telling is the fact that in today's economy, it becomes often times more profitable to invest in technological upgrading rather than invest in new mines. Moreover, to be a player in international and, increasingly, local markets, successful mining companies must apply the latest technologies to significantly reduce their production costs, thereby assuring themselves a place in the market for sustained medium-term development. As a result, we have witnessed over the last five years or so the putting into production in Australia, the U.S., Canada, ore bodies that in the past would have been considered marginal while high-grade deposits in Africa have remained largely untouched.

Countries that have not availed themselves of the opportunities afforded by a revitalized mining sector have thus denied themselves the potential for generation of major surpluses with which to finance their development programs. Three recent papers have shed light from different angles on this situation: "Mining Development in Sub-Saharan African Investment and Its Relationship to the Enabling Environment" (Division Note No.3), "Strategy for African Mining" (Division Note No. 12), and "Conditions for Exploration and Mining Development" (Division Note No. 18). The attached paper was published originally in the United Nations Journal, Natural Resource Forum of August 1992, and summarizes the introduction of advanced technologies and their policy ramifications for improved partnership between private industry and host countries.

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Mineral sector technologies: policy implications for developing countries

Over the past 20 years the mining industry has been a leader in the conception and application of advanced technologies. New thinking about earth tectonics as well as advances in geophysics, geochemistry, remote sensing, data processing and communications permit more effective and accurate geological exploration. Mechanization, more durable materials and more powerful explosives, as well as computer aided mine design and management have led to substantial gains in productivity. Minerals processing has similarly seen significant technological advances including solvent extraction, electro-winning of metal ores, bath smelting techniques, cyanide leach to produce gold, and bioleaching of sulphide and refractory ores. New technologies have dramatically improved mine health and safety as well as making possible control of water and air pollution. Improved communication and transport have stimulated competition and fostered the internationalization of mineral commodity prices. As these technologies are essentially market driven, developing countries should continue current efforts towards economic liberalization. Promoting investment in mining entails lifting many of the restrictions and taxes that can hinder efficient exploration and development. We examine some developments that have greatly increased the efficiency of exploration, mining and marketing. To obtain maximum benefit from many of these technologies requires governments to adopt a wide range of new policies which are examined in some detail.

Conventional wisdom would have us believe that the mining sector is devoid of technological innovation. It is not difficult to understand how this impression can be formed: the industry is viewed as dirty, environmentally destructive and based on nineteenth century technologies. Contrary to common perception, the world's mining industry has, in fact, undergone and, in many instances pioneered, dramatic technological innovations over recent years. Those innovations make finding mineral resources easier, extracting them more efficient, processing them environmentally less destructive, and marketing them more cost effective. An excellent example of the application of these technologies is in the US copper industry. In the early 1980's this industry was faced with historically low copper prices, antiquated plant and equipment, copper mine grades much lower than competitors, and restrictive labour contracts and practices. With considerable effort and much pain the industry restructured and invested in new technologies such as solvent extraction electro-winning. Today, the US copper industry is a competitive cost producer.

Developing country governments (including the Eastern European bloc countries and republics) seeking to develop their mining sectors face the challenge of putting into place the policies and economic incentives that will allow the best use of these new technologies. If they fail to do so, the competitive position of existing operations or contemplated new developments could be in jeopardy. This article will review a few of the recent developments in mineral exploration, extraction, processing, environmental, transport and marketing technologies. It will suggest some policy implications that should be taken into account by developing country governments to best foster and make use of those developments.
Exploration technology

Technology has yet to develop a replacement for the intrepid exploration geologist making his way through inhospitable environments, painstakingly mapping, collecting samples and noting geological observations. But, in the past 20 years technology has developed theories that have helped orient the search, provided tools to detect better the presence of mineralization, and provided time saving devices that allow improved analysis of data. Together those tools provide a cost-effective means for the geologist to cover previously unexplored or under explored areas.

Steady progress has been made over the past century in understanding ore-forming environments and their relationship to the Earth’s history. The theory of plate tectonics holds that the Earth was once composed of two super continents which over the course of hundreds of millions of years have coalesced into the continental configuration that we know today. The zones of contact between colliding plates and sub-plates are regions of heat flow normally associated with the accumulation of mineral deposits. There is evidence to suggest that the Appalachian mountain region of the eastern USA may once have been joined to Mauritania/Morocco, Florida to Senegal, Australia to India, and South America to Africa. For instance, certain rock formations in Brazil dating from the ancient Archaen era are known to contain numerous gold deposits and interpretation of plate tectonics gives rise to the hope that gold could be found in rocks of similar age in West Africa. Armed with such interpretive models, the geologist of today seeks to find viable mineral deposits. In this task he is aided by new exploration technologies as well.

Perhaps the most significant technological development of the past 10 years is the automated processing of geostatistics. The volume of scientific measurements and observations collected by the modern geologist would simply overwhelm human analytical capabilities if it were not for computers. These devices are used to process geostatistics to identify anomalies and to plot the results on maps. The interpretation of various types of data helps to orient a drilling campaign or to ‘model’ the mineral occurrence.

Importantly, rapid advances in memory capacity, miniaturization and interpretive software have put this technology well within the reach of the limited budgets of geological survey departments in developing countries as well as small and medium-sized mining companies. A personal computer, with 40 megabytes of memory, equipped with geostatistical software, such as Techbase, is capable of handling the data generated by 20 geologists in an exploration programme. The total investment for such equipment, based on U.S. retail price, would be around US$5000 per unit.

Significant advances in geochemistry and geophysics have increased both the accuracy and range of data used by the geologist to interpret the geological environment. The use of atomic absorption analysis, and more recently inductively coupled plasma analysis (ICP), permits rapid and inexpensive assaying for the presence of elements and mineral compounds. In a regional geochemical survey, for instance, soil samples are taken by junior geologists or field technicians on a predetermined grid. The samples are sent to a laboratory, sometimes on-site, prepared and inserted into a high temperature plasma arc. Elements in the sample emit light signatures which are analysed in a spectrometer for as many as 40 selected elements. The entire process takes seconds and allows the geologist to identify anomalous element concentrations which may indicate the presence of mineralization. A related and recently developed technique known as BLEG — bulk leachable extractable gold — is widely used in Australia and increasingly in other areas. The BLEG technique takes large samples (10-20 kg instead of 1-2 kg) which are then leached with sodium cyanide to extract gold. This technique is especially useful to identify low anomalous gold values where the gold may be difficult to detect by other methods.

Many developing countries are located in tropical zones which are covered by thick
lateritic soils that effectively mask the underlying geology. Geophysics can aid the geologist in penetrating this cover to observe the units and structural fabric of the geology underneath. Airborne or ground-based geophysics surveys which test the magnetic, electric and radiometric properties of the host rocks help the geologist find deposits for which surface evidence may be lacking. The interpretation of all such geophysical data is now aided by high speed data processing programmes which produce maps that enable the geologist to recognize the faults, folds and structural patterns of the underlying geology.

Geophysics has been of particular significance in Canada, the USA and Australia, where significant base and precious metals deposits have been discovered using geophysical methods. Although many areas in developing countries have been flown in the past using airborne geophysical methods, the poor quality of some of the data and its non-digitized format have hindered re-interpretation.

Recent developments in satellite technology and remote sensing have resulted in improved resolution not only of the visible spectrum but also of the invisible spectrum, such as infrared. Radar technology is currently available which allows the penetration of cloud cover and, to a more limited extent, the vegetation and soil cover. The French 'Spot' satellites have the ability to obtain high resolution images in 'stereo pairs' which enables the preparation of topographic base maps, of special significance in developing countries where such maps may be lacking or inaccurate. Satellites also make possible global positioning and improved communications. By using portable satellite trackers it is now possible for the geologist in the field to determine the exact longitude, latitude and elevation of a deposit. Satellite communications allow the transmission of data by voice, telex or telecopy from inaccessible areas without tying into the (often unreliable) local telecommunications system, achieving savings in time as well as cost.

**Extraction technologies**

Once the geologist finds and delineates an ore body it falls to the mining engineers and other specialists to extract the ore in the most cost-efficient manner. Advances in equipment capacities, automation and continuous movement machinery, maintenance programmes, explosives and computer assisted mine design and management have dramatically increased the efficiency of mining operations. Two statistics speak to the point: in 1960 one US miner produced 2458 tons of coal per annum; today that same miner produces 8000 tons/year. Between 1976 and 1987, the annual percentage growth in output per hour for US copper miners averaged 8.6%, higher than any other industrial classification except the manufacture of semiconductors. Faced with depressed global markets for mineral commodities, producers have lowered production costs by rationalizing the mining process, investing in new technology and applying modern mine management methods.

Mechanization and automation of the extraction process has perhaps been the single most important advance in mining during the last 30 years. The equipment in use today shows vast improvements in capacity, as is shown by the comparison of the capacity of 1960 and 1990 mining equipment in Table 1.

<table>
<thead>
<tr>
<th>Table 1. The capacity of mining equipment in 1960 and 1990</th>
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<tr>
<td><strong>Haul truck, capacity tonnes</strong></td>
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<tr>
<td><strong>Shovels, dipper size, tons</strong></td>
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<tr>
<td><strong>Front end loaders, capacity, m³</strong></td>
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<td><strong>Generators, capacity, MW</strong></td>
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It is important to note that increased capacity is the result of cooperative efforts between mine equipment manufacturers and their mineral-producing clients. For instance,
rubber tires developed in recent years allow haul trucks to carry heavier loads at higher speeds; electric motors now deliver greater power to drag lines than the diesel motors used previously.

The increased capacity of machinery has dramatically reduced the ‘cycle’ time required for the equipment to perform its assigned task. The ultimate in reducing cycle times is the development of continuous movement mining machinery. The bucketwheel excavators used in large open cast coal mines are the best examples of this development. Depending on the ore-body and mining conditions, a modern bucketwheel excavator can remove as much waste and ore material in one hour as a drag line can in an entire shift. In underground coals mines, long wall mining techniques shear a metre wide web of coal along a 300-1000 metre coal face, advancing automatically with the aid of remote sensors. Seemingly small advances in technology have made this advance possible. For instance, the development of high tensile strength carbide steels in the last 15 years has made the ‘teeth’ of the bucketwheel excavator as well as the long wall machine more durable and able to penetrate harder rock. Another example of continuous movement machinery is the conveyor belt. Advances in rubber technology now make possible not only higher capacity loads but also curved belts that follows the contours of the pit, as opposed to the previous practice of placing individual belts at right angles to one another in order to turn corners. The belts last longer and can be molded to wrap around the material being transported thus decreasing spillage.

The reliability of mining machinery has improved because scheduled preventive maintenance is now a standard practice in most mining operations. Instead of fixing the machine when broken, a dragline, for instance, is taken out of service one shift out of 21 for preventative maintenance. Of special significance in this respect are software programmes as well as sensing devices built into the machine which help the maintenance staff at the mine keep track of servicing requirements of the equipment.

Improved explosives, in terms of power as well as safety, allow larger chunks of ore-bearing and waste material to be loosened from the area being mined. The standard explosive used in open cast mining is a mixture of ammonium nitrate, a common fertilizer, and fuel oil — ANFO. In recent years high energy emulsions have been added to the ANFO to increase blast efficiency. The increased power allows greater spacing of blast holes with resulting savings in both operational and capital cost. Careful placing of the charges allow ‘cast’ or ‘throw’ blasting where the waste material is thrown directly into storage areas allowing the machinery to extract less waste material.

Another significant extraction advance is the use of computer assisted mine design and management. Software is commonly used to calculate the cost/price relationship of excavating material given assumptions on ore grade and mining conditions. Data collected during the drilling operations are used by the computer to design the optimum configuration of the open pit or the shafts and drifts of an underground mine. During operations the computer is used to keep equipment moving on an optimum schedule and to manage human resources, inventory, and accounting, among many other functions.

In situ leach is an extraction technology that involves injecting chemical solutions into ore bearing strate in situ. The pregnant liquor is then pumped to the surface for further treatment. One of the most common applications of in situ leaching is the Frasch process for extracting sulphur. It is used principally along the Gulf coast of the USA. Steam is injected into the sulphur domes deep underground. The molten sulphur is then pumped to the surface and dehumidified into a saleable product. The application of in situ leach to metal ores is infinitely more complex. Finding the right lixiviant that will dissolve the metal while at the same time causing no environmental damage can be difficult. Cyanide in situ leach for gold ores can release highly toxic substances into the groundwater table. Other chemicals may not have the same dangers, but a single chemical is rarely
sufficient for effective *in situ* leaching. Oxygen and other reagents must be injected which complicate the process. More important, there is little control over the process itself: temperatures, concentrations of the chemicals used and other technical specifications are difficult to monitor or control accurately. While the *in situ* leach process has found some applications, it is still years away from widespread use, especially for extraction of metals. Nonetheless, the advantages it promises are as significant as they are obvious. Digging and extracting mineral substances and waste materials from the earth is expensive. Reducing this cost could greatly enhance efficiency and represent a significant competitive advantage for the mine company that perfects the *in situ* technique.

**Processing technologies**

It is difficult to generalize about processing technologies because they vary by mineral commodity. For certain commodities, such as base and precious metals, there have been significant developments in processing technologies over the past 20 years. For other minerals such as iron ore and industrial minerals, technological innovation in terms of processing has been less pronounced. Nonetheless, there are several technological advances of special importance to the processing of mineral ore.

One of the most significant innovations is the solvent extraction electro-winning (SX-EW) of copper and other metals. This process was pioneered in a developing country (Zambia) and has since been applied in well over 40 mines worldwide. Ironically, none of the subsequent applications has been in a developing country (except Chile) even though there is significant potential for increased production. In the late 1960s and early 1970s what was then (and still is) the world’s largest solvent extraction plant was build at the Nchanga copper workings in Zambia. At the time, only pilot and bench scale tests on the solvent extraction process has been conducted; the Nchanga plant was built on a scale several orders of magnitude larger than anything that had been attempted. The plant significantly increased the production of copper from ores that otherwise would have remained untreated and it remains today the cheapest copper produced in Zambia.

Solvent extraction is used to process low grade ores and/or the material left after the high grade ores have been processed by conventional flotation techniques. Rather than send such material to the tailings dump where its copper content would be lost, the ores are leached in vats containing sulphuric acid. The resulting leach solution contains approximately 2 grammes/litre of copper which is up-graded by solvent extraction through the addition of organic chemicals (which are completely recycled) to render a copper concentrate solution of approximately 30 grammes/litre. An electrical current (electro-winning) is then passed through the high grade solution and 99.99% pure copper is deposited on cathodes.

The advantage of this process is that, at least in the case of Zambia, it makes use of sulphuric acid produced on-site as a by-product of smelting operations and of relatively cheap electricity available through the national grid. Significantly, solvent extracted electrolytically 'cathode' copper has become a benchmark grade of copper, currently comprising some 11% of copper traded on the international metal exchanges. It is a product that is saleable directly; a classic example of attaining greater value added through processing in-country. While solvent extraction finds its most common application in copper processing it can also be used on a more limited scale for other metals such as zinc, nickel and platinum.

A relatively new technology that opens exciting possibilities for small to medium-sized mines in developing countries is bath smelting. This process, developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, involves placing ore concentrates or residues into a vessel which is heated to produce a melt. A specially designed 'lance' injects fluxes (limestone), air or oxygen, an energy source (coal or fuel oil), and other reagents
into the melt. Waste slag is continuously removed and the resulting metal can be poured directly into moulds to produce metal ingots. The process has significant advantages for developing countries. It can be used in smaller mines, which do not have sufficient production to justify the construction of an expensive smelter. Higher value added can be achieved by avoiding the need to ship concentrates to a smelter/refinery outside the country. The technology is also relatively simple to use and the machinery has been designed so as to reduce maintenance and repair.

Large tonnage column flotation, developed in Canada and the USA 20 years ago, has only recently been introduced in developing countries. As the name implies, in flotation valuable minerals are separated from waste as they rise to the surface piggyback on air bubbles injected into the vat or flotation cell. The ‘froth’ at the top is then washed to remove the mineral from the waste material. The resulting concentrate is smelted to produce metal. The innovation of the last 20 years has been to increase the volume of concentrates treated in the flotation cell to achieve greater throughput. For instance, in 1960 the typical size of a copper flotation cell was 100 ft³; by 1990 the size had increased to 1000 ft³. Column flotation is used extensively in the African copperbelt, for instance, but larger cells have yet to be installed.

Cyanide leach for gold is a standard practice in many countries and has been in widespread use since the early 1920s. In contrast to earlier gravimetric techniques which only recover large (visible) particles of gold, cyanide leach is used to recover very fine or ‘invisible’ gold grading as low as 1 gramme/tonne. Cyanide leach is often done in vats where the pulverized material is put into a cyanide solution which dissolves the gold which then attaches itself to charcoal granules added to the solution. The gold is then stripped from the charcoal and subsequently electrolysed to produce a gold dore of around 85% pure gold. A variation of cyanide leach is ‘heap leach’. In this process ore-bearing material is configured in piles and then ‘sprinkled’ with cyanide solution. The pregnant liquor is then processed with charcoal and electrolysed to produce a gold dore. The great advantage of the cyanide leach process is that it permits the economic extraction of gold from ore bodies that are too low in grade to be treated by gravimetric of physical means. The technology is relatively simply and local workers can be trained to run the processing plants. The cyanide solution is re-circulated in the plant and closely monitored to prevent any escape into the environment.

A principal challenge facing metallurgists today is the economic treatment of refractory ores where the gold is bound together with sulphide or pyrite. Before cyanide leach can be used on such ores they must be oxidized. Three techniques are presently available or in an advanced experimental stage: pressure oxidation, whole ore roasting and bio-leach.

The first process, pressure oxidation, involves placing sulphide ores in solution into an autoclave or closed vessel, injecting oxygen and maintaining the vessel at high temperature. The gold molecules are liberated as the sulphide matrix breaks down and then leached with cyanide in the conventional manner. A problem involved with this technique as far as developing countries are concerned is that vast quantities of oxygen are required. Many gold deposits in developing countries are too far away from existing oxygen production facilities or are too small to justify installing such facilities. The cost of importing bottled oxygen in the quantities required is prohibitive.

Another method of treating sulphide ore is whole ore roasting. This process uses fluidized bed furnaces to heat the pulverized ore to liberate the gold from the sulphide matrix. Depending on the ore type, it is often possible to achieve autogenous oxidation, that is the sulphur or carbon in the ore itself is used as the energy source, dramatically reducing the amount of energy required.

New developments in bio-leaching technology hold promise for mineral processing in the developing countries, but those are only now being proven commercially.
on a large scale. Naturally occurring bacteria, when injected into tanks containing pulverized ore, ‘eat’ the sulphide material and this liberate the desired minerals. The resulting concentrates are then processed in the normal way. The great advantage of bio-leach is that it can eliminate the need to ‘roast’ ores thereby avoiding the problem of sulphur dioxide emissions. However, bio-leach still must overcome significant disadvantages. The ‘bugs’ are very temperamental. Precise balances of volume, humidity, temperature and throughput must be maintained at all times, or the bacterial cease to multiply. The process also takes considerable time and thus requires substantial investment in facilities in order to achieve desired throughput. Nonetheless, considerable research is being conducted on the process and over the course of the next few years more production scale facilities may be built.

**Environmental protection technologies**

There can be no doubt that production of minerals and metals is essential to modern civilization; there is equally no doubt that the process of extracting and processing them can be destructive to the environment. The world community has become acutely aware of the effects that mining can have on the environment as well as the risks that it can pose for the health and safety of mine workers and populations located nearby. The last 20 years have witnessed significant technology advances which make possible an attenuation of these environmental effects and assure safe mine practices.

According to many observers, one of the principal challenges for the mining industry is to control acid mine drainage. Opening holes in the Earth’s surface exposes sulphide materials to oxygen and water creating acids that dissolve harmful metals and trace elements. The problem is very pronounced in some coal mining regions where over time the sulphur content of coal has been leached producing acids which pollute ground and surface waters. Tailings left over from the milling process, waste rock and, in some cases, low grade metal ores stockpiled on the surface cal also be a problem. A recently developed technology, pioneered by the US Bureau of Mines, achieves proper pH balance in waste material through the addition of bacteria to retard and control the acid formation process. Additional measures such as covering the stockpiled material with an impermeable layer of clay and vegetation hinders the percolation of water through the waste and precludes the formation of acid. Permanent water cover is another effective control measure of inhibiting oxygen contact. Under-water disposal of reactive wastes as in backfilled flooded underground mines or ponded surface areas has been shown to reduce acid generation to negligible levels. When leaching of materials has already concurred, the acid solutions can be passed through 'bogs' where natural, chemical and bacteria action strips harmful trace elements and neutralizes the acid. For the past 20 years significant technical progress has been made in the reclamation of mined out areas, particularly of open cast mines. Certain coal mines, for instance, can 'backfill' mined out areas progressively as the coal seams are extracted. Many surface mines, however, cannot be economically backfilled because waste and treated material would have to be handled a second time. Technology and improved use of equipment has allowed substantial reductions of cost associated with reclamation but, it is nonetheless very expensive. It is estimated that approximately 2-5% of the value of coal produced by open cast methods in the USA must be reserved for reclamation.

Disposal of hazardous wastes is an issue of concern at the mine site. At a mine, oils and greases drained from heavy machinery are normally re-cycled, used for dust suppression on dirt roadways, or burned as fuel. Chemicals, solvents, paints insecticides and other substances used in the laboratory or other mine activities must be disposed of properly. At most mines shipping containers
for toxic reagents, such as cyanide, are burned. This is especially important in developing countries where such containers could be scavenged by the local population.

Until recently, only the largest mines or industrial plants could afford the installation of sophisticated monitoring devices to warn of the build up of noxious gases. Today, these devices have come down in cost to the point where they are standard equipment in most mines, replacing the legendary canary which accompanied the miners of old. Monitoring possible leakage of chemicals from the tailings dam or plant used to be a laborious process of taking samples and sending them to a central laboratory for analysis. Today, sensing instruments can immediately detect minute quantities of these toxic substances allowing mine managers time to remedy the situation.

Protective equipment and clothing, now designed to protect against specific chemical risks, has become more widely used as its cost has come down. However, training of the workforce in safe operating procedures is essential if those technologies are to work to best effect. It has been shown that lost time accidents (defined as a worker missing his next shift after an injury in a work related accident) decreases dramatically after a mine safety programme has operated for several months. Men working with heavy machinery in rapidly changing circumstances will always be hazardous. But with proper training and equipment, management procedures, and constant vigilance, work related accidents at the mine site can be reduced to acceptable levels.

**Transport and marketing technologies**

The mining industry has pioneered the development and optimization of bulk transport technologies to deliver mineral product to customers at the lowest possible cost. For instance, the carrying capacity of trains servicing coal mines has increased significantly, a result of more powerful locomotives, the use of lightweight aluminum to build railcars, and more efficient manning and personnel management. Experiments are being conducted in underground mines to 'pre-package' loads of mineral product (coal, for example) in standardized containers, to bring these to the surface using magnetic levitation, and put them directly onto railcars. Air hoisting of coal as well as other mineral ores through pressurized systems is also under experimentation in the USA, South Africa and Russia. Pipelines, in use since the 1970s, have proved an exceptionally cost-efficient method to transport iron ore and copper concentrates in slurry from inland locations to seaports. The size of bulk carrier ships has increased eightfold since the 1960s and port facilities have benefited from improvements in technology, notably continuous loading machinery. Increased carrying capacity of these transport and loading systems has allowed mining companies to achieve greater economies of scale and lower the unit cost of delivering mineral products to customers.

A significant technological development in the marketing of mineral commodities has been the improvement of communications and the availability of commercial data on market trends, prices and competition. Instantaneous communications enhances the role of major commodity exchanges, principally in London, but also in other major trading centers such as New York, Hong Kong and Tokyo. As late as the mid-1960s the price of copper, for instance, was set by a few major US companies (the 'US producer price'). This is no longer the case: prices are now set internationally as the major exchanges respond to the daily (or even hourly) changes in the balance of supply and demand. Information on prices and market trends is open and available to both governments and companies. The effect has been to increase competition amongst producer companies and countries, forcing them to compete on the basis of low cost production and customer satisfaction.
Policy implications for governments

It is recognized that the mining industry can generate substantial export and tax earnings, lead to the transfer of technologies, help create industrial infrastructure and stimulate development. Many developing countries have therefore given new priority to attracting private sector investment to mineral development and have put into place clear investment policies, transparent procedures and competitive fiscal regimes. It cannot be emphasized too strongly that mining technology is driven by free market competition and, to a lesser but very important extent, environmental imperatives. Benefiting from these new technologies depends in large measure on the continuance of the trend towards investment liberalization and the priority given to the mining sector by government policy-makers. The following comments suggest some specific measures that governments may put into place in order to make the best use of new development in technology.

In terms of exploration, a priority of both individual governments as well as international aid agencies should be to endow the agencies responsible for the sector, generally the national geological survey and the mines department, with the financial, technical and human resources necessary to conduct their activities efficiently. With few exceptions, developing countries lack the basic geological maps and data necessary to attract private investment. The objective of the geological survey should be to collect such data and to disseminate it to local and foreign entities to help them orient their own exploration work. Regional geophysical, geochemical and topographical reconnaissance surveys are indicated rather than expensive drilling and testing campaigns on mineral occurrences. The mines department, responsible for supervising activities in the sector, should establish consistent and easily followed procedures so as to issue exploration permits rapidly. Too often, local and foreign investors are discouraged by the time and effort required to obtain such permits. It is essential that the permit provides security of tenure and that the fiscal and legal regimes be clearly spelled out from the beginning of the exploration work.

Coordination among various ministries involved in establishing mineral policy must be improved to ensure that all relevant government agencies participate in the formulation of policy and are responsive to the operational requirements of the sector. For instance, even though the earth sciences hold few secrets of national security importance, the ministry of defence often blocks or delays the release of information (such as aerial photographs) or actually forbids exploration in border areas (as in the case in some Latin American countries). The state telecommunications monopoly often levies very high charges for communications services which are a significant cost to the exploration budget. Restrictions on sending geological samples outside the country can limit the use of advanced assay techniques. Burdensome import licensing and authorization procedures delay the timely arrival of goods and services critical to the exploration programme. Developing countries typically derive a significant portion of government revenues from customs duties and other excise taxes. Reducing or eliminating such taxes represents a real sacrifice to the public treasury. In some countries the sum of these taxes and duties can represent 25-40\% of the exploration budget. Mineral exploration is a high risk business. Why burden an exploration programme with indirect taxes and levies when those funds could be more effectively spent on a mineral exploration programme that may in the long-run return far greater revenues to the public treasury?

Government policies in respect of extraction and processing technologies must enhance the operating cost savings these technologies now make possible. Contrary to the common perception, operating costs in developing countries are generally higher than industrialized countries because of logistics and infrastructure difficulties as well as the lower productivity of the mine workforce, especially in the early stages of development.
before proper training takes effect. If the mine is to compete successfully on world markets it must be allowed to employ the appropriate technologies to keep its operating costs low.

Herein lies a paradox for developing countries. The reductions of personnel achieved through the use of modern extraction and processing technologies may not at first seem desirable to a government for which creation of jobs is a priority. It is necessary, however, to recognize reality; the number of jobs created per unit of capital investment is lower for the typical mine than it is, say, for the typical textile mill, tourist complex or electronic assembly plant. Government policies should capitalize on the strengths of the industry (export earnings, taxes and royalties, technology transfers) rather than foster inefficient job creation. For instance, staffing and manning requirements dictated by the government policy can negate the cost savings possible with new high capacity machinery. Labor practices in respect of shift duration, job classification, multiple tasking etc. should be flexible. Often the labor statutes of developing countries are out of date and based on practices prevalent during the former colonial period. Similarly, safety and hygiene regulations may be based on mine operating codes of nineteenth century Europe, rather than on modern operating standards. Immigration procedures need to be flexible to allow entry of a limited number of expatriates to operate some of the complicated equipment and processes as well as to train local staff. Licenses for the import and transport of sophisticated equipment, spare parts, reagents and maintenance supplies should also be granted in a timely fashion. Duties and import taxes on such items should also be exempted as these typically add to the already high cost of equipment and supplies not manufactured locally. Finally, government vocational training schemes should co-ordinate closely with the mining industry to ensure that local manpower is trained in skills appropriate to the new technologies.

No issue currently generates as much attention in the industry as the damage caused to the environment by mine operations. Over the course of the next few years the mining industry, developing country governments and the international community will be challenged to come up with appropriate environmental policies and procedures. Logic and experience would indicate that environmental standards used in industrialized countries, which can add significantly to capital and operating costs, may not be directly applicable in developing countries. Furthermore, technologies exist which can attenuate the damage caused to the environment by mining but they require government policies that allow their efficient use. Two elements are of principal concern in this respect.

First, environmental policies should be realistically adapted to the needs of the country, the specifics of the project and the requirements of the industry. It may be possible to achieve 95% remediation at reasonable cost but achieving 99%, even if the technology is available, will raise the capital and operating cost of the project to the point where it may not compete on world markets. Nonetheless, in the absence of local legislation most major mining companies apply strict internal environmental policies on a uniform basis irrespective of jurisdiction and regularly monitor the compliance of their operating units.

Second, government policies and procedures with regard to the environment should be clear and expeditiously applied. Endless public hearings, voluminous impact statements and escalating demands for information can cause serious delays to mine development with serious financial consequences. The rules should explicitly state on what grounds the government may deny a mining permit and provide for the right of appeal and due process in the event of rejection. Potential mine investors are quite naturally concerned with the possibility of being denied a mining permit simply because government officials do not understand the intricacies of the remediation measures proposed. Because of this, substantial scope exists for internationally financed programmes to train developing country specialists in
environmental protection and remediation techniques as they apply to the mining industry.

Rail and port handling charges are a significant component of the cost of getting bulk minerals to market. Government policies should be designed to maximize the economies of scale made possible by the new transport technologies. Featherbedding levels of manning, imposition of out-of-date work rules, and insistence on dual usage (passenger and freight trains, for instance) are but three examples of government policies that can significantly increase the cost of transport operations. To the extent that the railway and port facilities are owned by the government, as is the case in many developing countries, user charges should reflect the real costs of operation plus long-term amortization. Inflating these charges as a surrogate for other taxes, as has happened until recently in certain countries (for example, Australia), simply renders the product less competitive on international markets. Governments, perhaps with the participation of international financial institutions, should consider building the infrastructure needed for mine operations as few mines can carry the capital cost of such facilities. However, because of the failure of some infrastructure development schemes in the past, it is in the interest of governments, industry and international financial institutions to evaluate very carefully such projects against strict economic criteria.

Large mining companies generally have sophisticated marketing networks and will insist on control over marketing of mineral products. This is entirely logical and proper because customer relationships are built up over the long term and reliability of supply is critical. On the other hand, governments have very real and legitimate concerns about transfer pricing and achieving the best possible price for their exported minerals. The instantaneous access to major commodity markets made possible by the new communications technologies helps to allay these concerns. Modern communications technology provides access to information on prices, homogenizes marketing commissions and charges, and increases competition among mineral producers. In the past, government 'marketing boards' were created as a mechanism to maximize revenues to the state but this practice has been a failure almost everywhere it has been attempted. Governments should rather establish precise contractual guidelines for mineral product marketing, require that sales contracts be on an 'arms length' basis, and verify prices against the quotations on the international exchanges. In today's world, communications and information processing technologies make guidelines and monitoring much more effective than direct government marketing of mineral products.

Conclusions

The article has reviewed several new developments in mineral resources technology. It has outlined some of the policy implications that those technologies have for developing countries and recommended certain courses of action to ensure that they are used to best effect. Experience would indicate that technological innovation flourishes best in an atmosphere of commercial challenge and entrepreneurship. For this reason international donor agencies should continue to advise developing countries that reliance on free market mechanisms is a better alternative than direct government intervention in the mining sector. Excessive control, burdensome reporting procedures and unlimited discretionary power in the hands of the government to grant or deny mining titles can be significant deterrents to the private investor and thus hinder the introduction of appropriate technologies.

Government departments charged with the supervision of the mining sector must better co-ordinate their activities and understand the public policy implications of the exploration, mining, processing and marketing technologies to be employed by investors. This presents an opportunity for donor agencies to be more vigorous in training developing country officials in the non-technical aspects of the mining industry.
Training in mineral economics, mining law, mine finance, minerals marketing and investment decision analysis are woefully inadequate in most developing countries. Specific courses should be devised in these disciplines to familiarize government officials with the terminology and concepts employed by the private investor. Training should also be provided to help officials understand that mining technologies provide the means to enable the national minerals industry to compete more effectively on world markets.

The mining industry, too, should become more vigorous in explaining its use of modern technologies to the developing countries. Local officials and staff cannot be expected to understand the need to control costs if they have not been advised of the competitive requirements of the industry. Training schemes need to be thorough and well directed to ensure maximum productivity and to promote the transfer of technology. Finally, the industry should be more active in making its views known to the international organizations where debate on environmental and other issues often takes place.

A new spirit of partnership between private industry and developing countries is beginning to make itself apparent. But, industry and government are still some way from comprehending the needs of each other. The challenge of the next decade will be to ensure that a proper dialogue takes place and that policies are implemented that allow the technological progress outlined in this article to benefit developing countries and private investors alike.
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