Mining and the Environment
Case Studies from the Americas

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CHAPTER 1

ENVIRONMENTAL REGULATION, INNOVATION, AND SUSTAINABLE DEVELOPMENT

Alyson Warhurst

More than two decades ago, the famous “Report to the Club of Rome: The Limits to Growth” (Meadows et al. 1972) predicted that the principal problem facing the world would be the depletion of nonrenewable resources, notably fossil fuels and metals. It was projected that tin, for example, would run out in 1987. However, that year saw an oversupply problem in tin markets, and several mines closed. Indeed, with technical change, recycling, and the discovery of new oil and mineral reserves, those predictions have proven to be false. The Meadows et al. report stimulated a lively debate. For example, the Science Policy Research Unit (United Kingdom) argued that institutional change and a change in the world research and development (R&D) system, and therefore in the rate and direction of technical change, could avert the predicted crisis (Cole et al. 1973; Freeman and Jahoda 1978).

In the last decade, the environmental debate has focused on the depletion and degradation of renewable resources, such as water and air. Consequently, the term sustainable development has been used to reflect a growing concern about the interaction between economic activity and the quality of the environment. The 1987 Brundtland Report, of the World Commission on Environment and Development, defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their

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own needs" (WCED 1987, p. 43). This implies that economic policy should encompass environmental conservation and that the goal of more equitable economic growth refers to both intergenerational and geographic equity (Jacobs 1991).

Leaders of the G7 (group of seven leading industrialized nations) adopted the principle of sustainable development at the Toronto Summit in 1988 (Jacobs 1990, p. 59), and the 1992 Earth Summit in Rio de Janeiro heralded a more global commitment to its aims. However, the widespread adoption of the principle by policymakers, academics, industrialists, and environmentalists has not yet led to a systematic effort to make it operational through measurable policy targets or policy mechanisms for implementation. Nonetheless, regulation is slowly moving in this direction.

Previous policy, guided by the polluter-pays principle, dealt mainly with the results of environmental mismanagement — pollution — and its treatment after it occurred. The new regulatory principle — pollution prevention pays — aims to promote competitive and environmentally sustainable industrial production. This paper argues that successful implementation of the pollution-prevention principle will require the introduction of new policy mechanisms designed to both stimulate technological innovation in firms and encourage the commercialization and diffusion of those innovations across the boundaries of firms and nations. This means that government efforts to promote and regulate industry, which have traditionally been separate efforts, will need to be combined (Warhurst 1994).

This paper analyzes the challenge to policymakers posed by pollution-prevention approaches to environmental management. It develops the concept of corporate environmental trajectories for evaluating the relationship between regulatory regime and competitiveness and the implications for sustainable development. It then discusses policy mechanisms that may be used to stimulate the development and diffusion of clean technology. (The term clean technology is used here to refer to industrial processes that incorporate current best practice into environmental management. The term is not intended literally; indeed, a more accurate term would be cleaner technology.) Case studies of mining operations around the world, drawn from the research of the Mining and Environment Research Network (MERN), are used to illustrate these arguments. (The term mining is used here to cover all aspects of metals production, including mine development, extraction, smelting, re-mining, and waste management.) The paper shows how policy guided by the pollution-prevention principle represents an advance over previous policies guided by the polluter-pays principle. However, the paper highlights two flaws in pollution-prevention regulatory approaches: first, the firms that pollute the most are mismanaging the environment precisely because of their inability to innovate;
second, the most efficient firms are generally better environmental managers because they are innovators and are able to harness both technological and organizational change to reduce the production and environmental costs of their operations. The paper concludes by suggesting a new policy principle: environmental innovation.

This analysis recognizes that mining is a highly heterogeneous activity and that winning metals requires the removal and processing of vast quantities of rock (Winters and Marshall 1991; Tilton 1992). Some pollution can clearly be prevented, and the inevitable by-products of mining can be treated, recovered, or recycled. Radical technological and organizational innovation can change the broader context of metals production and the resulting pollution.

Although improving the environmental management of the mining industry production is the primary focus of this paper, the author recognizes that this is only one objective of sustainable development. Policy also needs to address poverty, education, health and welfare, the agricultural sector, and rural development. Nonetheless, the analysis may have implications for other industries for which institutional change, technology transfer, and training are requirements for sustainable development.

The policy challenge of pollution prevention

To meet the pollution-prevention principle requirement that pollution be reduced at source, firms must either change their technology or reorganize their production process, or both. To accomplish this, firms may need to develop new technological and managerial capabilities, form technological alliances with equipment suppliers, and collaborate with R&D institutions, which may in turn require policy mechanisms not currently part of pollution-prevention thinking.

The reasons for this are rooted in the determinants of environmental-management practices in the firm. Indeed, MERN's research suggests that the environmental performance of a mining enterprise is more closely related to its innovative capacity than to the regulatory regime under which it operates (Lagos 1992; Acero 1993; Lin 1993; Loayza 1993; Warhurst 1994). Capacity to innovate is in turn related to the entrepreneurial characteristics of the firm's management; to the firm's access to capital, technological resources, and skills; and to the broader policy and economic environment in which the firm operates. This suggests that technical change that is stimulated by the environmental imperative reduces both production and environmental costs, to the advantage of those dynamic companies with the competence and resources to innovate. Such companies include mining enterprises in developing countries as well as transnational firms. However, the evidence is strongest for large, new investment projects and
greenfield sites. In older, ongoing operations, environmental performance correlates closely with production efficiency, and environmental degradation is greatest in operations working with obsolete technology, limited capital, and poor human-resource management. Developing the technological and managerial capabilities needed to bring about technical change in such organizations would clearly lead to more efficient use of energy and chemical reagents and to higher levels of metals recovery. Thus, improved production efficiency would result in improved overall environmental management, including better workplace health and safety.

International standards and stricter environmental regulations may pose no significant economic problems for new mineral projects, but major costs and challenges may be involved for older, inefficient operations. Controlling pollution problems in many of these cases requires costly add-on solutions: building wastewater treatment plants, strengthening and rebuilding tailings dams, investing in scrubbers and dust precipitators, etc. Furthermore, in the absence of technological and managerial capabilities, there is no guarantee that pollution-control equipment — environmental hardware — will be incorporated or operated effectively in the production process. Crandall (1983) found that a significant fraction of mandated pollution-control equipment was never even installed. In some instances, regulatory requirements are leading to shutdowns, delays, cancellations, and reduced competitiveness. When mines and facilities shut down, the cleanup costs are frequently transferred to the public sector, which, particularly in developing countries, has neither the resources nor the technical capacity to deal effectively with the resulting problems. In most countries (except perhaps the United States), the lack of retrospective regulation means that the pollutee-suffers-and-pays principle is alive and well and would continue under a pollution-prevention regime, unless, of course, the new policy fosters improved production efficiency and stimulates innovative capacity.

**Environmental Innovators**

Although some mining companies have resisted environmental regulation of their existing operations, a growing number of dynamic, innovative companies are making new investments in environmental management. This is partly because these firms see an evolution toward stricter environmental regulation and because pushing forward the environmental and technological frontiers is to their competitive advantage. Being free of investments sunk in pollutant-producing, obsolete technology or having significant resources for R&D and technology acquisition, these firms develop cleaner process alternatives or select new or improved technologies from mining-equipment suppliers (who are themselves busy innovating). New investment projects increasingly incorporate economic and environmental
efficiencies into the production process, not just through new plants or equipment but also through improved management and organizational practices. Some examples of dynamic environmental innovators are discussed below in three categories: smelter emissions, gold extraction, and waste management.

**Smelter emissions**

**INCO LTD** — At one time one of the world’s highest-cost nickel producers, Inco Ltd was until recently the greatest single point source of environmental pollution in North America. This was due to its aged and inefficient reverberatory-furnace smelter, which emitted excessive quantities of SO$_2$. Inco had done all it could to improve the efficiency of this obsolete technology through incremental technical change when the Ontario Ministry of Environment introduced an intensive SO$_2$-abatement program to control acid rain. These factors prompted Inco to invest more than $3 billion in a massive R&D and technological innovation program (Aitken, personal communication, 1990). Indeed, more than 12% of Inco’s capital spending during the 1980s and early 1990s was for environmental concerns (Coppel 1992). Under the Canadian acid-rain-control program, Inco was required to reduce SO$_2$ emissions from its Sudbury smelter complex from 685,000 t/year to 265,000 t/year by 1994, a 60% reduction. To achieve this reduction, Inco planned to spend $69 million to modernize its milling and concentrating operations and $425 million for smelter-SO$_2$ abatement. The modernization process included replacement of its reverberatory furnaces with innovative oxygen-flash smelters and the construction of a new sulfuric acid recovery plant and an additional oxygen plant. By incorporating two of the flash smelters, the company reduced emissions by more than 100,000 t in 1992, and by 1994 the firm expected to achieve the government target levels. Inco is now one of the world’s lowest-cost nickel producers (Warhurst and Bridge 1997). Furthermore, like other dynamic companies responding to environmental regulations through innovation, Inco seeks to recoup R&D costs by aggressively licencing its technology to firms in other copper- and nickel-processing countries.

**KENNECOTT CORPORATION (UTAH)** — Kennecott Corporation (RTZ Group) recently launched a new smelter project in Utah. The dual aim of the project is to set a new emissions standard for smelters worldwide and to improve cost efficiencies in the processing of its ore. Advantages include the capture of 99.9% of sulfur off-gases (previous levels were 93%). Sulfur dioxide emissions will be reduced to a new world-best-practice level of about 200 lb/h (1 lb = 0.454 kg),

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less than 5% of the 4 600 lb/h permitted under Utah’s clean-air plan. The investment of 880 million United States dollars (USD) resulted in 3 300 new construction jobs and the transfer of 480 million USD to local companies through project-development contracts. The proposed Garfield smelter will expand the copper-concentrate-processing capability to the level of mine output (about \(1 \times 10^6\) t of copper concentrate per annum) at about half the previous operating cost. It represents the first application of oxygen-flash technology in the conversion of copper matte to blister. (Details are from Kennecott Corporation [1992] and Emery [personal communication, 1992].) The two-step copper-smelting process starts with smelting furnaces, which separate the copper from iron and other impurities in a molten bath, followed by converting furnaces, which remove sulfur from the molten copper. A new technology, known as flash converting, will be used in the second step.

Kennecott developed this unique technology in cooperation with Outokumpu, a Finnish company and a leader in the supply of smelting technology. Essentially, the new technology eliminates open-air transfer of molten metals and substitutes a totally enclosed process. Flash converting has two basic effects: it allows for a larger capture of gases than the current open-air process; and it allows the smelter’s primary pollution-control device — the acid plant — to operate more efficiently.

The smelter will include double-contact acid-plant technology that will improve the capture of \(\text{SO}_2\) gases as acid. The new smelter will have other environmental benefits. An extensive recycling plan will reduce water usage by a factor of four. Pollution prevention, workplace safety and hygiene, and waste minimization will be incorporated in all aspects of the design. In addition, the smelter will generate 85% of its own electrical energy by using steam recovered from the furnace gases and emission-control equipment. This eliminates the need to burn additional fossil fuel for power. The new facility will require only 25% of the electrical power and natural gas now used per tonne of copper produced.

Gold extraction

HOMESTAKE’S MCLAUGHLIN GOLD MINE (CALIFORNIA) — Opened in 1988, Homestake’s McLaughlin gold mine is a good example of a mine and processing facility designed, constructed, and operated under the world’s strictest environmental regime (see Warhurst 1992c). Environmental efficiency is built into every aspect of the mining process. The McLaughlin site is notable for its innovative process-design criteria, its fail-safe tailings and waste-disposal systems, and its

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extensive, ongoing mine-rehabilitation and environmental-monitoring systems. The mining operation, with its myriad of innovative technologies, defines best practice in environmental management.

The most interesting conclusion drawn from site visits and discussions with the firm's environmental officers is that most of these environmental-management initiatives have resulted in no substantial extra cost; indeed, many have improved the efficiency of the mine and made the overall operation more economical. An extensive environmental-impact analysis was undertaken before the mining started. All plant and animal species were identified and relocated in readiness for site rehabilitation once the mining operations end. Air, soil, and water quality were measured in detail and water-flow patterns were determined to provide the baseline for future monitoring programs. Assaying was done not just of the gold ore but also of the different types of gangue material so that waste of different chemical compositions could be mined selectively and dumped in specific combinations to reduce acid mine drainage. Local climatic conditions were evaluated to determine the frequency of water spraying needed to reduce dust; evaporation rates were evaluated to assist in water conservation and to determine the flood-risk potentials of tailings ponds. The tailings ponds were constructed on specially layered, impermeable natural and artificial filters, with high banking to prevent overflow and with secondary impermeable collecting ponds for use in the rare case of flooding.

At many other mining projects, site rehabilitation is seen as a costly task to be undertaken at the end of a mining operation, but at the McLaughlin gold mine rehabilitation began immediately and is an ongoing activity. This not only spreads expenditure more evenly over the life of the mine but also allows more efficient use of truck and earth-moving capacity and of construction personnel. When waste piles reach a certain size, soil (overburden previously stripped from the mine area and stored) is laid down and revegetation begins. Although mining at McLaughlin had been under way for only 3 years at the time of writing, extensive areas of overburden and waste had already been successfully revegetated, immediately reducing environmental degradation and negative visual impacts. In addition to these in-built environmental controls, Homestake has sophisticated environmental monitoring in place. Seepages, emission irregularities, and wildlife and vegetation effects can be detected and rectified immediately, reducing the long-term risk of expensive shutdowns, costly court cases (for water toxicity, for example), and the need for treatment technologies.
Waste management

In the minerals industry, marginal-ore dumps, tailings, and the removal of overburden result in considerable quantities of waste rock (Gray 1993). Any toxicity associated with that waste is principally a direct result of the loss of expensive chemical reagents or of metal values. Public policy has not yet taken up the challenge of promoting R&D geared toward waste-toxicity reduction or wastetreatment innovations. One interesting area of research is the application of biotechnology to waste treatment (Warhurst 1991a).

The task of improving environmental-management practices within ongoing mining operations may not be adequately supported, however, if waste treatment is considered a third priority, below pollution prevention at source and recycling. (For an explanation of the federal approach to pollution prevention in the United States, see the chapter on pollution prevention in Environmental Quality: The 23rd Annual Report of the Council on Environmental Quality, Together with the President's Message to Congress [CEQ 1993].) This again suggests that pollution-prevention policy needs to focus on the environmental-innovation process, rather than strictly on pollution reduction at source.

The following two examples demonstrate how innovation can reduce pollution. The approach taken — the integration of waste management into the production process — does not always represent an add-on regulatory cost as perceived by conventional wisdom; indeed, there are competitive advantages, as well as environmental benefits, to using such a strategy.

**WATER TREATMENT AT HOMESTAKE'S MINE AT LEAD (SOUTH DAKOTA)** — Facing regulatory pressure to clean up a cyanide seepage problem, Homestake was able to turn the situation to its own advantage. Its R&D staff developed a proprietary biological technique for treating the effluent, which led to the recovery of local fisheries and water quality in the mine's vicinity at Lead, South Dakota (Whitlock and Crouch 1990). To recoup and profit from its investment in R&D, the company is now actively commercializing the technology, which could be widely applied at other gold-leaching plants.

**WATER TREATMENT AT EXXON'S MINE AT LOS BRONCES (CHILE)** — Exxon is expanding its mining project at Los Bronces, Chile, into one of the largest open-pit copper mines in the world. The expansion will result in the stripping off of very large quantities of overburden and in the creation of low-grade ore dumps. Before the mine was developed, the Chilean government warned Exxon that it would be imposing financial penalties for the water-treatment costs for the
expected acid mine drainage into the Mantaro River, the source of Santiago’s drinking water.

This warning became the economic justification for a bacterial-leaching project at the mine. A feasibility study showed how profitable it can be to leach copper from waste at the same time as preventing otherwise naturally occurring pollution (acid mine drainage). More than $1 \times 10^9$ t of waste and marginal ore below the 0.6% Cu cut-off grade is expected to be dumped during the project’s life span. The waste could have an average grade of 0.25% Cu and would therefore contain a lucrative $2.5 \times 10^6$ t of metal, worth about 3.5 billion USD at 1985 prices (Warhurst 1990). The study demonstrated that with a 25% recovery rate, high-quality cathode copper could be produced profitably at 0.39 USD/lb by recycling mine- and dump-drainage waters through the dumps over a 20-year period.

This was shown to have the double advantage of extracting extra copper and avoiding government charges for water treatment. Both investment and operating costs were less than two-thirds of estimated costs for a conventional water-treatment plant, which would not have generated saleable copper. The Los Bronces mine demonstrates the potential economical benefits of building environmental controls into a mine at its development.

These few examples suggest that dynamic companies are not closing down, reinvesting elsewhere, or exporting pollution to developing countries with less-restrictive regulatory regimes. Rather, these companies are adapting to environmental regulatory pressures by innovating, improving, and commercializing their environmental technology and environmental-management practices, at home and abroad.

**Trends in distributing environmental costs: from “pollutee suffers,” to “polluter pays,” to “pollution prevention pays”**

Environmental regulation is frequently seen as a way to distribute the environmental costs of industrial production. Its aim is to shift the cost burden of environmental mismanagement from the pollutee to the polluter.

According to conventional wisdom, two types of costs are incurred in industrial production (Tilton 1992): the internal costs of labour, capital, and material inputs, which the company pays; and the external costs of environmental damage, such as ecological degradation, water pollution, and air contamination, which the company does not pay. This analysis runs the danger of assuming that a fixed cost is associated with each increment of pollution and that the reduction of this cost burden to society will result in a corresponding incremental increase in the firm’s production costs. Tilton (1992) described this view clearly in his account of the
relationship between the marginal social benefits (MSB) and marginal social costs (MSC) of industrial production, with pollution as an externality (Figure 1). The argument rests on the assumption that the socially optimal use of an environmental resource occurs when the additional benefits (in terms of goods and services it derives by permitting one more unit of pollution) equal the additional costs it incurs. In economic terms, this is the point at which MSB = MSC. If all social costs and benefits of pollution are incurred or internalized by the producing firm, the firm will have an incentive to pollute only up to this optimal point ($P_o$). However, if the firm realizes all the benefits associated with pollution, but not the costs, it has an incentive to expand its production until the additional benefits from causing a further unit of pollution are equal to zero. Note that in this circumstance, pollution has reached $P_a$, which is far beyond the optimal point, $P_o$.

The cost burden of this falls on society. Indirectly the pollutee pays, although the state may absorb these costs to a degree. Furthermore, as consumers do not pay the full social costs of production, pollution-intensive goods are usually underpriced and, consequently, overproduced and overconsumed. It is then argued that this situation can lead to production inefficiencies because “free” environmental resources may be substituted for labour, equipment, and other inputs (for which the firm must pay). For example, a firm may engage in the excessive and damaging use of water resources, rather than incorporating a treatment and recycling

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**Figure 1.** The marginal social costs (MSC) and marginal social benefits (MSB) of pollution.  
plant for effluent. This in turn reduces the entrepreneurial capacity of the firm and, most importantly, acts as a disincentive to innovate. Such a sequence of events explains in part the decline of Bolivia's state mining company, Corporación Minera de Bolivia (Comibol), and its related mismanagement of the environment (Jordan and Warhurst 1992; Loayza 1993). However, central to this idea is the assumption of a fixed environmental cost, to be either externalized or internalized. This paper challenges this assumption, arguing that technological change can reduce the environmental costs of production.

**External environmental costs**

For policymakers, estimating the costs of natural-resource degradation associated with mineral exploitation is a complex task. The most significant problem is devising ways to share these costs among the polluter, state, and community. Such costs are high, particularly with old and ongoing operations.

In the past, environmental costs were largely measured in terms of remedial treatment of degraded water, investment in environmental-control technologies, or compensation for damage caused to local farmland by toxic dust. More recently, environmental costs have been estimated in terms of extensive rehabilitation of the former mine and plant site for alternative uses; such rehabilitation could include revegetation or the construction of leisure facilities (Kopp and Smith 1989). However, in developing countries, it has been argued, the mining industry has traditionally been structured to externalize such environmental costs so as to maximize profit — the industry appropriates undervalued resources and shifts the environmental costs to others, rather than improving efficiency and innovating.

When it comes to evaluating these costs, it should be remembered that those most affected by environmental pollution from mining in developing countries are generally those least able to understand and respond to it — remote miners' families or isolated rural communities. Responses are typically short term and nonsustainable. For example, when farmlands were ruined by pollution from the Karachipampa tin-volatilization plant in Bolivia, the peasants were offered small compensation payments covering only the loss of particular harvests, rather than the potential loss of their livelihoods. In contrast, in the United States, the fastest growing area of consultancy is in the assessment of liability for natural-resource damage — propelled by the Comprehensive Environmental Response, Compensation, and Liability Act and Superfund Amendment and Reauthorization Act, or “Superfund” laws, which apportion blame for environmental damage to any one of a mine's past owners and charge them with the cost of government contracts to clean up and rehabilitate the damaged site.
Inevitably, some environmental degradation results from mining. Although such pollution has a negative economic impact, it often presents unrealized economic opportunities — for firms, as well as for society. For example, toxic byproducts that could be economically reprocessed are frequently dumped instead. This is the case especially in developing countries, where inaccurate sampling or inefficient technologies result in such loss. Mining high-grade ore and dumping low-grade ore may be a short-term expediency for boosting foreign-exchange earnings in times of crisis, but it results in greater environmental degradation (higher risk of acid mine drainage from dumps) and the loss of long-term revenue. Water-treatment projects are often instigated at the time of mine closure, which is more costly than preventing acid mine drainage from the outset. Such pollution control could result in the recovery of metal values, through solvent-extraction or electrowinning techniques. Finally, some companies have had to pay the healthcare costs for communities that drink degraded water, which are in many cases greater that the cost of the technical change needed to treat the chemical effluent in the first place. Even if firms are forced to absorb some of the environmental costs of their operations in the long term, this does not necessarily translate into improved efficiency in the short term.

Considerable work is still needed to quantify the nature and extent of environmental degradation caused by metals production. Currently, only isolated case studies exist, and little systematic analysis of the problem has been undertaken. It is difficult to generalize because local geological, geographic, and climatic conditions affect mineral and ore chemistry, soil vulnerability, and drainage patterns and hence the extent of the environmental hazard. Furthermore, the degree of environmental hazard is affected by the social and economic organization of the production unit, including such factors as the firm's size, history, and ownership structure, as well as its propensity to innovate.

The polluter-pays principle and the internalization of environmental costs

A combination of political, economic, and environmental elements has given rise to the polluter-pays principle, which in essence requires polluting companies to internalize the external costs of environmental damage caused by their production of goods and services. Member countries of the Organisation for Economic Co-operation and Development have endorsed this principle for many years, and the 1992 deliberations of the United Nations Conference on Environment and Development (UNCED) heralded commitment to its application on a more global scale.

The norm for environmental regulations incorporating the polluter-pays principle is for governments to set maximum permissible discharge levels or minimum levels of acceptable environmental quality. Such command-and-control
mechanisms include Best Available Technology (BAT) standards (including Best Available Technology Not Entailing Excessive Costs standards), clean-water and clean-air acts, Superfund laws for determining cleanup and liability, and a range of site-specific permitting procedures, which tend to be the responsibility of local government within nationally approved regulatory regimes. Implementation and enforcement of command-and-control mechanisms tend to be the responsibility of administrative agencies and judicial systems. However, such polluter-pays regulations may not promote real reductions in environmental degradation or improve environmental management in metals production on a broad scale.

First, the polluter pays only if discovered and prosecuted. This requires technical skills and a sophisticated judicial system, often activated only after the pollution problem has become apparent and caused potentially irreversible damage. Moreover, in developing countries, serious economic and political constraints limit the implementation of environmental regulations and the penalization of polluters (Warhurst 1994). For these reasons, environmental regulations tend to address the symptoms of environmental mismanagement (pollution problems), rather than the causes (economic and technical constraints; lack of access to technology or information about better environmental-management practices). This neglect can be serious because for certain types of pollution, such as acid mine drainage, it is extremely costly and sometimes technically impossible to trace the cause and thus to rectify the problem and prevent its recurrence. Certain environmental controls may only work if incorporated into a project from the outset (such as buffer zones to protect against leaks under multitonnage leach pads and tailings ponds) or if combined with economic incentives.

Second, a plant may meet BAT standards at start-up without being able to achieve the specified effluent and emission levels throughout its life span. Technical problems may arise; cumulative production inefficiencies are not unusual; and the quality of concentrate or smelter feed may change if supply sources are changed. Moreover, the site-specific nature of mining operations has serious implications for monitoring, as technology has to be fine-tuned for each mineral deposit. It would also be erroneous for a regulatory authority to assume that standards are met simply because a preselected item of technology has been installed. Ongoing management and environmental practices at the plant are as important as technical hardware in achieving environmental best practice. Evidence from MERN research suggests that these problems are endemic to metals production in many developing countries (Núñez 1992; Hanai 1993; Loayza 1993; Warhurst 1994), where obsolete technology is widely used without modern environmental controls or safeguards. In the industrialized countries, new concentrators and roasting plants tend to be computerized. Automatic ore assaying and in-stream analysis
give an accurate picture of the chemical composition of the ore feed, information that is needed for fine-tuning the pressure, heat, cooling, and environmental-control systems and for accurately predicting and monitoring emissions. However, where these controls are missing and, in particular, where ore feeds are of variable composition (in terms of, for example, sulfur, lead, and arsenic content), the pollutant effects of emissions also vary. Furthermore, pollution increases with the inefficient or excessive use of fossil fuels, particularly by poorly lagged roasters, inefficiently operated flotation units, and energy-intensive smelters. It could, therefore, be argued that command-and-control regulatory instruments are unlikely to result in a reduction of pollution, as they do not alter the capacity of a debt-ridden and obsolete mining enterprise (especially in developing countries) to implement technical change. Such a firm might find it preferable to risk detection, pay a fine, or mask its emission levels than to face bankruptcy from investing in new technology while its capital is scarce.

Third, BAT standards and environmental regulations of the polluter-pays type tend to presume that technology is static — they’re based on a technology that was best at one time. Such regulations act as a disincentive for equipment suppliers, mining companies, and metal producers to innovate. Or perhaps they have innovated, but their innovations, which may have required substantial R&D resources, have been superseded by a regulatory authority’s decision about what constitutes BAT for their activity. Ashford and Heaton (1979) described instances where the use of environmental innovations that were superior to the specified BAT was discouraged because the regulators were unfamiliar with their design or operation.

Regulations obliging the polluter to pay tend to lead to end-of-pipe, add-on, or capital-intensive solutions (such as smelter scrubbers, water-treatment plants, and dust precipitators) for existing technology and work practices, rather than promoting alternative environmental-management systems and technological innovation. Moreover, if regulations are incremental, they may promote technical change that is also incremental, involving the addition of numerous new controls at greater cost and with more overall degradation than if a new, more radical change had been introduced in the first place (see Kemp and Soete 1990; Freeman 1992). Such regulations may also require specific reductions in pollution without regard to cost or local context. The regulations may refer to the chemical composition of an effluent in isolation, disregarding the site-specific precipitation, evaporation, or soil and geological conditions that affect the discharge rate and pattern.

Such regulations also result in a single-medium approach; consequently, firms may respond by shifting pollution from one medium to another (such as from emissions to effluent). An interesting example of this occurred at the Alcan
Lnd bauxite mine and alumina plant in Jamaica. Foreseeing impending envi-
ronmental regulations and responding to public concerns in its home country
(Canada), Alcan gave support to a local university to develop an innovative solu-
tion for the disposal of red-mud sludge from the bauxite mining operations.
Previously, the sludge had been dumped in a large catchment pond, but toxic
seepages into surrounding soils and groundwater were reported. The university
developed a process called red-mud stacking, which involves sun-drying to remove
much of the moisture from the sludge and stacking of the material in much less
obtrusive piles. However, this technology does not address the toxic seepage of
the previously dumped slurries. Nor does it offer a solution to pollution per se
because it replaces water pollution to a large extent with dust pollution, which is
less stringently regulated. Moreover, a change in the production process to facili-
tate the recovery of caustic soda from the “mined” dry-mud stacks means that
more of that chemical is discharged than with the previous method. The dust pol-
lution, plus overflows from those parts of the dry-mud stacks that become water-
logged during tropical rain showers, presents a greater toxic hazard than the
previous low-level seepages.

Also, industry may cooperate less with this regulatory approach because
the rules are continually changing and the costs of complying are increasing.
Finally, such regulations ignore the human-resource contribution to sound envi-
ronmental management because they emphasize a specific pollution-control tech-
nology (environmental hardware), rather than training, managerial approaches, and
information diffusion (environmental software).

TOWARD POLLUTION PREVENTION — Interest has been growing in the use of
market-based mechanisms whereby polluters are charged for destructive use based
on estimates of the damage caused. An important justification for market-based
incentives is that they give companies greater freedom to choose how best to
attain a given environmental standard (OECD 1991). Market-based incentives, by
remedying market failures or creating new markets, may permit more economi-
cally efficient solutions to environmental problems than government regulations
substituting for imperfectly functioning markets would. Two categories of
incentives exist (O’Connor 1991; Warhurst and MacDonnell 1992). One group,
based on prices, includes a variety of pollution taxes, emission charges, product
charges, and deposit-refund systems. For example, a mercury tax has been dis-
cussed in Brazil; a cyanide tax, in the United States. The other group of incen-
tives, based on quantity, includes tradable pollution rights or marketable pollution
permits. A related measure is the posting of bonds up front for the rehabilitation
of mines upon closure. This is now standard practice in Canada and Malaysia.
Few governments have designed systematic incentives for industry to innovate and develop new environmental technology. An approach such as this might change the very essence of environmental costs by no longer assuming they are fixed. Indeed, in two further areas, policy approaches may contribute to improved environmental-management practices. First, private, bilateral, and multilateral credit is frequently contingent upon the use of environmental-impact assessments and best-practice environmental-control technologies in new minerals projects. Requiring mandatory pollution-prevention plans as a condition for obtaining mine permits would be a complementary policy mechanism. A growing number of donor agencies — in Canada, Finland, Germany, and Japan, for example — are also emphasizing training in environmental management. Second, some governments are promoting R&D (jointly and within industry and academic institutions) to evaluate toxicity from mining pollution and develop cleanup solutions. For example, the Canadian government has funded R&D programs on abatement of acid mine drainage and SO$_2$ emissions. However, considerable scope remains for expanding these approaches, as argued below.

**Pollution prevention and the demise of the environmental trade-off**

The pollution-prevention principle differs from the polluter-pays principle because intrinsic to the notion of reducing pollution at source is a nonstatic vision of the environmental costs of production. The polluter-pays principle implies that firms internalize a fixed environmental cost. However, firms' pollution-prevention efforts demonstrate a diminishing intrinsic value of that environmental cost (not its shifting to others), and this leads to the demise of the environmental trade-off.

The US Environmental Protection Agency (EPA) is still defining pollution prevention in terms of internalized fixed environmental costs: “pollution prevention requires a cultural change — one which encourages more anticipation and internalizing of real environmental costs by those who may generate pollution” (Habicht 1992). Clarifying the concept of pollution prevention is important because it will inform the design and implementation of policy to achieve it.

The concept of corporate environmental trajectories (see Figure 2) illustrates the fundamentally different nature of technical change and therefore of the environmental costs of applying pollution prevention to metal-mining operations. Such trajectories describe the evolution of a firm’s competitiveness in response to both changing market conditions and regulatory requirements. Governments and, indeed, corporate strategists need such policy tools to predict the environmental practices and competitive behaviour of firms under various market conditions and regulatory regimes and to identify the warning signs of declining competitiveness, impending mine closures, and their environmental effects. For example, combined
regulatory and market pressures may prompt mine closure in advance of expected ore depletion. But in many countries a bankrupt firm is no longer responsible for its cleanup problem, so the burden frequently falls on the state, which has neither the resources nor the skills to deal with such a large-scale and complex problem. (See Warhurst and MacDonnell [1992] for a discussion of the case of Carnon Consolidated Ltd in the United Kingdom and numerous articles about the Summitville Mine Superfund site in Colorado.)

**Technical change and corporate environmental trajectories**

Characteristically, enterprises respond slowly to environmental pressures, and their responses predominantly reflect the regulatory regimes and public climate of their home countries. Their responses also depend on the nature of their operations in terms of

- The minerals;
- The level of integration of mining and processing;
- The stage in the investment and operations cycle; and
- The economic and technological dynamism of the firm (whether it has the financial, technical, and managerial capabilities to be an innovator).

After a period of using static technology, the mining and mineral-processing industry is currently going through a phase of technical change, with dynamic firms developing new smelting and leaching technologies in response to economic as well as environmental constraints. This trend is stimulated by rapidly evolving environmental-regulatory frameworks in the industrialized countries and the prospects of their application, reinforced by credit conditionality, in the developing countries. Changes in technological and environmental behaviour in this context are evident, particularly in the large North American and Australian mining firms, and are increasingly apparent in firms based in developing countries, such as Brazil, Chile, and Ghana. However, it seems that only new operators and dynamic private firms are changing their environmental behaviour; state-owned enterprises and small-scale mining groups in developing countries continue, with some exceptions, to face constraints on their capacity to change environmentally damaging practices.

Inevitably, only dynamic firms with new project-development plans are in a position to invest in R&D to develop more environmentally sound alternatives
or to raise the capital to acquire them from technology suppliers. After a long period of conservative and incremental technical change, firms are developing alternative processes for mineral production that are more economical and less environmentally hazardous. Furthermore, these firms are beginning to sell their technologies, preferring to commercialize their innovations to recoup their R&D costs than to sell obsolete technology and risk shareholders’ displeasure or retrospective penalties as developing countries start to enforce environmental regulations. Some mining firms have even pushed technology beyond what is required to meet existing regulations. These firms are seeking ways to increase regulation, particularly on a worldwide scale, because they can meet stricter standards and use their new environmentally sound technologies to competitive advantage.

The assumption that environmental regulation represents a cost burden to the firm is challenged by evidence that improved environmental management in mining operations need not be detrimental to economic performance and may in some cases even have economic benefits. This is intrinsic to the pollution-prevention-pays principle. Environmental regulations are here to stay, and they’re bound to become more widely adopted, more stringent, and better enforced. It follows, then, that a greater share of the metals market will be lost by those firms that avoid environmental controls (only later to be forced to internalize the high costs of having done so). This share will be won by firms that get ahead of the game, play a role in changing the industry’s production parameters, and use their innovative capabilities to improve their competitive advantage. Implementing lean-production practices is one example of this.

Much can be learned from the manufacturing sector about the development and success of lean production and related Japanese work methods, such as just-in-time inventory control, waste reduction throughout the system, total quality management, and statistical process control. Lean production is defined by a simple principle: eliminate all costs that do not add competitive value to a product. Secondary principles are reduce waste, minimize space, eliminate inventories, and integrate quality control into the production process. The implementation of lean production characteristically results in the reduction of managerial roles, with increased responsibility being given to engineers and workers and a concomitant increase in multitask activities (Womack et al. 1990). A study of more than 90 plants in 14 countries, representing half of the world’s automobile-assembly capacity (Womack et al. 1990; see also Graves 1991), showed that lean production, used principally by Japanese companies, has significantly improved productivity, quality, product development, and model range. The average European and North
American plants required 118 and 49%, respectively, more effort than the average Japanese plant to undertake the same manufacturing activities. Such efficiencies in Japanese plants have translated into both cheaper and better-value products, leading to the rapid growth and supremacy in Western markets of Japanese firms like Toyota, Nissan, Honda, and Mitsubishi.

The implications of applying lean-production principles to mining, or of radical process innovations with similar effects, can be expected to be remarkable. A combination of markedly lower investment and production costs and the halving of mine-development times and mine life spans would significantly affect the competitive structure of the industry and reduce negative environmental and social effects. Few mining companies have taken these ideas on board. Those that have considered alternative organizational methods include CRA Ltd (Australia), Homestake's McLaughlin gold mine (California), and Scuddles mine, of the Poseidon Group in Australia. Scuddles has implemented an innovative, multi-skilled approach to human-resource development at its underground mine in Western Australia (Mining Magazine 1991). Also important are management training and new work methods for engineers and miners. There is a clear relationship between good housekeeping at the plant site and environmental practices.

Figure 2 categorizes the environmental trajectories that different mining firms might take in response to environmental and market conditions. Companies and governments could use this diagram as a planning tool to evaluate the environmental and economic implications of different policies.

The average mining firm is competitive (that is, to the left of the threshold of economic competitiveness, $X$, in Figure 2). To a greater or lesser extent these firms produce environmental pollution, and to a greater or lesser extent they have internalized the cost of the environmental degradation associated with their metals production, in response to the regulatory regime they are working within. (The threshold of environmental competitiveness for a given regulatory context is also $X$, and company operations in compliance have environmental trajectories in the quadrants below the horizontal axis.) However, as a result of market pressures — mainly a real decline in metal prices — and their own economic inefficiencies, some of these firms are going bankrupt (on a trajectory toward quadrant B). They will leave a legacy of environmental pollution, and as happened with Comibol (in Bolivia) and Carnon (in the United Kingdom), the burden of cleanup will fall on the state and society. Other firms will respond by innovating (moving into quadrant D), building improved economic and environmental efficiencies into the new
Figure 2. Corporate environmental trajectories.
generation of technology. At the same time, these innovators are protecting themselves from having to undertake more costly add-on, incremental technical change and rehabilitation at later stages of their operation. Indeed, freed from the incumbent costs of retrofitting sunken investments, dynamic greenfield plants in particular can use the latest best-practice technology incorporating improved economic and environmental efficiencies.

Nonetheless, if obliged to add on environmental controls in line with new regulations, a growing group of firms would have to close down because the cost of the controls and cleanup would render their operations uneconomical. The environmental trajectory of this group is toward quadrant C. Currently, examples of this are scarce, and it is difficult to differentiate between purely environmental factors and other factors that may be causing a firm's cost curve to increase. However, as Figure 2 shows, that group can be expected to grow because combined market and regulatory pressures will lower the threshold of economic and environmental competitiveness to the extent that the average firm will survive in the new regime only if it innovates. Therefore, even previously dynamic firms will need to keep their environmental trajectories moving ahead of the encroaching threshold of economic and environmental competitiveness ($X_1$ and $X_2$).

These trajectories imply a serious constraint on the regulatory process for two reasons that distinguish mining firms from their manufacturing counterparts. First, if a mine closes down as a result of regulatory burden, its environmental degradation may continue. Pollution in metals production is not all end-of-pipe pollution, which stops when production ends. Rather, the closure of a mine heralds a new phase of environmental management — decommissioning, cleanup, and rehabilitation, all of which pose significant costs. Second, in most countries, the former operators of closed mines are not liable for the cleanup (the United States, with its Superfund liability laws, is an exception). Therefore, pushing forward the technological frontier and moving the threshold of economic and environmental competitiveness may result in an overall increase in environmental degradation (particularly where there is no liability).

The policy challenge that pollution-prevention advocates face is one of keeping firms sufficiently dynamic to reduce their pollution at source, to profitably clean up pollution that escapes, and in the meantime to generate increasing economic wealth. The policy challenge is therefore to promote environmental innovation. This means combining the regulation and promotion of industrial activity in an integrated policy.
Policy mechanisms to promote environmental innovation and stimulate diffusion of these innovations

A number of important policy implications follow if one accepts the argument that the environmental practices of firms correlate most closely with their innovative capacity and that regulations are only really effective if firms have the innovative capacity to respond and change their production processes and products, including waste products. Production inefficiency and environmental mismanagement go hand in hand.

Low rates of metals recovery, high-intensity use of energy, excessive use of reagents, and so on are symptomatic of production inefficiency and are also associated with pollution, such as metal particulates, SO$_2$ emissions, and toxic chemical effluent. The question of economies of scale in metals production further constrains the choice of technology for minimizing waste and maximizing metals recovery.

A major implication for pollution-prevention policy is that in tackling the most significant polluters, it must also target the most inefficient (this means targeting the least innovative). Such a strategy poses a potential problem for pollution prevention: promoting innovation is key to reducing pollution at source, but the firms generating the most pollution have insufficient technological and managerial capabilities or capital resources to innovate.

A corollary of this is that the most successful metals producers use reagents and energy efficiently and have high rates of metals recovery. They are constantly engineering incremental improvements to optimize these levels. Therefore, concentrating environmental policy on pollution prevention at source might fail to optimize the potential of dynamic companies to develop and diffuse innovations to reduce pollution at any point in the life cycle of the mine and its products.

Another problem stems from the huge volumes of rock involved in mineral extraction — although the percentage releases of toxins may be small, the scale of pollution can be great because of the sheer bulk of throughput (Gray 1993). Therefore, policy needs to have a dual focus: innovation to prevent pollution at source; and innovation to promote profitable waste treatment, reagent and metal recycling, and re-mining. The latter focus may require a different range of incentives (along with the removal of disincentives to re-mine and treat waste under regulatory regimes), such as the Resource Conservation and Recovery Act of the United States. Environmental innovation is the key to progress on both fronts. It recognizes the need to integrate environmental regulations and promotion of industrial activity.
Consequently, two policy options are available for achieving pollution prevention. First, punitive regulation can be used to put the inefficient and most serious polluters out of business. Second, a range of policy mechanisms and incentive schemes can be developed to promote production efficiency and innovation in environmental management, focusing on the entire metals-production process, from mine development to waste management.

Although the first option is superficially attractive, two problems arise from pursuing sustainable development in this manner. One is that for many economies (particularly developing ones), minerals production is a crucial source of foreign exchange, government revenue, and direct and indirect employment. Punitive regulations thus put development objectives at risk, which in turn threatens the economic part of the sustainable-development equation. The other problem is that this strategy threatens the environmental part of that equation by pressuring firms to move into the close-down, cleanup quadrant of the corporate environmental trajectory (C in Figure 2). As noted earlier, this is an unattractive option because the pollution problems associated with decommissioning and rehabilitating mining sites can be horrendous and often become a responsibility of the state. Several studies have shown that retrospective legislation, such as the Superfund in the United States, is an inefficient mechanism for achieving the optimal use of resources for environmental protection (Portney 1991; Acton et al. 1992; Probst and Portney 1992; Tilton 1992).

The policy challenge for pollution-prevention advocates (if their ultimate aim is sustainable development) is thus to keep the mining industry dynamic enough to reduce pollution at source, profitably treat waste, clean up pollution on closure, and generate economic wealth (using best practices in environmental management) throughout a mine’s life span. This paper argues that environmental legislation to support pollution-prevention goals must be underpinned by two further sets of policy mechanisms: mechanisms to promote environmental innovation; and mechanisms to stimulate the diffusion of these innovations among firms.

Although governments may only be explicitly concerned with the diffusion of innovation among firms within national boundaries, the commercialization of these innovations abroad can bring in revenue and improve the overall competitiveness of national mining firms and sectors. International organizations — including banks, donor agencies, and institutions concerned with implementing UNCED objectives — also need to consider policies to promote the international diffusion of clean technology.
This is not an argument against regulation but a recommendation for a more sophisticated approach to public policy. Such a policy would define the regulatory goals relating to both the production process and the output stream — that is, set something to aim at — and be underpinned by an informed technology policy to guide and stimulate industry along the fastest, most efficient route to those goals.

**Mechanisms to promote environmental innovation**

Policy mechanisms to promote environmental innovation in industry are of two types: expenditure programs to support clean-technology R&D, training in environmental engineering, and so on; and incentives to reward firms for environmental innovation.

**Expenditure programs**

Technology-policy mechanisms that support clean-technology development include expenditure programs funding R&D in selected areas of pollution prevention. Examples are Canada’s R&D programs in acid mine drainage and biotechnology to clean up effluent. Another example is cofunded R&D projects involving industry–industry, industry–university, or industry–research-institution collaboration. Such programs could be supported through easily accessible, centrally compiled information-dissemination programs concerned with moving technological and regulatory frontiers.

A crucial factor in targeting R&D support is the innovation process in industry. Too often, policy documents conceptualize innovation as something that builds on government or university R&D and then is magically applied throughout an industry’s operations. Such thinking is reflected to a certain degree by EPA’s aims in the area of technological innovation. Evidence suggests, however, that in most cases innovation is industry driven, with firms drawing on research institutions and other firms for the additional knowledge, expertise, and technology needed to complement their own in-house R&D and engineering efforts (Rothwell 1992; Warhurst 1994). An important function of technology policy to promote source-reduction innovation should be to inhibit a possible tendency of firms to divert resources from conventional business R&D to compliance-related R&D. Focusing R&D on process innovation and making pollution prevention at source part of the overall effort to improve efficiency can be complementary aims.

Promoting innovation in pollution-prevention technology requires important changes in thinking. A multimedia approach is required because pollution prevention requires changes in process technology, not the addition of off-the-shelf, end-of-pipe controls that tend to shift pollution from one medium to another. This
implies the need for a range of engineering skills to reduce or eliminate the pollutants at source (independently of where they may ultimately be discarded). New technology must be designed to deal with water and air quality and waste, as well as workers’ health and consumer-product safety. Thus, training for R&D engineers in industry should be another target of policy mechanisms.

EPA policy documents on pollution prevention fail to emphasize training. Technology hardware is only one part of the equation. Of equal importance is organizational change. Mechanisms that foster lean and clean production are also needed.

**Incentives**

Taxation policy may need to be changed to promote environmental innovation. According to Ashford (1991), the United States gives taxation incentives in the form of accelerated depreciation for pollution-control equipment, thus supporting end-of-pipe pollution control. However, no similar incentives apply to investments in new production technology, with the result that dollar for dollar a firm is better off buying from an environmental-technology vendor than developing its own process changes. Direct taxation incentives can relate to investment in pollution-prevention technological or organizational change; R&D; engineering projects and training in specific areas of environmental management; and bonds posted up front for future pollution prevention or for reclamation on closure. The impact that punitive taxation on reagent or energy use will have on firms’ competitiveness and behaviour requires careful consideration — the geological and chemical characteristics of each deposit are unique, and this affects energy- and reagent-consumption patterns. Operators may perceive such taxation as prejudicial and unfair.

Flexible taxation provisions that allow and even encourage industry to be innovative are needed to complement strict standards and regulatory goals. Regulators must possess an intimate knowledge of the types of gains firms make from technological change. With this knowledge, they will be able to determine how best to promote technological innovation and can adapt or ratchet regulations accordingly (Milliman and Prince 1989). Innovative firms should be able to use environmental regulations to their competitive advantage. The innovator would benefit from stricter technology-forcing regulations that stimulate other companies either to invest in new technology or to licence (or purchase) the innovator’s technology (thus enabling the innovator to recoup some of its initial investment in R&D). Regulatory authorities need to be seen to respond in this way. For the informed regulator, the rate of technological advance in pollution control is probably the most useful measure of the effectiveness of environmental policies, a view held by a growing number of researchers, including Orr (1976), Kneese
and Schultze (1978), and Milliman and Prince (1989). Training for regulators, including industrial experience as environmental engineers and corporate strategists, is thus an important part of the pollution-prevention approach.

Pushing the technological frontier forward will pull the thresholds of economic and environmental competitiveness deeper into quadrant D, as shown in Figure 2. Consequently, market conditions governing metals production will also change, to the innovator’s advantage.

An important corollary of an incentives-to-innovate policy is that regulators give rewards for innovation. Usually the reward is a prize for sound environmental management, such as EPA’s recent Environmental Leadership program to reward US innovators. However, regulators should make the reward side of the equation more sophisticated by analyzing the ways firms realize and expand commercial gains from technological innovation and technology diffusion.

Milliman and Prince (1989) analyzed five regulatory approaches: direct controls, emission subsidies, emission taxes, free marketable permits, and auctioned marketable permits. They found that direct controls, which are the most common regulatory tool, provide the least incentive for technological innovation; free permits and emission subsidies also provide little incentive. Emission taxes and auctioned permits are the best incentives because they reward the innovator through gains the firm makes from diffusing its technology to other firms, over and above the benefits the firm derives from its own application of the technology (Milliman and Prince 1989). This is not surprising, as polluters facing high costs for abatement will find it cheaper to buy permits than to reduce their emissions, and polluters with low abatement costs will sell their permits accordingly. Firms therefore have a constant incentive to cut emissions, as this allows them to sell permits. Tradable permits, unlike pollution charges, can guarantee the achievement of particular pollution targets because the authorities control the number of available permits.

Finally, on this issue, incentives are needed to stimulate auxiliary firms to develop and commercialize innovative clean-up technologies, including re-mining techniques. In developing countries particularly, the market for such technologies is vast, and donor agencies and development-assistance grants could play a key role in stimulating such investment. For example, more than two-thirds of the current mineral reserves of Bolivia are in dumps and tailings (Warhurst and MacDonnell 1992). Furthermore, in many developing countries, such as Peru, dynamic small- and medium-scale firms supplying a range of inputs to the mineral sector could, with incentives, expand their activities to the environmental arena (Núñez 1993). In the United States, liability regulations should be reassessed
because the current barriers to re-mining and treating mining waste need to be removed.

**Mechanisms to stimulate the diffusion of environmental innovations**

Technological and managerial capabilities are required for innovating and for dealing with new and emerging technologies, and they are also vital for resolving pervasive inefficiencies if a firm's environmental-management strategy is to use existing technology. Technology transfer and technology partnership through joint ventures or strategic alliances are ways to build up technological and managerial capabilities. This is particularly pertinent in the developing countries, although such strategic alliances are emerging in all the major mineral-producing countries. Recent collaborative partnerships in environmental innovation include Outokumpu and Kennecott Corporation; Outokumpu and the Chilean state copper corporation, Corporación Nacional del Cobre S.A.; Cyprus Mines and Mitsubishi; Comalco, Marubeni Corporation (Japan), and the Chilean power company, Empresa Nacional de Electricidad S.A.; Battle Mountain (United States) and Inti Raymi (Bolivia); and Compañía Minera del Sur S.A. (Bolivia) and Compañía de Minas Buenaventura (Peru).

However, the concept of technology transfer should be broadened to include a real transfer of environmental-management capability. Technology transfer has traditionally meant a transfer of capital goods, engineering services, and equipment designs — the physical items of the investment — accompanied by appropriate training for operating the plant or equipment. Consequently, the innovative capacity of recipients is undeveloped and they remain purchasers and operators of imported plants and equipment. This is especially the case in developing countries, where many recipients become dependent on their suppliers to make changes or improvements to successive vintages of technology. Contractual conditions may reinforce this situation.

New forms of technology transfer in environmental management are needed to embrace

- The knowledge, expertise, and experience required to manage technical change — of both an incremental and a radical nature; and

- The development of human resources for implementing organizational change to improve overall production and energy efficiency and environmental management throughout plant and facility — from mine development, through production, to waste treatment and disposal.
This new concept of technology transfer emphasizes training and skills acquisition in environmental R&D, engineering, management, troubleshooting, repair and maintenance, environmental auditing, and so on.

In global industries like mining, international firms supply significant amounts of managerial and engineering expertise through joint ventures and other collaborative arrangements. These contributions are usually limited to the immediate requirements of the specific investment project or of the equipment purchased. Flows of technology may even be structured to match regulatory requirements. Cumulative command-and-control regulations tend to lead to incremental, add-on, end-of-pipe, capital-intensive technical change and therefore successive rounds of technology imports (Warhurst and MacDonnell 1992). However, empirical research in other sectors demonstrates that these contributions can be considerably increased without adversely affecting the supplier's strategic control of its proprietary technology (Bell 1990; Warhurst 1991a, b; Auty and Warhurst 1993).

Such an approach was at the heart of the strategy of China's National Offshore Oil Corporation, which required major oil companies, under technology-transfer agreements in their investment contracts, to transfer the skills needed to master selected areas of technology (Warhurst 1991b). Another interesting example is the Zimbabwe Technical Management Training Trust. It was founded by RTZ in 1982 to train South African Development Community professionals in technical management and leadership. Participants receive a combination of academic and on-the-job training in the operations both at home and overseas. Accelerated managerial training is possible through exposure to on-the-job problem-solving situations, with experienced colleagues, in a range of challenging technical scenarios.

Similar in-depth training programs, concentrating on environmental management, could be built into many of the proposed mineral-investment projects throughout the world. Preference could be given to investors and technology suppliers with proven environmental-management competence and a willingness to transfer their skills and knowledge. It cannot be overemphasized that all technology transfer and training efforts represent a cost to the supplier, and this cost must be covered to ensure optimal results. The danger of failing to budget for this cost is ending up with a training program in operational skills instead of one in technological mastery. Corporate partners, the government, and, in the case of developing countries, donor agencies or development banks can assist in financing these schemes. Moreover, governments, organizations, or firms will have more power to negotiate the objectives and scope of the programs if they have helped finance them.
Mine operators can purchase capital goods, engineering services, and design specifications through a range of well-established commercial channels; however, the market for knowledge and expertise, including training programs, is less mature. Active development of this market will reward innovators in pollution-prevention technology. Bilateral and multilateral agencies, development banks, and government organizations can play a major role in improving this. Agenda 21, one of the main outputs of UNCED, proposes two programs of relevance (Skea 1993) that can be expected to lead to greater industry involvement. One of these programs encourages interfirm cooperation, with government support, to transfer technologies that generate less waste and increase recycling. The other program, on responsible entrepreneurship, encourages self-regulation, environmental R&D, worldwide corporate standards, and partnership schemes to improve access to clean technology. Moreover, Agenda 21 (chapter 34) recognizes that for technology transfer to be effective, a substantial increase in the technological capabilities of recipient countries is required (Barnett 1993). The capacity to effect technical change, not just the skill to operate an item of environmental-control technology, will ultimately determine whether a recipient firm can build up the competence it needs to be successful in environmental management and environmental innovation. Broadening the concept of technology transfer to encompass these issues would also enable government and industry policymakers to more accurately assess barriers to the diffusion of clean technology.

Implications for policymakers

This analysis suggests the need for a two-tier policy approach. Policy concerning ongoing projects must cover the challenges of production inefficiency, its environmental consequences, and the clean-up requirements for mine closures and plant decommissioning. Policy concerning new investment and expansion projects should stipulate that environmental management and the flexibility to engage in further environmental innovation be built into the project at the outset. This requires negotiation among operators, equipment suppliers, and credit sources at the earliest stage.

The analysis of technology transfer for a pollution-prevention policy has two implications. First, if the policy is to work as a means of achieving sustainable industrial development (even if only a means for firms and countries to comply with UNCED recommendations), it must be underpinned by a technology policy with financial incentives that promote the commercialization of pollution-prevention innovations in overseas markets, including Eastern Europe and developing countries. Although this paper has highlighted some of the barriers to the diffusion of pollution-prevention technology, these barriers are not so much due
to the absence or inadequacy of regulations as to a lack of technological and managerial capabilities, insufficient investment resources, information constraints, etc. It is argued here that industry, governments, and international organizations, including development banks, have an interest in overcoming these barriers. One route is fostering the real transfer of technology, as described above.

Second, environmental policy needs to be integrated with other government policies, such as those covering industry, trade, and technical assistance. Firms can learn a great deal from one another. Indeed, this is reflected in the formation of the International Council on Metals and the Environment (ICME) and the recent set of strategic alliances between leading technology suppliers and mining companies (see above). A major purpose of ICME is to promote sound environmental and health policies and practices to ensure the safe production, use, recycling, and disposal of metals. An important rationale for its establishment was the view that industry can benefit from pooling its expertise, exchanging information, promoting sound environmental and health policies, and working cooperatively and proactively with regulators, labour, and scientific and environmental groups. Great scope remains for the further diffusion of knowledge (environmental software) and technology (environmental hardware) among firms, between firms and regulators, and across firms and national boundaries.

Technology transfer is frequently perceived as being relevant only to industrializing countries. This paper shows its relevance to industry on a global scale, in terms of the broad objective of sustainable development.

Conclusion

This paper suggests that the concept of environmental sustainability can be made operational if governments set measurable policy targets and design policy mechanisms that support implementation. The new regulatory principle — pollution prevention pays — aims to promote competitive and environmentally sustainable industrial development. The requirement that pollution be reduced at source implies a requirement for technical or organizational change, or both, in the production process. This, in turn, requires that firms develop new technological and managerial capabilities, technological alliances with equipment suppliers, and collaboration with R&D organizations. This paper argues that for successful implementation of pollution prevention, regulatory approaches must be underpinned by technology-policy mechanisms designed to stimulate technological innovation and best practice in environmental management within firms and to encourage the commercialization and diffusion of these innovations across the boundaries of firms and nations. As a contribution to sustainable development, pollution-prevention
policy represents an advance over previous policies, such as those guided by the polluter-pays principle. However, it contains two flaws.

First, the firms that pollute the most are mismanaging the environment precisely because of their inability to innovate. Environmental degradation is greatest in operations with low levels of productivity, obsolete technology, limited capital, and poor human-resource management. Yet, under the pollution-prevention regulatory regime, it is assumed that such firms, if obliged by law, will automatically introduce technical change to reduce pollution at source. This is unlikely to occur unless pollution-prevention regulations are underpinned by technology policies and financial incentives aimed at encouraging the least-efficient firms to develop the technological and managerial capabilities to innovate. Using punitive environmental regulations to put the least-efficient and most-polluting firms out of business is a short-sighted alternative. In developing countries particularly, such an approach would threaten the economic objectives of sustainable development and lead to further problems because the cleanup and mine-rehabilitation costs would be transferred to the state or society.

Second, the most efficient firms are generally better environmental managers because they are innovators. They are able to harness both technological and organizational change to reduce the production and environmental costs of their operations. Furthermore, where the costs of complying with environmental regulations threaten competitiveness, the dynamic firm can offset these costs by improving production efficiency. In the minerals industry, regulatory costs cannot be passed on to consumers because international metal prices are determined in terminal auction markets and cannot be controlled by the producers. The policy of requiring firms to reduce pollution at source, which necessarily involves changing their production technology and organization, overlooks the possibility that firms might already be searching for new ways to improve metal recovery, reagent use, energy efficiency, water conservation, and so on as part of their corporate strategies to increase competitiveness.

It is therefore more likely that pollution-prevention regulations will serve their objectives if they are underpinned by technology-policy mechanisms and economic instruments. The following approaches are suggested:

- Stimulate and reward innovation in pollution prevention through tax breaks for R&D and technology investment, other taxation reforms, auctioned pollution permits, new lines of credit, targeted R&D support, and training programs;
- Require mandatory pollution-prevention and reclamation plans in project development, and stipulate bonds for that purpose;

- Stimulate profitable innovation in waste management, such as re-mining, reagent and metals recovery, and biotechnological waste treatment, and remove legislative barriers to re-mining and waste treatment;

- Reward firms for innovations in clean technology;

- Use mechanisms such as credit conditionality to facilitate the commercialization and diffusion of pollution-prevention technology and work practices across the boundaries of firms and nations; and

- Promote new approaches to technology transfer, such as interfirm collaboration to develop the technological and managerial capabilities to innovate, in-depth training to manage technical and organizational change, and information-dissemination programs.

Innovation can change the context of metals production and pollution, and the widespread diffusion of innovation can reward the innovator, as well as contributing to best practice in environmental management for sustainable development. Mechanisms to support pollution-prevention policy will be more successful if they focus on the process of innovation at any point in the life cycle of the mine, rather than penalizing firms for excessive use of inputs or production of polluted outputs. The production of outputs varies too much among operations because of site-specific geological and geographic conditions. Penalties can differentially distort the operations' cost structures and be an inefficient way to stimulate innovation in pollution prevention.

This paper also makes a case for training regulators so that they have the experience and understanding to evaluate technological advance, an important indicator of the effectiveness of environmental regulations. Ratcheting the existing regulations in line with this evaluation would further enhance the competitive advantages of firms. Regulators and corporate analysts might also enhance their strategies for competitive environmental best practice by defining corporate environmental trajectories in various economic and regulatory contexts. This would help in evaluating the evolution of a firm's competitiveness in response to changing market conditions and regulatory requirements and, therefore, in evaluating the firm's contribution to sustainable development.
Broadening the range of regulatory goals and the technology-policy mechanisms and economic instruments to support them, as proposed here, would be a more integrated policy approach to regulating and promoting industrial development and to promoting trade and technical assistance abroad. Pollution prevention at source would have a key role in this policy, without always taking priority in the competitive and environmentally sustainable development of industry in developing and industrialized countries. This aim of this new, more comprehensive policy approach is environmental innovation.