1. Introduction

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This volume deals with corporate response to the environmental imperative in the copper industries during the last 20 years, with a special emphasis on developing countries and transition economies. As a result of the dramatic increase in energy prices in the 1970s, and the concomitant tightening of environmental legislation in primarily the United States, Canada, Australia and Europe, a process of profound structural changes started in the copper industries in the West. The reason was that the copper industry is not only very energy-intensive but it is also one of the most polluting industries in the world.

Thus, increasing energy prices, plus the new environmental imperative, led to closures of many copper plants, especially in the United States. Rising costs and volatile world market prices made it difficult for many copper companies to survive. However, others have stayed in business, responding to the new challenge by investing in energy-saving and environmentally sounder technology. However, investment is as a rule quite costly and therefore prohibitive to many companies working with low profit margins. Even so, the price fall in the 1980s made mining companies realize that the only way to survive was to find a formula to increase productivity and drastically cut production costs, which could only be achieved through the introduction of new technologies.

The objective of the research underlying this volume has been to take a closer look at the main copper producers in developing countries and transition economies, with a particular focus on Chile, China, Peru and Russia. How have these companies responded to the new challenges and the environmental imperative? How have state companies (the main producers in the 1970s) responded, and to what extent has privatization facilitated technological change, necessary restructuring of the industry, and an adequate response to the new environmental imperative?

As examples in this volume show, the non-ferrous metals industry (and the copper industry is no exception) has been slow to innovate, historically speaking, and this has made the environmental imperative both more important and difficult to respond to. It has been suggested that reasons for the slow rate of innovation in the non-ferrous metals industry

rest with the nature of the industry, since ‘producing homogeneous raw materials that have a long productive chain before reaching the final consumer, does not provide a fertile environment for aggressive innovation’ (Gana 1992).

THE WORLD COPPER INDUSTRY

The copper commodity chain can be divided into the following phases of production: extraction of minerals, crushing and grinding of the copper ores, smelting of the concentrates into blister copper, fire refining into anodes, and further refining electrolytically into cathodes, and finally the processing of semi-finished and finished products. Table 1.1 shows the distribution of world production of copper, from mine production to anodes and cathodes, in 1985 and 2001.

World mine production increased from 8.4 million tons in 1985 to 13.4 million tons in 2001, or by 59 per cent. Anodes and blister production from smelters increased from 8.7 million tons to 11.9 million tons in the same

Table 1.1 Shares of world copper output (Cu content) of leading producers: mine production, anodes and cathodes in 1985 and 2001 (percentage shares)

	1985			2001		
	Mine	Anodes	Cathodes	Mine	Anodes	Cathodes
Chile	16.1	12.1	9.1	35.6	12.5	18.3
United States	13.2	13.3	14.7	10.1	7.7	11.6
Japan	0.5	10.4	9.6	0.0	12.1	9.3
China	2.9	3.1	4.2	4.2	7.2	9.3
Canada	8.8	5.8	5.1	4.7	5.4	3.7
USSR/Russia	12.3	12.7	14.4	4.1	5.4	5.7
Australia	3.1	2.0	2.0	6.7	4.0	3.7
Poland	5.1	4.2	4.0	3.7	4.2	3.3
Peru	4.6	4.0	2.3	5.4	3.3	3.1
Indonesia	1.0	—	—	7.8	1.8	1.4
Mexico	2.1	0.8	1.3	2.6	2.8	2.6
Africa	14.5	13.2	9.0	3.5	3.8	2.9
Others	16.8	18.4	24.3	19.3	29.8	25.1
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0
Kilotons	8405	8689	9749	13400	11900	15300

Source: Elaborated from MBR (1998) and RMD (2002).

period, or by 37 per cent, while refined copper (cathodes) output increased from 9.7 million tons to 15.3 million tons, or by 58 per cent, while smelter production (anodes) only increased by 27 per cent, in contrast to refinery production (cathodes) that increased by 42 per cent. The main reason for the difference in growth patterns between refinery and smelting output is that refinery production also includes cathode production through solvent-extraction/electrowinning processes (Sx/Ew), a rather new phenomenon discussed in detail in Chapter 2. In addition, cathodes are also produced from recycled scrap in so-called secondary smelters.¹

The United States was until recently the world leader of processed copper (that is, anodes from smelters and cathodes from refineries) with Chile trailing close behind. Chile has, however, in recent years become the largest producer in the world not only of copper ores and concentrates (mine production), with over one-third of world output in 2001, but also of anodes (12.5 per cent of world output in 2001), and of cathodes (18.3 per cent of world output in 2001). The reason for the relatively higher share of refined copper is explained by the rapid development of hydrometallurgy, that is, Sx/Ew technology used to produce refined copper from low copper content oxide ores.

The four countries analysed in this volume – Chile, China, Peru and Russia – accounted for 49 per cent of world mine output in 2001, for 28 per cent of world smelter output (blister and anodes), or 36 per cent of world refined output of copper (Table 1.1). A comparison with all developing countries and transition economies shows that these four countries accounted for 62 per cent of total mine output, for 40 per cent of total smelter output, and for 50 per cent of all refined copper production. One could thus safely conclude that the countries studied in this volume account for significant shares of total output, and thus the questions addressed in this book on technological change and the environmental imperative are important for the world copper industry as a whole.

THE SMELTERS: THE GREAT POLLUTERS

There are around 100 primary copper smelters in the world that process blister copper (anodes), using pyrometallurgical processes (based on sulphide ores), which are then treated electrolytically in refineries (tank-houses). As mentioned, there is also another process suited to low-grade oxide ores, solvent-extraction/electrowinning (Sx/Ew), which eliminates the smelting phase and much of the pollution problems. This process is rapidly growing and at present there are around 35 Sx/Ew plants in the world, with a total capacity of some 1.2 million tons, compared to some 11.5 million tons

capacity of the primary electro-refineries (Biswas and Davenport 1994, Tables 2.4 and 2.5).

The interest of copper companies in developing hydrometallurgical treatment of oxide ores started in the 1970s and the 1980s in the search for alternative, more cost-efficient technologies as a consequence of the soaring fuel prices. Hydrometallurgy has many advantages over pyrometallurgical processes. Its strength lies in its 'ability to treat lower grade ores (even waste dumps) economically, flexibility in scale of operations, simplified materials handling, and good operational and environmental control' (OTA 1988, p. 140).

We will in this volume, however, primarily deal with smelters and smelter technology based on pyrometallurgy. A large number, or 28 per cent of the world's primary copper smelters, still use conventional technologies, that is blast furnaces or reverberatory furnaces. About 45 per cent have already installed oxygen-based smelting technologies, of which Outokumpu flash smelting accounts for the lion's share (over half) and the other half is divided between Inco flash and Noranda flash (both Canadian), Mitsubishi continuous smelting, the Ausmelt process (Australia), the Teniente converter (Chile), the Vanyukov process (Russia), and the Chinese Baiyin process.

The pyrometallurgical process consists of the application of high temperatures to the concentrates, a process that develops chemical reactions leading to the production of matte, a liquid with high copper content, together with slag and sulphur dioxide (OTA 1988, p. 8). The smelting process generally consists of three stages, roasting, smelting and converting. Through roasting, the concentrates (20–30 per cent copper content) are prepared for smelting by applying heat to dry them, partially removing the sulphur content and volatile contaminants (such as arsenic). The dried concentrates are then molten in furnaces (traditionally blast furnaces or reverberatory furnaces), leading to the production of matte with a 50 per cent to 75 per cent copper content. Matte grade in the reverberatory furnace has normally been in the range of 35 to 45 per cent. After being separated from the slag, the matte is then ready for conversion, leading to the separation of blister copper, or anodes, with 98.5 per cent or more copper content, plus slag that still has a high copper content, and that can generally be recycled to the furnace. The most common converter is the Peirce-Smith converter (an innovation dating from the beginning of the twentieth century). The molten matte is poured into the converter while air is blown into the matte through nozzles, called 'tuyeres' (OTA 1988, p. 135).

Pollution problems in copper production occur mainly in the smelting phase of the processing of sulphide ores. Pyrometallurgical processes are used to process sulphide ores through smelting at high temperatures. The primary environmental concern is the sulphur dioxide (SO₂) produced,

which must be fixed as a liquid, sulphuric acid being the most common by-product.

In contrast, in hydrometallurgy the copper (or nickel) is leached at lower temperatures. Hydrometallurgical processes eliminate SO_2 emissions but frequently produce hazardous wastes and effluent. Secondary copper (scrap), is processed in primary smelters or specific secondary smelters. Pollution in this process is evidently less, although the presence of volatile and heavy metals is a major concern.

There is a clear tendency in the world for copper companies to switch to energy-reducing processes that at the same time are less harmful to the environment. Ironically, however, it was not primarily environmental concerns that were the initial driving force behind technological change in the industry. Rather, 'productivity increases, energy savings and improved workroom environment were key forces driving technological change in the 1970s' (Díaz et al. 1995, p. 12). When public concern about the environmental damage caused by acid rain was awakened, and governments started tightening environmental legislation, the leading copper producers in the United States responded to the challenge with new and cleaner technologies.

This has led to increasing innovative activity – for instance, to the development of energy- and pollution-efficient oxygen smelting processes, and to the mentioned drive towards Sx/Ew technologies.

ADVANTAGES AND DISADVANTAGES OF CURRENT SMELTING TECHNOLOGIES

An overview of current smelting technologies is found in Table 1.2. For a long time the reverberatory furnace was the favourite of the copper industry worldwide because of its versatility in handling all types of feed. However, due to its considerable use of energy it became increasingly uneconomic with rising oil prices. The reverberatory furnace also produced SO_2 with too low levels of density in order to be recoverable in acid plants, making it unviable in the longer run due to the emerging environmental imperative. In the 1970s air quality regulations forced most US companies to adopt electric or flash furnaces, while others were closed down. The driving force behind the selection of flash smelting was profitability, since this technology offered high sulphur recovery with lower operating costs and with reasonable investment costs. In the United States, the last copper reverberatory furnace was closed in 1995 when Copper Range decided to shut down its plant for good, after agreeing to pay large fines for emission violations (Díaz et al. 1995, p. 4). The major disadvantages with reverberatory furnaces are thus low productivity, due to high fuel consumption, and

Table 1.2 Overview of current smelting and converting technologies

Technologies	First developed	Latest innovation	Energy requirements (million Btu/ton)
Reverberatory furnace	Beginning of 1900s	Oxy-fuel burners (around 1975)	30.93–35.18
Electric furnace	Around 1925		42.52
Outokumpu flash	Late 1940s	Use of O ₂ (1970)	18.92
INCO flash	1950		21.26
Noranda reactor	Around 1970		24.01
Mitsubishi reactor	Around 1970		19.77
Peirce-Smith	Around 1910		No data
El Teniente	Around 1975		No data
Mitsubishi continuous converter	Around 1970		No data
Kennecott- Outokumpu flash converter	Started operation in Salt Lake City in 1995		No data

Sources: Information compiled from OTA (1988), Biswall and Davenport (1994), and Nuñez-Barriga (1991).

low capture of SO₂ gases, although there is some remedy through retrofitting with oxy-fuel burners as complement to the furnaces.

The electric furnace (first developed in the 1930s) is similar in operation to the reverberatory furnace but has better environmental control conditions for the effluent gases. A drawback is, however, that it has to rely heavily on external energy and high prices of electricity can lead to prohibitive energy costs. Outokumpu started the use of electric furnaces in the 1930s at Imatra, and continued at Harjavalta in the 1940s before developing flash smelting. There are only four electric furnaces installed in the world. They were all installed in the 1970s, replacing reverberatory furnaces. The electric furnace, however, has not proven to be competitive with flash smelting and other more recent processes (see below). The reason is that electric furnaces use a lot of expensive electrical energy, and SO₂ concentration levels are relatively low, albeit higher than in reverberatory furnaces equipped with oxy-fuel burners (Biswas and Davenport 1994, p. 149).

The flash furnace (first developed in the late 1940s), on the other hand, is an autogenous process. It thus requires no external energy (using commercial oxygen or oxygen-enriched air) and therefore has relatively low fuel

costs, and the off-gases are rich in SO_2 , permitting economic pollution control through acid plants. Flash smelting has been given its name from the fact that the reaction of the concentrates with the injection of oxygen is very fast, with a high liberation of heat that permits the smelting to proceed without additional heat. The use of oxygen also began to be used in reverberatory furnaces in the 1960s through the use of oxy-fuel burners (Nuñez-Barriga 1991, p. 18)

Flash smelting, originally developed by the Finnish company Outokumpu,² saves considerable amounts of energy compared to other smelting methods since the smelting reaction utilizes the energy released by the oxidation of sulphur and iron contained in the concentrates. More than 99 per cent of the sulphur-rich off-gases from the process are recovered and utilized for the production of sulphuric acid. Competing, conventional smelting methods achieve recovery rates of approximately 70 per cent.

It has been calculated that without flash smelting the annual world sulphur dioxide emissions would be 5–10 million tons higher. About 40 per cent of the world's primary copper output is produced with this method (Outokumpu, 1992). Flash smelting is thus superior to conventional smelting methods (for instance, blast furnace or reverberatory furnaces). However, it involves costly investments and, in order to have a reasonable pay back, quite high volumes of production are necessary from the outset. Sulphuric acid plants, for example, are costly and account for one-third of investment in new smelting plants (Nuñez-Barriga, 1991, p. 24). As a rule, there is little or no market for sulphuric acid in developing countries (except in the leaching process of oxide ores).

Flash smelting has now become the industry standard. In flash smelting, dry concentrates are fed to the furnace along with oxygen-enriched air (or pure oxygen). Quicker throughput raises the concentration of SO_2 , which makes it economic to produce sulphuric acid (that can, for instance, be used in hydrometallurgical leaching processes). Thus, flash smelting is more cost-efficient (especially energy saving) than conventional processes. It should, however, be stressed that cost-efficiency is also dependent on recovery rates of copper, and the value of possible by-products such as zinc, lead and precious metals like silver and gold (not the case, for instance in oxide ore production).

Outokumpu flash smelting is the most widely used technology worldwide. It is an autogenous smelting process, yielding high-grade matte, and a constant and high density of SO_2 (between 10 and 50 per cent). It is also quite flexible as to scale of operations, a great advantage in developing countries. A major disadvantage is the high copper content (1–2.5 per cent) of the slag that makes it difficult to use the furnace to process converter slag. Recent developments have included improving SO_2 capture, lowering

energy consumption further, increasing productivity, improving working conditions and lowering costs in general.

Continuous production of blister copper has long been the dream of copper producers, that is, combining roasting, smelting and converting into one operation, producing blister directly from concentrates. The benefits of continuous processing 'include lower capital cost, reduced material handling, low heat losses, very low energy requirements, economical SO₂ gas recovery and the ability to apply online computer controls to the entire copper-making process' (OTA 1988, p. 137). There are only a few continuous reactors (processes) and they are in limited use, primarily the Noranda and Mitsubishi processes (both developed at the end of the 1970s), and the rather recent Kennecott-Outokumpu process. The Noranda process was developed to produce blister copper from concentrate but in practice separate converters have been necessary. Mitsubishi is a continuous process but smelting and converting take place in separate vessels. The Kennecott-Outokumpu process is claimed to substantially reduce the costs of acid production. It has been estimated that continuous smelting/converting could result in additional energy savings of about 10 to 20 per cent (Farmer and Newman, 1998). Both the Noranda and Mitsubishi processes were originally designed as continuous smelting processes but, as noted above, neither has proven to be truly continuous.

INCO flash smelting is an autogenous process with a constant and high density of SO₂. Converter slag is returned to the smelter in a molten form with lower-grade copper slag discarded. Overall capital costs are relatively low and it can produce sulphuric acid. One disadvantage is that expansion is more difficult since pure oxygen is used. Another disadvantage is its limited experience. The furnaces have all been installed in order to replace reverberatory furnaces. As of yet, there is no case of an INCO furnace as part of a new smelter.

By 1993 there were only three Noranda reactors in operation in the world, although several are under construction. In 1997 one started operations in the Daye copper plant in China (Daye), and another was at one point being commissioned by the Shenyang smelter, also in China (see Chapter 4). Noranda is also installing a reactor in its recently acquired Altonorte (Refimet) plant in Chile (see Chapter 3). The El Teniente converter is an innovation developed at the El Teniente division of Codelco, the Chilean state copper corporation (see Chapter 3). It has many features in common with the Noranda reactor. Thus, it is autogenous, primarily installed to expand existing operations. Its disadvantages are high power consumption, waste gas interruptions, waste power generation is difficult, and slag at 6 per cent copper requires retreatment.

THE CHAPTERS IN THIS VOLUME

Two of the chapters in this volume address specifically technological choices that are available to copper companies committed to respond to the environmental imperative. Alyson Warhurst and Gavin Bridge discuss these issues in an overview study (Chapter 2), and Pekka Hanniala and Ilkka Kojo discuss the future of flash smelting technologies in the final chapter (Chapter 7). The other four chapters are devoted to in-depth case studies of the experiences of four countries: Claes Brundenius discusses the experiences of Chile (Chapter 3) and Peru (Chapter 5). Bo Göransson addresses the situation of the copper smelters in China (Chapter 4), and Boris Kuznetsov and Igor Budanov discuss the experiences of the Russian smelters after liberalization of the economy and privatization of the copper industry in the 1990s.

The chapters involving the case-studies primarily address two important issues. Firstly, the privatization of the copper industry, including the impact of increasing flows of foreign direct investment (FDI) after liberalization of the world economy in the 1980s and, primarily, in the 1990s; and to what extent these new trends have contributed to technological change and environmental concern in the copper industries of the countries in question. Secondly, the dilemmas of choosing technology considering the costs/benefits involved, of weighing environmental dividends against social costs (such as employment reduction), and of choosing between short-term profits and long-term costly investment in environmentally friendly technologies.

NOTES

1. Copper is in fact a good example of the recyclability of metals. Almost 80 per cent of all copper ever mined in the world is still in use and recycled, and approximately 38 per cent of world copper demand is met with scrap (Outokumpu 1992 and Henstock 1999). China is the largest importer of copper scrap. Nevertheless, there is a tendency among copper companies to expand primary copper smelting capacity since this is where the major gains in cost efficiency can be made.
2. The fascinating story of the innovation and development of the Outokumpu flash smelter is told in Särkikoski (1999).

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