INDUSTRY AND ENERGY DEPARTMENT WORKING PAPER
INDUSTRY SERIES PAPER No. 52

International Trends in Steel Mini-Mills

Keeping Pace with Technological Change

December 1991

The World Bank Industry and Energy Department, OSP

INDUSTRY AND ENERGY DEPARTMENT WORKING PAPER
INDUSTRY SERIES PAPER NO. 52

International Trends in Steel Mini-Mills

Keeping Pace with Technological Change

December 1991

The World Bank Industry and Energy Department, OSP

INTERNATIONAL TRENDS IN STEEL MINI-MILLS: KEEPING PACE WITH TECHNOLOGICAL CHANGE

Ashoka Mody*, Jerry Sanders**, Rajan Suri,**
and
Eric Thompson***

December, 1991

* The World Bank, Washington D.C.
** University of Wisconsin, Madison
*** Holland, Michigan

PREFACE

Competition in a period of rapid technological change is the subject of this and three companion reports.[1] Four relatively mature industries of considerable interest to less developed countries were chosen to investigate whether organizational and technological innovations are of any relevance to them. The answer is a resounding yes. Organizational changes, automation, and use of new materials to change the production process and to transform the product itself were found to be of tremendous importance in each sector. These changes quite overwhelm simple differences in factor costs.

This research was financed by the World Bank's Research Committee, to which we are all very grateful. Numerous colleagues have supported this work and we would like specially to thank Nancy Barry, Carl Dahlman, Sandra Salmans, and Masami Shimizu. Our greatest debt is to managers and engineers in dozens of companies in six countries who spent their valuable time with us.

1/ International Competition in Printed Circuit Board Assembly.
International Competition in the Bicycle Industry.
International Competition in the Footwear Industry.

1. INTRODUCTION

1.1 Background

Diffusion of innovation proceeds at varying rates in different countries, creating differences in the productivity with which resources are used, and hence affecting the competitive position of nations. At this moment, there is a special ferment in the world of manufacturing as organizational innovations, automation, and new materials are transforming not only the manufacturing process but also, in many cases, the product itself. The speed at which these innovations are absorbed is likely to have a significant impact on a country's ability to compete. Developing countries face a special challenge as they determine how best to keep pace with the changes.

A particularly good example of such ferment is the steel mini-mill industry. Spirited entrepreneurship has been the leitmotif of steel mini-mills. A progression of innovative technological and management practices has been organized around the electric arc furnace (EAF), resulting in what is arguably the most successful revitalization of any basic industry. Mini-mills worldwide were amongst the earliest adopters of continuous casting technology. U.S. mini-mills are now setting the pace in introducing thin casting. U.S. mini-mills have also, without any fanfare, introduced many Japanese-style management practices, such as long-term employment, profit sharing and delegation of responsibility to shop-floor workers. Having swept away competition in simple steel products, mini-mills are poised to take on the traditional integrated mills in increasingly sophisticated products.

The rise of the mini-mill is the single factor most likely to affect steel's international trade picture, as well as the domestic situation in many countries. In this study, we project the effect of innovative manufacturing technologies on the long-term productivity of firms and countries. We believe that, through such analysis, we are enriching the debate on differences in international productivity, and suggesting new policy directions to improve productivity in developing countries.

1.2 The Mini-Mill

The basis of the mini-mill is the electric arc furnace (EAF), which relies mainly upon scrap and, to some extent, upon directly reduced iron (rather than upon coal and iron ore) as feedstock. The EAF was developed around the turn of the century, primarily for refining steel and producing specialty (carbon and alloy) steel that required slow heating. Technological improvements came slowly, and it was only in the 1960s that a U.S. company first installed an EAF to produce construction-grade steel from scrap.

Older mini-mills had an annual capacity of 100,000 tons, compared with the 2 million tons of the average integrated steelmaker. Modern mini-mills are no longer so small; most plants being set up in developed countries today have a capacity of over 600,000 tons, and a few can produce as much as a million tons a year.

The first generation mini-mills typically had two or more small furnaces with a processing capacity of about 40 tons each. At the efficiency levels prevailing then, the annual production capacity of a 40-ton furnace was about 100,000 tons. This furnace is being replaced with a larger furnace (typically 150 tons), possibly equipped with water-cooled panels, an ultra high-powered (UHP) transformer, fuel supplement devices, eccentric bottom tapping (EBT), scrap preheating and process automation to lower energy and material costs and enhance product quality (McManus 1988A). Continuous casters and rolling mills are being similarly upgraded. In addition, mills are increasing investment in direct reduction of iron to supplement their source of feedstock (Marcus and Kirsis 1989). All these factors are increasing the minimum economic scale of production for mini-mills. In the 1990s, it is expected that competitive mills will have an annual capacity ranging from 500,000 to a million tons, with the larger mills producing 2 million tons annually.

Mini-mills have traditionally specialized in a far narrower range of products than have integrated mills, concentrating mostly on lower-value rods and beams rather than the higher value-added flat-rolled products for the appliance and automotive industries. They have built near their sources of scrap and their markets, and emphasized customer service with quick changes in production mix and scheduling.

Mini-mills have developed a cost advantage over integrated mills in lower-value products primarily because of their lower capital cost per ton of steel produced. See Appendix A. The smaller size of the mini-mill has also afforded flexibility in introducing technical changes at a more rapid rate than in integrated mills. In addition, mini-mills have had less fractious labor relations.[1/]

In recent years, U.S. mini-mills have produced at costs that would make them competitive with the cheapest imports. Jeffry A. Werner of Chaparral Steel Co., a leading U.S. mini-mill, is reported to have said: "If a Korean mill had zero wages, the mill's delivered cost in the U S. would exceed Chaparral's. The two manhours going into Chaparral's steel would cost less than the ocean freight from Korea" (McManus 1988B). Our cost estimates basically confirm this assertion.

Does the relatively small scale of mini-mills make them relevant and appropriate for low-wage countries? How are the trends in technology, particularly those related to the use of microelectronics for process control, likely to affect their competitiveness? The answers, we shall see, are pessimistic. The small size of the mini-mill does confer some advantages for prospective LDC steel producers. However, the small share of wage costs in a mini-mill and the high sensitivity of costs to the price of electricity and scrap make it difficult for LDC mini-mills to compete internationally. Some LDCs, notably Turkey, have overcome these disadvantages through rapid adoption of modern technological innovation.

1/ However, the safety record of mini-mills has been less than exemplary.

1.3 Location of Production

Total world steel production has been virtually flat for the last decade, leveling off between 700 million and 750 million tons. Steel produced by mini-mills has grown slowly but steadily. In the late 1980s, over 25 percent of steel was produced by mini-mills (see Table 1.1). Mini-mills have been particularly attractive to countries that have some industrial base but could not afford large integrated facilities. These include many of the smaller European countries and the so-called newly industrializing economies (NIEs).

Table 1.1 STEEL MINIMILL PRODUCTION TRENDS

	World	U.S.	Japan	Italy	Portugal	Spain	Turkey	Brazil	Mexico	Venezuela	India	Rep. of Korea	Taiwan (ROC)
1982	134.7 (23.4)	21.0 (31.1)	26.5 (26.6)	12.6 (52.6)	0.3 (55.9)	6.8 (51.9)	1.1 (33.8)	3.5 (26.5)	3.1 (43.5)	[illegible] (81.31)	2.4 (21.6)	3.0 (25.2)	1.5 (36.2)
1983	142.9 (24.1)	24.1 (31.5)	27.6 (28.4)	11.7 (53.5)	0.3 (47.7)	7.4 (56.9)	1.2 (32.6)	3.6 (24.9)	3.2 (45.7)	1.9 (83.1)	2.2 (21.7)	3.5 (29.1)	1.6 (32.0)
1984	155.8 (24.6)	28.5 (33.9)	29.2 (27.7)	12.7 (52.8)	0.4 (55.7)	8.1 (60.1)	1.5 (34.5)	4.8 (25.9)	3.2 (42.2)	2.2 (80.1)	2.3 (21.4)	3.8 (29.5)	1.7 (33.3)
1985	159.9 (25.1)	27.2 (33.9)	30.5 (29.0)	12.5 (52.4)	0.2 (33.7)	8.7 (61.5)	1.7 (35.5)	5.0 (24.6)	3.2 (43.9)	2.6 (84.5)	3.0 (25.5)	4.2 (31.4)	1.7 (34.2)
1986	161.6 (25.9)	27.6 (37.2)	29.2 (29.7)	11.9 (51.9)	0.3 (36.1)	7.1 (59.3)	2.4 (40.3)	5.3 (24.9)	2.8 (39.8)	2.8 (82.2)	3.2 (26.2)	5.0 (34.5)	1.9 (34.3)
1987	169.6 (26.4)	30.9 (38.1)	29.4 (29.8)	12.3 (53.7)	0.3 (38.1)	6.8 (57.8)	3.2 (44.9)	5.2 (23.4)	3.3 (43.5)	3.2 (84.9)	3.6 (27.7)	5.4 (32.4)	2.1 (34.9)
1988	181.4 (26.7)	33.4 (36.9)	31.4 (29.7)	13.3 (56.2)	0.3 (41.3)	7.1 (60.0)	3.8 (47.3)	5.9 (23.9)	3.6 (45.9)	3.1 (84.4)	3.8 (26.5)	6.1 (31.6)	2.7 (32.3)
1989	184.0 (26.4)	31.4 (35.5)	33.0 (30.6)	14.0 (55.6)	0.3 (47.3)	7.2 (56.1)	4.7 (59.0)	5.7 (22.7)	4.0 (51.9)	2.9 (85.5)	3.8 (26.5)	6.5 (29.5)	2.6 (30.5)

Note: Figures in parentheses represent mini-mill production as a percentage of total crude steel production.

Source: International Iron and Steel Institute. Steel Statistical Yearbook. Various years. Brussels: Committee on Statistics.

Despite their suitability for smaller economies, the world's most dynamic mini-mills have emerged in the United States. These firms have been pioneers in introducing new technologies and are setting the pace for the production of an increasing range of steel products. Inexorably, production is shifting to the mini-mills. Donald F. Barnett, a steel expert who was formerly chief economist of the American Iron and Steel Institute, estimates that US mini-mills, now producing about a quarter of steel in the United States, will account for 40 percent of all U.S. steel production by the year 2000. (Barnett and Crandall, 1986, pp.98-100)

Of the approximately 50 mini-mill companies in the United States, two-thirds still produce fewer than 60,000 tons per year. But analysis predict that, by the mid-1990s, as many as five North American mini-mills will have up to 6 million tons of raw steelmaking capacity and annual sales of $1 billion to $2 billion apiece--thus surpassing all but four of Big Steel's onetime behemoths (Business Week, June 13, 1988, pp. 100, 102).

There has also been a wave of joint ventures between U.S. mini-mills and foreign steelmakers. Birmingham Steel Corp. owns 50 percent of a new flat rolled steel plant in Houston; the remaining equity is owned by Proler International, a Houston recycler, and Daniell & C. Officine Mec-chaniche S.P.A., and Italian engineering firm. Nucor's new plant in Blytheville, Ark., is a joint venture with Yamato Kogyo Co., which has provided its casting technology. However, the trend is not confined to the mini-mills; Big Steel also has such joint ventures.

Turkey has also had a vibrant mini-mill sector. About 15 private mini-mills produce more than half of Turkey's steel, and their share has been growing despite the rapid growth of the integrated sector. Turkey's oldest mini-mill, Metas, is a technology pioneer. It was amongst the first in the world to introduce continuous casting and has since maintained a strong tradition of improving production technology and operating practices (Steel Times, July 1988, pp. 346-356). See Appendix B on Turkey. Unlike the United States, Turkey imports a substantial amount of scrap for use in the electric furnaces. About half the steel produced is exported.

Brazil, Korea, Taiwan, Mexico and Venezuela are some of the other countries where mini-mills have thrived. In Taiwan, the proportion of steel produced by mini-mills has fallen over the years as major investments have been made in integrated public sector firms. In Brazil and Korea, mini-mills have held their own despite the dynamism of the integrated sector. In Mexico and, more so, in Venezuela, direct reduction of iron is being used to feed the electric arc furnace in a major way. A Mexican firm, HyLSA, has developed a highly innovative direct reduction process.

Smaller European countries (such as Sweden, Italy and Spain) have long relied on mini-mills. However, in the past several years these mills have stagnated. Ironically, the European Community's steel cartel, by protecting the integrated steelmakers there, has had the effect of slowing the development of mini-mills (Barnett and Crandall 1986). Growth has also been limited by controls over movement of raw materials and energy. However, both the system of protecting integrated steel mills and the irrationality of transportation costs are being phased out. It is believed therefore, that the European mini-mill sector is poised for growth. Northern European firms are beginning to direct attention to high value-added products, requiring downstream integration into specialized fabrication and distribution; Spanish and Portuguese firms are, like Turkey's, going to focus on "commodity" products. (Collier, Iron Age, January 1990, 43-44)

1.4 Trade

For such a bulky product, steel crosses national borders in surprising volume. At least a quarter of the steel produced is traded internationally, and one estimate suggests that the proportion traded has grown in recent years to 30 percent (Marcus and Kirsis 1989).

Mini-mills have traditionally not transported their products over large distances. "Neighborhood" mills have produced a variety of products for their immediate geographical vicinity. Over the last decade, "market" mills have specialized in a few products for neighborhood and distant markets.

No comprehensive data is available on worldwide exports by mini-mills and only indirect inferences can be drawn. Products which mini-mills produce competitively (semifinished steel, bars, rods and light sections) and their internationally traded volumes are presented in Table 1.2. Since no division between mini-mill and integrated steel mill exports in these categories is available, the only statement that can be made is that mini-mills have between 15 and 20 percent of world trade as their immediate target.

A trend of some importance to mini-mills is the long-term increase in trade of semifinished products (ingots, blooms and slabs). The share of semifinished products traded has gone up steadily since the 1960s and is projected to increase further (Marcus and Kirsis 1989). Table 1.2 shows that, in the second half of the 1980s, the share of semifinished steel in total steel trade tended to stabilize at 5 percent. Marcus and Kirsis anticipate a sharp increase to 8 percent in the next five years.

Table 1.2: SEMI-FINISHED STEEL EXPORTS a/ AS A PERCENTAGE OF TOTAL STEEL EXPORTS (%) c/

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
World	3.9	3.2	3.0	3.3	4.0	5.3	5.0	5.4	5.1	5.1
Brazil	10.9	3.9	4.4	5.4	14.5	24.9	25.7	38.4	N.A	N.A
Korea	13.35	4.4	4.1	6.9	4.5	3.9	1.7	2.1	N.A	5.9
Turkey	2.6	0.4	0.1	3.4	7.2	15.6	21.3	15.7	22.4	25.6
Mexico	0.9	0.8	13.3	3.2	1.6	4.4	11.2	6.0	N.A	9.8

LOW-END STEEL PRODUCT EXPORTS b/ AS A PERCENTAGE OF TOTAL STEEL EXPORTS (%) c/

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
World	15.6	12.9	13.1	14.4	15.0	16.4	14.6	13.2	12.4	12.6
Brazil	17.3	27.4	22.9	25.1	27.0	28.4	20.4	17.5	N.A	N.A
Korea	18.5	13.1	13.0	16.3	18.5	20.0	12.8	N.A	8.7	45.5
Turkey	45.5	41.2	63.1	63.5	55.3	40.5	38.4	41.1	37.8	36.3
Mexico	6.0	1.1	34.0	25.6	23.0	13.1	26.2	16.7	N.A	9.7

Source: Comtrade Database, International Computing Center, Geneva.

a/ Ingots, blocks, blooms and slabs: SITC codes 6720, 6721, 6723, 6725.

b/ Wires, bars and small sections: SITC codes 6730, 6731, 6732, 6735.

c/ Estimates of shares are based on value of exports and not on quantity. Total Steel exports = SITC 67 - SITC 671.

The trend towards greater trade in semifinished steel partly reflects the advances in rolling and finishing technology. Rolling for high-quality products, in particular, has become highly capital intensive, much more so than the production of steel in mini-mills. Given declining freight costs, it makes sense to split production across international sites to take advantage of relative factor proportions. Another trend favoring this development is the rationalization of steel production in western countries. Firms are specializing in specific operations. Often such rationalization is a result of merger activity. After merging, the constituent units focus on fewer operations, requiring the movement of semifinished product from one unit to another. Particularly in Europe, this has resulted in increased trade in semifinished steel.

Brazil, South Korea, Turkey and, increasingly, Mexico among the developing and newly industrializing economies are suppliers of semifinished steel. Except for Korea, the share of semifinished steel in their exports has expanded steadily (Table 1.2). Brazil has been the largest exporter, and also the most geographically diversified. Japan and the United States have been large buyers of semifinished steel from all these countries, Japanese imports from Korea being particularly large. Turkey has had large markets in the Middle East, but is rapidly diversifying. Though these countries are growing suppliers, they are also large importers of semifinished steel. This is not surprising, given the large variety of end uses and hence types of steel traded.

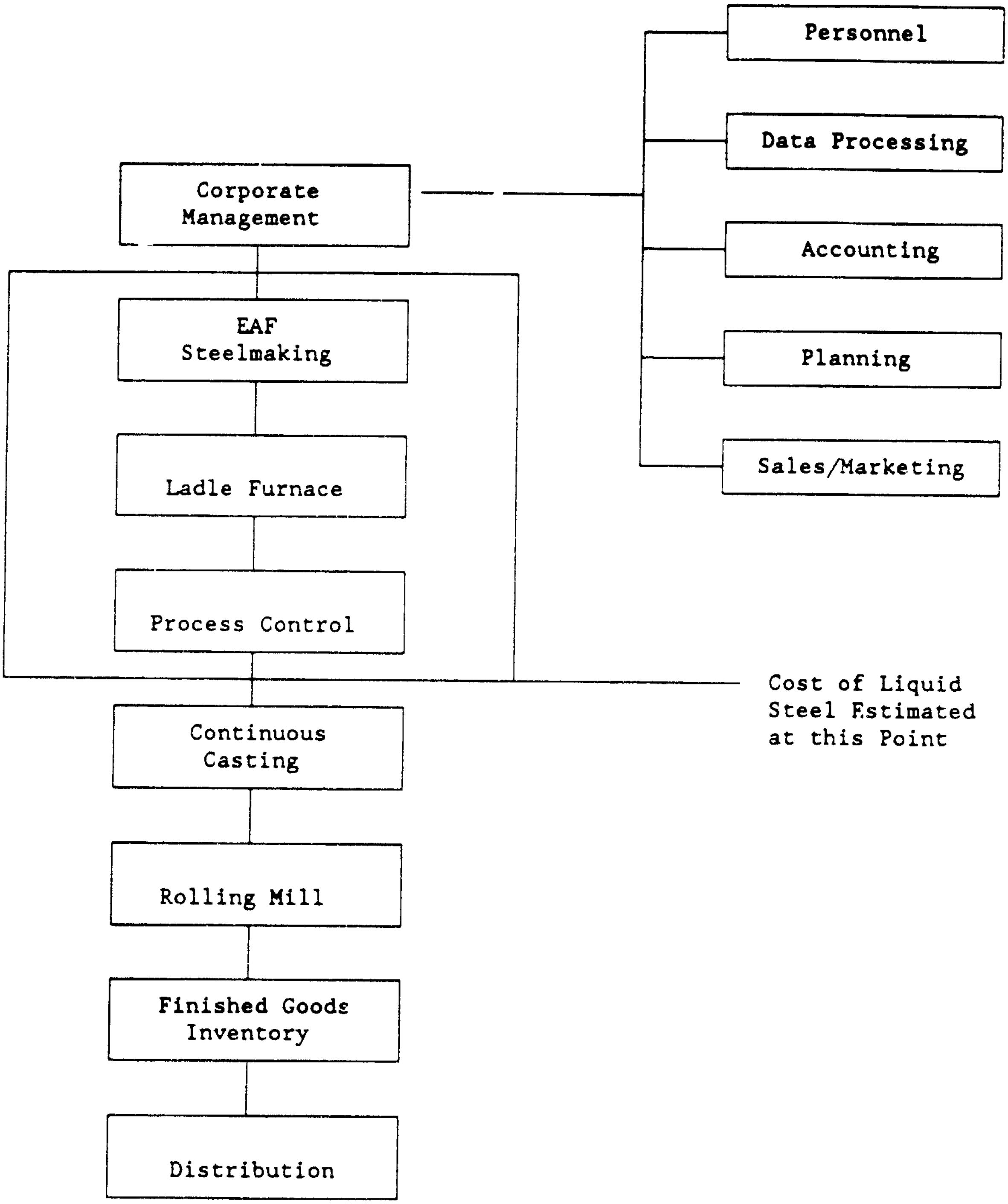
Bars, rods and light sections are the other major export opportunity for mini-mills. These products are also exported in large amounts by the four countries just discussed. Unlike semifinished products, bars, rods and light sections are imported to a much smaller extent by these countries, suggesting that they have a strong comparative advantage in such low-quality products.

It should be reemphasized that the numbers on semifinished steel and bars, rods and light sections refer to exports by all steel mills, not just mini-mills. Particularly in Brazil and Korea, integrated steel producers also are substantial exporters of these products. However, these are clearly products that mini-mills can export, as is demonstrated by the strong export performance of Turkish mini-mills. As mini-mills move into new product areas, their range of exports should grow.

1.5 Scope of the Study

The scope of the study is described in Figure 1.1. We consider the manufacturing process for producing liquid steel. Once liquid steel has been produced, it is cast, rolled and shaped into specific products. Detailed cost models are developed that allow us to account for production cost differences across countries and firms within a country. The models allow an analysis of changes in total costs and cost structure when a new technology is introduced. Though our cost analysis stops at the point liquid steel production is complete, we include a qualitative discussion of continuous casting technology.

FIGURE 1.1: SCOPE OF THE STUDY



1.6 Country Stylizations

We study the competitive position of three stylized groups of countries. The newly-industrializing economies (NIEs) are represented by South Korea and Singapore. Although our interviews in Japan provided us with substantial information on the frontiers of production technology, the benchmark cost estimates for developed countries (DCs) are based on conditions in the United States. Less-developed countries (LDCs) are represented by Mexico and Indonesia.

1.7 The Plan of the Study

Product and manufacturing strategies of a sampling of firms visited for this project are described in the next chapter. On the basis of these visits, the manufacturing literature, and our engineering knowledge and experience, we created benchmark factory cost models defined at a fine level of specification (Chapter 3). These benchmark models are intended to replicate production costs of "representative" factories in the countries visited. A series of cost scenarios based on the adoption of modern management practices and new hardware technologies are examined in Chapters 4 through 6. Throughout, the lessons from our cost models are illustrated with concrete case studies based on our field visits and the industry literature. The concluding chapter comments on the shifts occurring in the competitive abilities of different country types.

2. THREE MANUFACTURERS: A STUDY IN CONTRASTS

2.1 Objectives

In the following chapters, we will simulate changes in unit costs when alternative techniques are adopted by stylized, country-specific benchmark factories. The discussion here provides some of the basis for stylizations discussed later in the report. We summarize first the basic pattern of technology adoption by companies visited for this project and then discuss in some detail three companies representing the three country types. The objective is to relate the choice of production technique to the company's economic environment, product strategy, and human resource strategy.

Nine steel mills in five countries were studied in considerable depth, usually over a day with some follow-up questions and visits. In addition, similar interviews were conducted with 32 other firms (in the electronics assembly, bicycle, and steel industries), and the stylizations that emerge for steel production conform to the overall project results.

The manufacturers we visited were chosen for their representativeness of one of the three country-types. Extensive consultation with industry and country experts, review of the industry literature, and our industrial consulting experience were the basis for choosing particular firms. The visits were not intended to generate primary data on the basic manufacturing process; that was drawn from our experience and expertise. The visits were intended, instead, to enhance our grasp of the range of manufacturing competence. Thus, the relatively modest number of visits to manufacturers in each sector was effectively amplified by visits to manufacturers in other sectors.

2.1 Technology Usage Summary

Before examining three mini-mills in the three country types, let us consider first the summary of technologies in use at the mini-mills we visited (Table 2.1). Oxygen lancing (adding oxygen along with the scrap charge to decarburise the steel) was adopted by all mills. At the other extreme, the heavy investment requirement for scrap preheating, which increases the melting rate and decreases energy consumption, had limited its adoption to two mills, one in a DC and the other in an NIE. Adoption of other technologies was generally high, except in LDCs.

The NIE mill had adopted all the practices discussed in this report. This is not surprising. Given their scrap and energy cost disadvantage vis-a-vis developed country firms, NIE firms can compete only by adopting material and energy saving technologies.

However, to focus on the state-of-the-art condition of the NIE mini-mill in our study would be to devalue the extent to which the DC mills have adopted technologies and practices critical to productivity. All of the DC mills had installed ladle furnaces, which improve the quality of steel produced, give the mill more flexibility in meeting customers' needs and improve the efficienc of downstream activities. Three of the four DC m visited had adopted foamy slag practice (the controlled uniting of carbo oxygen during steelmaking), and half used oxy-fuel burners. Both techno reduce electricity input and raise EAF productivity by melting the scrap more quickly, efficiently, and uniformly. This reduces tap-to-tap time ‹ increases annual capacity for liquid steel.

Three of four DC mills also had some form of materials managen although certain industry characteristics make it difficult for the mills adopt just-in-time (JIT), an inventory reduction practice that relies on rationalization and streamlining of internal procedures, and on stable dem

2.2 Developed Country Firm: Company A

Company A is a market mill with annual capacity over one millior tons of finished carbon steel: special bar quality steel, flats, round bars channels, angles, and reinforcing bars for use in diverse industries. Approximately 75 percent of sales are through warehouse and distribution centers.

Table 2.1: TECHNOLOGY USAGE SUMMARY

COMPANY/	DCs				NIEs		LDCs		
TECHNOLOGY	A	B	C	D	E	F	G	*H	*I
Oxygen-fuel Burners	●		●		●		▼		
Oxygen Lancing	●	●	●	●	●	●	●	●	●
Foamy Slag Practice	●	●	●		●				
Scrap Preheating				●	●				
Ladle Furnace	●	●	●	●	♦				
Materials Management	●	●	●		●				
Highly Automated Computer Controlled Monitored Processes	●		●		●			♦	♦

● Technology in place
▼ Technology being considered
♦ Implementing technology
* Integrated steel company

Each year, 15 percent of gross profit is invested in new equipment or upgrading existing equipment. The objective is to be the lowest-priced steel producer, while maintaining quality and customer service. Company A relies heavily on its research and development department. A company spokesman stated, "A company must continuously be involved with research and development in order to know what is the latest in technology." He added that mills that rely heavily on consulting firms are not using the latest technology, since consulting firms typically sell information based on past experience.

Company A incorporates techniques from high technology sources for its meltshop, continuous casting and rolling mill operations. Technological improvements have helped increase production, improve quality and save labor and energy. Each EAF is equipped with eccentric bottom tapping (EBT), which increases the quality of the steel produced by affording greater control of the slag. By tapping from the furnace to a ladle furnace or a continuous caster (CC), a mill transfers fewer impurities with the molten steel, as the slag forms on the top. Bottom tapping is also quicker than top pouring of a furnace, which was common practice in the past.

The company capitalizes on benefits from oxygen-fuel burners, oxygen lancing, and foamy slag practice to increase melting rates in EAF steelmaking and lower costs on a per ton basis. There is no plan to use scrap preheating, due to the capital investment, limited floor space, and control of EAF dust.

Company A uses a highly automated, computer controlled/monitored process to lower processing times, material costs and energy consumption, while producing a consistent, high-quality product. The computer control system continually assists R&D by supplying data generated from input and actual processing conditions while providing guidance in obtaining the most economical and efficient EAF operation. The control system also helps use scrap charging and alloying effectively, ensuring that the quality of the final product meets customer requirements while providing a means for continuous improvements to the steelmaking process.

The company expects mini-mills will continue to reduce workforce to raise their tonnage per worker ratio. Personnel policies such as continuous training and production incentives, which create motivated, skilled workers, will be central to the process. Company A trains operators to maintain their own equipment in their work area and encourages them to solve problems on their own. The operators use their hands-on experience to help engineers in R&D improve process flow and cut operating costs.

The company wants to move away from a highly centralized management structure to one delegating more responsibility to employees. To promote this change, it offers wage incentives to employees who attend training courses in different areas of steelmaking. The company also offers profit sharing to all employees and feels this has helped the work force unite behind common goals.

Company A uses careful market studies to determine the products that will sell and allow it at the same time to achieve high productivity. Such decisions must be made carefully, because the producer gets locked into those products for extended periods. Company A maintains that customers are seeking a long-term commitment from steel suppliers. Continuity and good working relationships, in addition to providing competitively priced products of consistent quality are, therefore, critical in the steel industry.

The company typically schedules a production plan for made-to-stock (MTS) products. These long production runs put the continuous casting equipment to high use, while requiring fewer changes on the mill's rollers. A product is repeated as often as every six weeks, though a 12- to 16-week rotation is more typical. This type of production scheduling creates a larger inventory of finished products and favors sales to warehouse and distribution centers which can buy large volumes. The company expects the just-in-time concept can be achieved mainly in the flat-rolled market, where the buyer is an automotive manufacturer already attuned to JIT.

Another area to which computers may be applied is electronic data interchange (EDI), a standard for the automated exchange of business documents. EDI provides a valuable link between purchasers and suppliers so they can exchange purchase orders, invoices, price lists, bills of lading, and other business documents, in addition to performing electronic funds transfers. Such capability is believed to give users an edge over competitors who lack the technology.

Company A is profitable because of its management style, highly-skilled labor force, and continuous use of technology to improve the steelmaking process.

2.3 Newly Industrializing Economy Firm: Company E

Company E is a market mill with annual capacity exceeding 750,000 tons of finished product. Its product line consists of carbon steel reinforcing bars and rods for the local construction industry and some exporting. Company E sells to seven distribution centers locally, while also selling directly to end users. Management views the export market as highly risky due to fluctuations in shipping costs, trade regulations, and exchange rates. The primary goal is to meet domestic demand.

The company emphasizes customer service. For example, customers can order special sizes and lengths of reinforcing bars, and receive on-time deliveries consistently, regardless of order size. Company E typically schedules a production plan for made-to-stock items. It carries large inventory levels in all diameter sizes to offer customers shorter lead times in these products.

Management believes that it must continue using the newest, most efficient equipment available, to be cost-effective and competitive on quality, deliverability, and flexibility. A company spokesman stated, "Top management recognizes that being on top of new technology development is a competitive advantage and realizes that there are risks associated with capital ventures utilizing new equipment." The company exercises rigorous quality control at all stages of the steelmaking process. It uses all the technologies discussed in this report and others. Continuous improvements in manufacturing have given it a reputation as a reliable producer and supplier of high-quality steel.

A company spokesman said, "The steel industry is such a dynamic environment, human interface will always be required." Recognizing this, Company E continuously trains employees in all areas of steelmaking. Quality control circles meet regularly to ensure that a safe working environment is maintained, while sharing recommendations for improved, more efficient manufacturing.

Company E has installed an on-line, real-time computer-controlled monitoring system. Through experience, the company has found it more cost-effective to supply electricity to only two of the three EAFs at one time when all three furnaces are on-line together. Oxygen-fuel burners assist in the melting of scrap, further saving on electricity. A computerized process control system for the input and duration of power also helps boost productivity.

The company has also installed a computer-controlled spectrometric analyzer, equipped to analyze up to 40 elements. It can analyze a sample of molten steel in one to two minutes. Four samples per heat cycle are taken: one during the meltdown stage, to confirm that the input data on the grade of scrap steel used is correct, compared to the actual sample; a second during the refining stage, to ensure that the carbon composition is correct; and a third sample prior to tapping, to ensure that the metallurgy meets the customer's specification. During the pouring into the continuous caster, a final sample is taken to ensure uniformity of the melt.

The results of each reading may be disseminated to all processing equipment, for updating. For example, a sample taken during the meltdown stage might reveal that a longer tap-to-tap time is required then originally anticipated, since a larger percentage of impurities were found in the scrap charge. The control system would automatically send a signal to the continuous caster (CC) to slow down casting speed, as pouring into the CC would be delayed. This type of integration helps save processing costs associated with schedule delays, since continuous operations are the most cost effective.

At any stage of the process, an operator can obtain a display of current operating conditions on a PC. Company E's control system is not an artificial intelligence system, since it still requires people to make decisions based on information provided by the system, as well as inputting data and using output data for statistical purpose. A spokesman said, "Scrap grades are inconsistent from one source to another, while the quality of scrap seems to be continuously decreasing. Because of this, an EAF producer will never be able to obtain a cookbook recipe for real-time steel processing. To further complicate the matter, the delay and accuracy of sensors and measuring equipment prohibit real-time, artificial intelligence systems. For these reasons, operators will always be required during the steelmaking process."

Company E continues to increase capacity and profits in a dynamic and highly competitive environment. A spokesman stated, "The key to success is through technology, which will allow steel to be produced more efficiently and consistently. Controls for process planning and production planning will be key issues in the future."

2.4 Less Developed Country Firm: Company G

Company G is a market mill with annual capacity of approximately 45,000 tons of finished product: plain and deformed reinforcing bar, supplied mainly to the domestic construction industry. The company competes against two other local rebar producers. Company G uses customer service as a competitive advantage. It offers rebar in standard 12-meter lengths, with longer lengths available by one-meter increments. It will separate its delivery of orders, shipping to different location. There is virtually no competition from imported steel, because of high import taxes. The exception is specialty steel imports, since little specialty steel is produced in this country.

Company G schedules production runs for made-to-order and made-to-stock items, with the typical run consisting of made-to-stock. The setup time to change from plain rebar to deformed rebar is typically 8 hours. Production runs are usually scheduled for 8 to 10 days before switching product type.

The furnace is equipped with eccentric bottom tapping. The company is considering a new EAF, which would increase capacity. The company could also consider adding oxygen-fuel burners and slag foaming.

The tap-to-tap time for Company G is twice as long as that for more efficient furnaces in developed countries. Besides using oxygen-fuel burners and a foamy slag practice, Company G could consider using a higher rated transformer, allowing for a higher input energy to capitalize on the EAF's ability to melt scrap steel efficiently and effectively.

Like other manufacturers in LDCs, Company G has a problem with a reliable electricity source. Typically once or twice per month, the electricity will stop. Power delays lead to higher production costs.

The company has no computerized process planning or control. It gathers information on an isolated basis during the steelmaking process, with no communication link to other areas in a real-time, information network. The control system can monitor and display only a limited number of control variables (temperature, pressure, carbon content, etc.) and relies heavily on the operator's experience to make rapid decisions. Because the process is so dynamic, accurate information is often lost. A computerized process control system could improve quality, increase predictability, and lower liquid steel cost per ton.

Compared to efficient mills in more developed countries, Company G employs a very large workforce. Since labor is cheap, the total labor cost per ton is easily absorbed in the overall cost, allowing the company to be competitive on price locally. However, excess use of labor reflects not merely the substitution of labor for capital, but inefficient use of resources. If the firm is exposed to greater competition, survival may not be easy. Adoption of new steelmaking practices may become inevitable. Company G also needs to develop a skilled workforce that is flexible and trained in several areas of steelmaking. This can help reduce the labor content and, through employee awareness, raise quality.

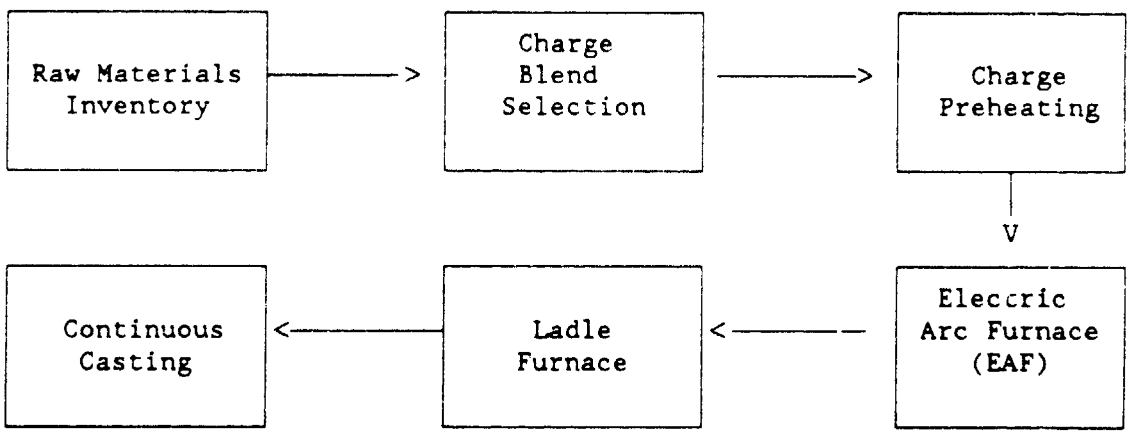
3. STEELMAKING: THE BENCHMARK FURNACE

3.1 Mini-Mill Process Flow

In the mini-mills visited, the process flow of steelmaking was straightforward and fundamentally the same. Figure 3.1 shows a typical flow of materials. The distinguishing feature of the mini-mill process is melting of scrap in the electric arc furnace (EAF).

To aid international cost comparisons, we assume the existence of a benchmark mini-mill. The output of this mill is carbon steel, chosen because it was produced by mini-mills in all five countries visited. Costs of production are determined at the point where liquid steel is produced, i.e., either after the material has been melted in the EAF, or when the optional ladle furnace has been used to further refine the melted scrap. In other words, we do not model the costs of casting, although the process is shown in Figure 3.1. However, in Chapter 6 we discuss qualitatively the trends in casting technology and their implications.

FIGURE 3.1: MINI-MILL PROCESS FLOW



We have developed a process model of steel production in mini-mills. This model may be thought of as a simulated factory. Each phase of the process is summarized in terms of number of machines, number of workers, and the operational efficiency of the machines and workers in that phase. Equations linking the performance of different phases complete the model. A detailed descript'on of the equations underlying the benchmark model is provided in Appendix C. The model has been implemented on a computer spreadsheet, making sensititivity tests and analysis of technical change quick and easy.

As noted in the previous chapter, through reference to the relevant industry literature and our engineering experience, we had developed a basic process model even before the field visits. The intensive field visits provided a richer understanding of the process and also some estimates of the range of process performance indicators. The model thus developed was used to replicate the output and cost performance of the firms interviewed.

3.2 The Benchmark Mill

Some of the key features of the benchmark process should first be noted. We assume the benchmark furnace to have a size of 150 tons which, working at full capacity, yields about 600,000 tons of steel a year. Although smaller furnaces are used, 150-ton furnaces are increasingly the international benchmark and even 350-ton and 400-ton furnaces are in use. Developing country firms are not obliged to set up such large furnaces and may in any case be unable to do so, given the $100 million price tag. A smaller furnace eases entry, but raises unit costs of production since economies of scale exist. The key disadvantage of smaller furnaces is their much higher energy loss, which raises sharply their energy use for a ton of steel produced. As we show below, using a smaller furnace would only worsen a developing country's position vis-a-vis developed countries.

Even in the past, small EAFs were efficient only in a narrow sense. The chemistry of operations within an EAF was largely unknown and hence the output was very unpredictable. Minor changes in scrap composition and/or operating parameters of the EAF could result in large amounts of unusable output (Hess, Iron Age, October 1989). Prudence dictated the use of small furnaces in which losses were limited, and capacity was expanded by adding another small furnace. Over the past decade, careful experimentation has greatly expanded knowledge about how an EAF works and can be controlled, and operators are more confident of running scrap through larger EAFs.

A central parameter that dominates all influences on the cost of steelmaking is the "tap-to-tap" time (Table 3.1) or the time taken by the EAF to process the scrap. It is so-called because it represents the period between successive tappings of batches of steel. During this time, the furnace is charged, the scrap melted and refined, and the molten steel tapped. Much ingenuity has been devoted to reducing melting and refining times.

It helps the perspective to note that much technical progress is embodied in what we describe as a "benchmark" furnace. In the early 1980s, tap-to-tap times of three hours or more were not uncommon, although Japanese mini-mills had already lowered processing times to two hours (Hess, p. 22). Our benchmark furnace has a tap-to-tap time of just under two hours (113 minutes). The changes described in the next chapter have occurred in the last five or six years and have made it possible to lower tap-to-tap times to about 80 minutes or less.

Table 3.1: PARAMETERS FOR BENCHMARK MODEL

EAF Parameters	Units	Parameters
Furnace size	tons	150
The tap weight	tons	150
Arc furnace transformer	MVA	90
Charges per heat	charges/heat	2
Total energy consumption	kWh	500
Charging loss time	minutes	10
Refining time (20-40 minutes)	minutes	25
Tapping time (5-10 minutes)	minutes	10
Meltdown time	minutes	68
Tap-to-tap time	minutes	113

Source: Center for Metals Production 1987.

Fixed costs can be broken into three sources: interest, depreciation and maintenance expenditures. The base assumptions regarding these three sources of expenditure are given in Table 3.2. We have assumed that depreciation rates do not differ across countries but interest rates do. A depreciation rate of 10 percent reflects our judgment that, irrespective of their location, firms will have to make new investments continuously to remain competitive. In practice, of course, new investments will get lumped and hence the assumed smoothness of the depreciation schedule is artificial.

Table 3.2: SOURCES OF FIXED COSTS
(percent)

	DC	NIE	LDC
Interest rate	8	10	12
Depreciation rate	10	10	10
Maintenance rate*	4	4	4

* Maintenance expenditure per $100 of capital equipment.

It is not easy to pin down the interest rate being paid by a firm, and it is even more complicated to account for various tax measures that influence the effective interest being paid by the firm. For that reason, we have done a number of sensitivity tests around the base rates assumed. These are reported later in the chapter.

Table 3.3 presents the variable input coefficients and the prices of these variable inputs. The noteworthy features of this table are as follows. We have assumed that the cost of scrap is lower in a developed country than in either an NIE or an LDC. This is based on our field interviews and reflects the higher levels of industrialization in developed countries, which gives them an advantage in scrap availability and price. Turkey, the one less industrialized country that has made a major effort to develop mini-mills, relies heavily on imported scrap.

Table 3.3: VARIABLE INPUTS

Input	Input per ton of liquid carbon steel	Price of input (US$) DC	NIE	LDC
Scrap (tons)	1.03	90.00	115.00	115.00
Flux (ton)	0.03	55.00	55.00	55.00
Alloy (pound)	10.00	0.30	0.30	0.30
Refractory & panel ($/ton)	4.00	1.00	1.00	1.00
Others ($/ton)	1.00	1.00	1.00	1.00
Electricity (kWh)	500.00	0.035	0.050	0.080
Electrodes (pounds)	7.50	1.25	1.25	1.25
Lance oxygen (mcf)	0.32	3.00	3.00	3.00
Labor (manhours)	0.64	21.00	5.00	3.00

The cost of electricity is another important variable across country types, with the lowest costs, on average, prevailing in developed countries and the highest in LDCs. Costs of steel production are extremely sensitive to electricity costs, as shown below.

In LDCs' favor, on the other hand, are the lower labor costs. The question is: Are lower wages sufficient to make LDCs competitive in producing steel via mini-mills? In view of our discussion in Chapter 1, where we noted the small share of labor in total costs, it is not surprising that low wages have a very limited effect.

The benchmark estimates of costs of steel production in the three prototype countries are given in Table 3.4. Developed countries are most competitive and the two major sources of that are quite clear: scrap and electricity costs.

Table 3.4: COST OF PRODUCING LIQUID STEEL IN A "BENCHMARK" FURNACE (US$ per ton of liquid steel)

	Less developed countries	Newly industrializing economies	Developed countries
Material	128.10	128.10	102.35
Electricity	40.96	25.96	18.46
Electrode	9.38	9.38	9.38
Labor	1.92	3.20	13.44
Maintenance	6.44	6.44	6.44
Interest	19.34	16.11	13.09
Depreciation	16.11	16.11	16.11
Total	222.24	205.29	179.06

Source: Appendix C.

3.3 Sensitivity to Interest and Electricity Rates

Estimates presented in Table 3.4 replicate the ordering of costs that we observed. However, the cost disadvantage of LDC plants can be greater than suggested. LDC plants are smaller and, given the (limited) scale economies, have higher costs on that account. Three other factors that we explore here are variations in interest costs, electricity rates and production efficiency.

Table 3.5 is a matrix for electricity costs and interest rate variations for an LDC. Two clear conclusions emerge from this table. Interest rate changes have a limited impact on production costs. A five percentage point increase (from 10 to 15 percent) raises costs by only $8 per ton. However, costs are very sensitive to changes in electricity rates. An increase in rates from 8 cents/kWh to 14 cents/kWh increase costs by $30 per ton. Since the 14 cents/kWh rate is common in many LDCs, higher production costs will also be seen to prevail.

Table 3.5: SENSITIVITY OF COSTS TO ELECTRICITY AND INTEREST RATES

Electricity Cost (US cents/kWh)	Interest Rate (%)					
	10	11	12	13	14	15
3.5	196.51	198.13	199.74	201.35	202.96	204.57
5.0	204.01	205.63	207.24	208.85	210.46	212.07
6.5	211.51	213.13	214.74	216.35	217.96	219.57
8.0	219.01	220.63	222.24	223.85	225.85	227.07
9.5	226.51	226.13	229.74	231.35	232.96	234.57
11.0	234.01	235.63	237.24	238.85	240.46	242.07
12.5	241.51	243.15	244.74	246.35	247.96	249.57
14.0	249.01	250.63	252.24	253.85	255.46	257.07

(US$/ton of liquid steel)

3.4 Efficiency

Finally, we have assumed that the process is operated in an efficient manner. However, many sources of inefficiency can creep in. Among the most important is lack of scrap monitoring. In a scrap monitoring program, scrap is sampled, tested and segregated according to size and purity. Residuals in the scrap reduce the ability to control the furnace and lead to longer processing times and higher production costs. Impurities also greatly influence the quality of steel produced. Similarly, blending the scrap with alloying agents and fluxes, and monitoring energy and electrode consumption have direct effects on costs and also indirect effects through their impact on furnace panels and refractories.

These inefficiencies result in increasing input requirements above the levels presented in Tables 3.2 and 3.3. It is common to equate process efficiency with labor productivity. However, that is a very narrow definition of efficiency. Labor use has fallen to levels such that even a doubling of that level increases production costs by only $2 or $3 per ton.

Efficiency in the wider sense of scrap, energy and furnace management has no simple measure. It is, however, commonly believed in the industry that lack of efficient management of these inputs can increase costs by 5 to 7 percent, or between $10 and $15 per ton.

There are probably many causes for such system-wide inefficiency. Poor quality labor is a major contributory factor. Producers tended to agree that a motivated, skilled and experienced work force can play a crucial role in cutting costs. These features of the workforce are becoming increasingly important as the more advanced technologies (described in the following chapters) requiring a workforce that has multiple skills and flexibility for many assignments. Most mini-mill operators in DCs ensure good worker relations through profit-sharing, frequent training courses, the opportunity for involvement in process decisions, and promotion programs. A good example of an integrated worker development strategy is discussed in Box [illegible].1.

U.S. mini-mills also have flat hierarchies. Among the many identifying symbols of the industry is the tiny rented office that serves as the headquarters of Nucor Steel, housing a staff of 20 people in a company with 5,600 employees. Nucor uses a pay system based primarily on incentive bonuses. The principle of delegation of authority has been promoted over the last twenty years, well before it became fashionable. The combination of worker incentives and delegation of authority has been a major factor in Nucor's ability to absorb new technologies rapidly. However, critics also note that the extreme pressures this creates has led to a less than exemplary safety record (Financial Times, May 29, 1991, p. 12).

Besides their own high quality production and engineering staff, developed country mini-mills also draw upon specialized input providers often located in close geographical proximity. A significant share of engineering work is farmed out to engineering firms. Firms also rely on suppliers of capital equipment for technical input and implementation service. These clusters of engineering services from consulting firms and suppliers are critical in supporting efficient operation.

A further interesting feature of the steel mini-mill industry in the U.S. is the phenomenon of informal know-how trading between mini-mill operators. Through plant tours, industry association links, and even specific consultancy services, engineers provide information on the production process to their counterparts in competing firms (von Hippel 1988). The know-how trading, though informal, is done on a crude reciprocal basis (through "handshakes" rather than through contracts). Similar close links between mini-mill steel producers (and between producers and their supplier) are found in Turkey (see Appendix B).

BOX 3.1: LABOR PARTICIPATION IN TEXAS

Profit-sharing and participative management are integral to the personnel philosophy of Chaparral Steel, a mini-mill operation owned by Texas Industries that is the tenth largest steel producer in the United States. In Midlothian, TX, Chaparral is a market mill with an annual capacity of 1.5 million tons.

All employees are salaried, and earn an average of $30,000 to $35,000 annually. The work force is non-union and likely to remain so; there have been no layoffs at Chaparral in the company's 15 years. All of the mill's 960 employees are invited to participate in profit-sharing, and 80% of them do; they are paid from a fund into which Chaparral deposits 6% of its gross profit.

The producer has set itself a goal of bringing down the work force to between 700 and 800 employees, while lowering man-hours/ton by a third. Chaparral believes that it can reduce the ranks of middle management through participative management. Employees are encouraged to solve problems themselves, thus reducing the need for supervision, and to assume responsibility for production; shift workers are required to stay on the job if their replacements fail to show up on time.

A worker can expect to receive about 12 hours of training each month for the first three and a half years of his employment, before Chaparral considers that he is completely trained in all areas. Operators learn to maintain their own equipment in their work area, and help engineers in R&D improve process flow and lower operating costs--savings that come back to the work force in profit-sharing.

It is the interaction between incentive pay systems, participative management, and large investment in training that combine to continuously raise productivity. These very Japanese management features have been a part of the history of mini-mills and are at least as much responsible for their success as the technical characteristics of the electric arc furnace that allows scrap to be converted into steel.

3.5 Summary

Costs of steel production using a benchmark furnace depend heavily upon scrap and electricity costs, and only marginally upon labor costs. Prices of these two inputs and the efficiency with which they are used determine the ability to compete internationally. Hiqh quality labor force, training and incentives to continuously upgrade workers, clusters of specialized input suppliers, and informal trading of know-how are the sources of continual knowledge generation and diffusion. These are not quantifiable benefits but are clearly central to an industry being internationally competitive.

4. METALLURGICAL INNOVATIONS

Innovation in the mini-steel sector has been driven by the need to reduce material, energy and capital costs. Our process models show that when the focus is on saving material, energy and capital, labor is saved as a by-product. Increasing labor productivity in isolation is possible when labor is being very inefficiently used. However, when inputs are being used efficiently, technical change directed primarily towards saving labor is almost never the goal, even in countries with expensive labor.

In this chapter we consider metallurgical innovations directed principally at reducing energy and capital costs. We will first describe three melting practices that lower production costs: oxygen-fuel burners, oxygen lancing with added carbon (sometimes referred to as foamy-slagging) and scrap preheating. Then we will consider refining in a ladle furnace, a practice that not only lowers cost but also improves quality and production flexibility. The benchmark estimates of the previous chapter are used here as the reference point for analysis of process improvements.

4.1 Melting Technologies

High electricity costs have driven research to pursue alternative forms of energy and greater energy efficiency for melting scrap charges. In this section, we describe three practices for saving energy. As noted, other costs fall as a by-product.

Oxygen-fuel Burners

Oxygen-fuel burners can shorten meltdown times by 5 to 15 minutes. The thermal efficiency of burners is about 50 percent, which is slightly above that of an EAF. The fuels used in oxygen-fuel burners, also called jet-burners or oxy-fuel burners, are kerosene, light oil and natural gas. Energy costs are cut if the fuel is cheap compared with electricity.

Oxy-fuel burners can, therefore, be used to provide additional energy to a furnace. They are specially used at selective times to offset peak-load electricity pricing. Oxygen-fuel burners also increase uniformity in melting the scrap as they add energy to cold spots in the scrap charge.

However, oxygen-fuel burners have limitations:

- They are applicable only to furnaces equipped with water-cooled linings.
- They require exhaust systems to extract fumes.
- Burners and associated mechanisms may be damaged by radiant heat or by falling pieces of scrap during charging.

Oxygen Lancing and Carbon Addition (Foamy Slag Practice)

Typically, a mini-mill adds oxygen at the end of a melting period to remove carbon from (decarburise) the steel. However, such sequential addition is inefficient, particularly when ultra-high power transformers are being used. Energy consumption and tap-to-tap time increase, raising cost.

Mills have, therefore, started adding oxygen along with the scrap charge. However, such oxygen "lancing" also increases oxidation of the scrap. To avoid this, mills pneumatically inject coal into the furnace (Adolph and Paul, 1989). The controlled uniting of carbon and oxygen during steelmaking produces a foamy slag. Besides controlling oxidation, the foamy slag improves heat transfer from the electrodes to the scrap charge while protecting the water-cooled panels from arc overheating and the refractory wall from forming hot spots.

Scrap Preheating

Preheating scrap to increase the melting rate and decrease energy consumption is a simple concept and has been carried out in some shops for many years.

Scrap preheating can be accomplished by using either fossil fuels, such as gas or oil burners, or by using the exhaust or off-gas from the furnace (Center for Metal Production 1987). A typical energy balance for an EAF indicates that about 20 percent of the energy, or over 110 kWh, leaves the furnace as hot gases. Additional equipment, such as heat exchangers, is required to use these gases effectively. Furnace off-gases and extra combustion air can preheat scrap to 930° F, thus saving about 50 kWh while shortening tap-to-tap time by about 10 minutes. Preheating to 1650° F is possible with special equipment and some subsidiary fuel, potentially saving as much as 100 kWh/ton.

Apart from power savings and shorter melting time, useful indirect benefits are drying of the charge and pre-combustion of oil. Both of these are important prerequisites for safe "hot heel" practice, in which some of the liquid steel is retained in the furnace instead of all of it being removed during tapping. This practice promotes heat transfer during the next charging of scrap (Center for Metal Production 1987).

Most mini-mills in the U.S. were not designed to accommodate scrap preheating. Space is short, buckets used to charge the EAF with scrap have limited capability to withstand heat, and preheating causes difficulties with certain exhaust fumes (McManus (A) 1988). Newer plants being installed have a preheating system.

In Europe and Asia scrap preheating is widely practiced. Mini-mills we visited in Japan and Singapore considered their batch preheating systems to be successful in reducing process time and cost.

Batch preheating should not be confused with the Consteel process (which is in the latter stages of development with a furnace operated by Nucor at Darlington, S.C.). The Consteel process is a continuous steelmaking process which combines scrap preheating with furnace off-gases and auxiliary burners, with continuous melting and periodic bottom tapping. Batch preheating operations described here represent a more fully developed technology (Center for Metals Production 1987).

4.2 Cost Implications of Melting Technologies

We examine cost savings and changes in cost structure following the adoption of the above process improvements. Oxy-fuel burners, preheating to 900° F and preheating to 1800° F are the three practices considered. For reasons of data availability, we have combined the foamy slag practice (oxygen lancing with carbon addition) with the preheating practices and studied their combined, rather than separate, implications.

Oxy-fuel burners are cheap to install, but preheating can be expensive (Table 4.1). The adoption of all three practices lowers electricity use. On the other hand, consumption of oxygen and natural gas goes up (Table 4.1 and Table C.3 in Appendix C). The net effect then depends upon the relative prices of these substitute energy sources. For the range of input prices observed, there is a decline in total energy and electrode costs.

Finally, total labor employed is not significantly affected by the introduction of these practices. Since output increases, labor input per ton of steel falls.

Table 4.1: PARAMETERS FOR ALTERNATIVE TECHNOLOGIES

	Units	Standard Furnace	Oxy-fuel Burners	900°F preheat*	1800°F
Investment	US$ million	100.0	100.6	114.6	135.0
Variable Inputs					
Power consumption per ton of scrap melted	kwh	500	420	323	273
Lance: oxygen	mcf		0.32	1.13	1.13
carbon	lbs			20.00	20.00
Burners: oxygen	mcf		0.36		
Natural gas	mcf		0.18		
Preheat natural gas	mcf				1.06
Electrodes	lbs	7.50	7.00	6.00	4.00
EAF Operational Characteristics					
Charging time	minutes	10	10	10	10
Melting time	minutes	68	57	44	37
Refining time	minutes	25	25	25	25
Tap time	minutes	10	10	10	10
Tap-to-tap time	minutes	113	102	89	82
Capacity	thousand tons	620.8	686.7	787.7	852.9

* Includes oxygen lancing and added carbon (also known as foamy slag practice).

A feature common to all three practices is that the melting time in the EAF is reduced (see Table 4.1). The consequent increase in capacity outstrips the increase in investment, leading to a lower capital cost per ton of steel produced.

The aggregate cost implications are summarized in Table 4.2. All three technologies represent a significant improvement over the standard furnace. The largest cost savings potential is in 900° F preheating (along with foamy slag practice), followed by oxygen-fuel burners. When these practices are implemented in the same mill, the benefits are more or less additive. For a developed country firm, the adoption of oxy-fuel burners and 900° F therefore results in a cost savings of about $17 per ton of steel (9 percent). Since the initial share of labor cost is not very high, the benefit to a developed country from the indirect lowering of labor costs is modest. The labor cost decline contributes only $4 to the $17 savings, the rest coming from lower capital and, primarily, energy (including electrode) costs.

Table 4.2: COST IMPLICATIONS OF MELTING TECHNOLOGIES

Cost Category	Country	Standard Furnace Unit Cost	Decrease in cost (US$/ton of liquid steel) Oxy-fuel Burners	900° F preheat*	1800° F preheat*
Material	DC	102.35	0	0	0
	NIE	128.1	0	0	0
	LDC	128.1	0	0	0
Electricity + Electrode	DC	27.84	1.63	4.83	4.85
	NIE	35.34	2.83	7.48	8.25
	DC	50.34	5.23	12.78	15.06
Labor	DC	13.44	1.29	2.85	3.66
	NIE	3.20	.31	.68	.87
	LDC	1.92	.18	.41	.52
Maintenance	DC	6.44	.58	.62	.11
	NIE	6.44	.58	.62	.11
	LDC	6.44	.58	.62	.11
Interest	DC	13.09	1.37	1.45	.42
	NIE	16.11	1.46	1.56	.28
	LDC	19.34	1.76	1.88	.35
Depreciation	DC	16.11	1.46	1.56	.28
	NIE	16.11	1.46	1.56	.28
	LDC	16.11	1.46	1.56	.28
TOTAL	DC	179.06	6.12	11.10	9.11
	NIE	205.29	6.63	11.89	9.79
	LDC	222.24	9.10	17.24	16.30

* Includes foamy slag practice.

The absolute cost saving from the adoption of oxy-fuel burners and 900° F preheating (with foamy slag practice) is greatest for a developing country: $25 per ton. The reason a developing country benefits most is that these technologies economize on capital and electricity, the two resources that are most expensive in developing countries. If energy and interest costs were higher in a developing country than we have assumed, as is likely to be the case, the gain from adopting these practices would be even greater.

The scenario developed here is a useful illustration of the pitfalls of narrowly characterizing technical change. If an analyst focussed only on capital and labor, he would conclude, quite rightly, that the new technologies make the production process more capital intensive, i.e., the ratio of capital to labor costs goes up in all countries. Technical change, therefore, seems biased against developing countries that have an abundance of labor. However, two aspects of the change make the adoption of these technologies desirable from a developing country's point of view. First, there's a large saving in energy input. Second, even though the ratio of capital to labor increases, there is a fall in the use of both capital and labor per ton of steel produced. Hence an absolute resource saving occurs even though the relative share of the scarce resource (capital) goes up.

Summary

All practices discussed here reduce cycle time and hence save on energy. Clearly, the message is "go faster to save energy" (Sheridan 1989). Oxygen-fuel burners and oxygen lancing with the injection of low-cost carbonaceous material (foamy slag practice) substitute other fuels (kerosene, natural gas, oxygen) for electricity. Preheating increases the efficiency of electricity use. All practices have the added effects of lowering unit capital and labor costs. For developing countries, these practices are particularly relevant as they save on energy and capital.

4.3 Steelmaking via Ladle Furnace

The EAF has proven its ability as an efficient melting unit but is less efficient in refining the liquified steel. The loss in efficiency is due to the large bath surface area when the EAF is used for refining. In superheating a steel melt in an EAF, the energy efficiency is on the order of 30 percent. However, efficiencies may be 60 percent or higher when superheating is performed in a ladle furnace where the bath surface area is greatly reduced (Cotchen 1988).

More importantly, the ladle furnace improves the quality of steel produced by optimizing combustion temperatures and alloying agents to adjust the molten steel to proper conditions before it is cast. Refining in the ladle furnace leads to fewer surface defects, improved cleanliness and greater consistency in mechanical properties. These features, while desirable in themselves, also improve the efficiency of downstream activities, such as rolling.

The ladle furnace further allows steelmakers to meet requirements for final products with varying grade and end use requirements. At Border Steel Mills, Inc., in El Paso, Texas, the ladle furnace has been used for increasing the range of products offered (Wolfe et. al 1988). Bar products for forging applications and rods for oil field applications are demanded in various grades. The ladle furnace has been used to good effect.

Today, some mini-mills are using the EAF primarily to melt charges of scrap, while capitalizing on the advantages of the ladle furnace for the refining stage. Several ladle refining methods are available to process nearly any type of steel. Ladle refining may generally be classified into four main categories: Stirring, injection, vacuum treatment, and reheating. Table 4.3 lists the basic functions and processing techniques for the various refining methods (Teoh 1988A).

Table 4.3: BASIC FUNCTIONS AND PROCESSING TECHNIQUES FOR VARIOUS SECONDARY STEELMAKING METHODS

	Function	Techniques
(1)	Metallic composition control	• Gas stirring of molten steel
	• Homogenization of main elements • Adjustment of temperature	• Heating of molten steel
	• Narrow range control of main	• Thorough mixing of additions (ferroalloy, powder, etc.) and stirring
	• Residual elements control	
(2)	Nonmetallic compounds control	• Slag control
	• Elimination of total amount	• Retaining an inert gas atmosphere
	• Convert to a noninjurious composition	
	• Convert to a useful composition	• Refining of steel by the use of synthetic slags
(3)	Gaseous elements control	
	• Elimination of [H], [N], and [O]	• Vacuum treatment of gas removal
	• Control to required level	

Source: Teoh 1988A.

4.4 Economics of the Ladle Furnace

A ladle furnace adds to investment cost by about $3 million. However, once the ladle furnace is introduced, the EAF has less work to do. Specifically, the refining task, which took 25 minutes in the standard furnace, is now completely transferred to the ladle furnace. The throughput of the EAF is therefore increased. Considerable effort is required in logistically matching the ladle furnace to the EAF. Provided that such coordination is achieved, the throughput of the entire system is increased to almost 800,000 tons. As in the previous cases, the increase in output is large enough to substantially lower unit capital costs.

The total cost savings from introducing a ladle furnace are reported in Table 4.4. The structure of cost savings is very similar to that of the melting technologies and is not reported here. As before, developing countries gain the most, due to features that carry forward from the previous technologies: capital and energy cost savings. The higher the interest rate, the greater the absolute cost reduction. See Table 4.5.

In addition to lowering the cost of production, the ladle furnace also allows for higher product quality with greater scope for producing a variety of steel products. By lowering unit costs of production and raising product quality at the same time, the ladle furnace will soon have the effect of rendering obsolete a range of low-quality products.

Summary

Once considered a luxury and a liability, the ladle furnace today is recognized as an indispensable tool for clean steel production. Customer demand for higher-quality steel is forcing mini-mills to adopt the ladle furnace. Its role is likely to increase as mini-mills add to their lines products that require longer refining time to lower the residual content. Ladle furnaces have diffused rapidly all over the world (International Iron and Steel Institute 1990). Even LDC firms producing relatively low quality products can derive significant cost benefits from a ladle furnace. See Box 4.1.

Table 4.4: COST IMPLICATIONS OF A LADLE FURNACE

(US$/ton of liquid steel)

Country type (1)	Standard Furnace (2)	Standard + Ladle Furnace (3)	Cost Difference (4)=(3)-(2)
DC	179.1	165.5	-13.6
NIE	205.3	192.3	-13.0
LDC	222.4	206.3	-16.1

Table 4.5: INTEREST COST REDUCTIONS THROUGH A LADLE FURNACE
(US$/ton of liquid steel)

Country type (1)	Interest rate (%) (2)	Interest Costs When Using: Standard Furnace (3)	Standard + Ladle Furnace (4)	Cost Difference (5)=(4)-(3)
	----------US$/ton of liquid steel----------			
DC	8	13.1	10.4	-2.7
NIE	10	16.1	13.0	-3.1
LDC	12	19.3	15.6	-3.7
	15	24.3	19.5	-4.8

Box 4.1: PRODUCTION BOTTLENECKS IN INDONESIA

The lack of a ladle furnace is a serious handicap at the mini-mill operated by P.T. Pulogadung Steel in Jakarta, Indonesia. The mill, which produces about 48,000 tons per year, has a tap-to-tap time of 135 minutes; by contrast, the tap-to-tap time for this report's benchmark furnace is 113 minutes, and the time in some developed countries is only 60 to 70 minutes.

The electric arc furnace is the bottleneck, since there is an imbalance between the EAF and the plant's two rolling mills. Pulogadung is installing a second EAF, which will increase its steelmaking capacity. However, if Pulogadung had a ladle furnace for refining its higher-quality products, it would free the EAF exclusively for charging (melting).

Pulagodung has other production problems. Like many manufacturers in LDCs, it cannot depend on the reliability of electricity; service typically stops one or twice each month. Nor is electricity cheap. The local supply of scrap is limited, and nonexistent for specialty steel, so scrap must also be imported from the United States and Hong Kong. The company has introduced computerization at a minimal level, for inventory control and some manufacturing operations.

5. ROLE OF COMPUTERS IN STEELMAKING

In any industry the effective use of computers requires that the production process be well understood. The computer is an instrument for accurate and rapid computation. But for the computations to be of value, they must be performed on relationships that are good representations of the production process. We noted in Chapter 3 that such knowledge has been acquired only slowly over the last decade. Computers have, therefore, spread within mini-mills at a slower rate than within integrated mills. Innovations described in the previous chapter have led to greater controllability of the process and the rapid spread of computers now seems imminent.

The principal effect of computers thus far has been improved scrap management. Examples of full process control are rare but are rapidly increasing. Computers continue to decrease in size, increase in power and accept more powerful and user-friendly software. Computers connected with control operations allow users to coordinate production procedures so that material flows from one process to the next with the minimal delay and handling; they also facilitate tighter quality control.

5.1 Computerized Materials Management Program

Today, more and more steel producers are also using computers extensively for data logging and information acquisition to support materials management. Purchase, storage, and use of materials in the right quantities and the right sequence is a complex operations research problem that is usefully committed to large computers. Materials management programs seek to minimize the materials cost per ton of product, consistent with quality requirements.

Scrap, fluxes, alloys, refractories, and electrodes in varying quantities and qualities are the major cost components for makers of carbon steel products. A materials management system draws on information about these inputs from the raw materials marketplace, melt shop operations, and product quality specifications.

To establish a materials management program, it is necessary to create an information-gathering system to log data in sequence to help characterize the raw materials and their use. Materials must be classified by chemistry, by iron yield, by integrity of scrap, and by price (Schroeder 1985). Monitoring materials use on a heat-to-heat basis can help set rules on how and in what order materials are committed to production.

Sophisticated linear programs are used for scrap management. Constraints resulting from EAF process parameters, scrap chemistry, scrap inventories, scrap price and availability drive the program. For the final product desired, the program chooses the least-cost combination of materials. Such sophistication is critical if mini-mills are to upgrade the quality of their products. Rapid changes in product composition also require detailed control over raw material management. Table 5.1 shows the percent savings possible through computerized materials management (Schroeder 1985).

Table 5.1: SAVINGS POSSIBLE BY COMPUTERIZED MATERIALS MANAGEMENT PROGRAM

Cost center	% of total cost	% of material saved	% savings to total cost
Scrap	58.2	8	4.65
Ferroalloys	3.6	15	0.54
Oxygen	0.7	30	0.21
Flux	1.7	20	0.34
Investment	1.6	10	0.16
Labor	1.9	10	0.19
Refractories	1.6	10	0.16
TOTAL			6.25

Source: Schroeder 1985.

5.2 Computers for Process Control

Linking shop-floor computers to central control operations over the entire steelmaking process creates a closed-loop control system. The use of real-time information, so all stages of the process have the same information simultaneously, enhances productivity, reduces cost and, most important, improves quality. Today there is a big push to integrate all areas of steelmaking.

Once an extensive data logging and acquisition system to record information is established, conventional mathematical control algorithms can be used to make decisions in response to process events by manipulating a set of rules programmed by the software. The major cost and effort for computerized process control is in the development of application software.

Advanced personal computers (PC's) can provide decisions in fractions of a second, or a few seconds at most, for process control applications. PC's are being used on the shop floor to give personnel immediate information about the process, resulting in faster decision-making and better process control (Horne 1988). The cost of these systems has fallen considerably in recent years, while the software language can be mastered without too much difficulty.

User-friendly software is extremely important, as the real measure of any computer-controlled process system is whether human knowledge of procedures and corrective remedies can be readily translated into a form that the computer can understand and manipulate. Since operators and in-house engineers best understand their own mill's environment, software is most often developed in-house for a mill's specific operation.

5.3 Examples of Process Control

In 1984, National Iron & Steel Mill (NISM), Singapore, which produces bar products of carbon steel, launched a major program to modernize and expand its melt shop operation. Table 5.2 describes the performance of the melt shop after the computer control system was implemented. Power demand fell and better furnace productivity led to fewer processing delays. The computer control system paid for itself in less than one year (Hock and Schroeder 1988).

Table 5.2: MEL: SHOP PERFORMANCE BEFORE AND AFTER IMPLEMENTATION OF A COMPUTER CONTROL SYSTEM

Year	Tap-to-tap reduction Time (min)	Billet production increase Tons/month	Electrode savings kg	Power consumption savings kWh/billet ton
1985-1986	4	2,203	0.16	12
1986-1987*	2	856	0.03	2

* First six months of 1987.

Source: Hock and Schroeder 1988.

In addition, the quality of the steel improved and the efficiency of continuous casting increased. See Box 5.1 for a description of how these improvements become possible.

BOX 5.1: PROCESS CONTROL BY COMPUTER IN SINGAPORE

At Singapore's National Iron & Steel Mill (NISM), every step of the process is controlled by an on-line, real-time computer system. A computer regulates, for example, the amount and duration of power going to each of the mills's three EAFs, with automatic switch-over from one furnace to another. Because electricity is not cheap, this is an important area for savings.

In 1987 NISM installed a computer-controlled spectrometric analyzer that can handle up to 40 elements. The analysis, which takes only a minute or two, involves taking three samples per tap: one during the meltdown stage (to confirm that the input data on the grade of scrap steel is correct); one during the refining stage (to ensure the carbon composition is correct); and one during the final ladle stage (to ensure the product meets customer specifications). A fourth sample is taken when the steel is poured into the continuous caster.

At each step, if changes are necessary, the results are disseminated throughout the process. If the sample taken during meltdown reveals that a longer tap-to-tap time is required than originally input, for example, the control system automatically sends a go-slow signal to the continuous caster because pouring into the caster will be delayed. Such measures, which allow the system to run continuously, result in savings on energy and material.

In general, the computer control system allows NISM to coordinate power demand and process flow, and to turn out a consistent product. It also supports R&D efforts aimed at reducing processing times and costs, by supplying data on actual times, conditions and inputs.

At Lukens Steel Company, Coatsville, PA, raw material handling, EAF melting, ladle refining and continuous slab casting are all linked through computer loops (Hess, 1989). Also linked are auxiliary equipment such as oxy-fuel burners, oxygen lance and carbon injector. Mechanical motions are regulated by programmable controllers. To maximize benefits from this computerization program, Lukens' engineers have worked at designing scrap charges, developing melting practices and improving maintenance capabilities.

5.4 Computerization of the Benchmark Mill

If we apply the potential benefits of a computerized process control system and materials management program to our benchmark mill in each country type, we can estimate the potential cost savings on a per ton basis. Table 5.3 displays the breakdown of cost savings per ton of liquid steel before and after implementation.

Table 5.3: COST SAVINGS THROUGH COMPUTERIZATION
(US$/ton of liquid steel)

Cost Category	Country	Standard Furnace Unit Cost	Decrease via Computerization
Material	DC	102.35	8.60
	NIE	128.10	10.66
	LDC	128.10	10.66
Electricity + Electrode	DC	27.83	1.64
	NIE	35.79	2.55
	LDC	50.34	8.04
Labor	DC	13.44	1.99
	NIE	3.20	0.47
	LDC	1.92	0.10
Maintenance	DC	6.44	0.25
	NIE	6.44	0.25
	LDC	6.44	0.25
Interest	DC	13.09	0.71
	NIE	16.11	0.64
	LDC	19.34	0 77
Depreciation	DC	16.11	0.64
	NIE	16.11	0.64
	LDC	16.11	0.64
TOTAL	DC	179.06	13.61
	NIE	205.29	14.74
	LDC	222.24	15.40

Process control system and materials management are used to monitor and control all functions in the melt shop, from scrap selection through billet casting. Capital investment for the computer control system is assumed to be $1 million worldwide.

Lower power and materials consumption, along with associated savings from a reduced meltdown time (such as electrode consumption, maintenance, capital recovery, and labor) cut the final cost per ton of liquid steel by $13.61 (7.6 percent) for a DC benchmark, $14.74 (7.2 percent) for an NIE, and $15.40 (6.9 percent) for an LDC.

As in other scenarios, the absolute cost advantage is greatest for an LDC. In this case, savings in materials costs are the major benefit. Developing countries, being importers of scrap, gain the most from technologies that economize on scrap.

Summary

Since materials constitute a major percentage of the liquid steel cost in mini-mills, material savings (based upon a computerized process control system and materials management program) can substantially reduce unit costs.

The benefits of computer control reach beyond cost savings to quality improvement. A computerized process control and materials management program can create a predictable environment that permits much greater stability and consistency in final products. A consistent, high-quality product will give mini-mills a competitive edge in the steel industry.

One area of concern, however, is the availability and cost of technical expertise. For a computer system to be successfully installed, maintained, and operated, trained engineers and operators are required.

6. IMPROVEMENTS TO CONTINUOUS CASTERS

Recent technological changes to continuous casters have improved their operating performance, enabling steel producers to increase production rates and improve quality. In this chapter we will discuss some of the most important advances.

Virtually all mini-mills now run in tandem with 100 percent continuous casting operations. In a continuous caster, molten steel from a ladle is teemed into an elevated tundish, a structure that functions rather like a funnel. Through an opening in the bottom of the tundish, the liquid steel flows onto a water-cooled copper mold. The metal and the mold move downward together for about 25 millimeters until the skin of the strand of steel freezes. Then the mold is moved rapidly upward, breaking loose from the solidified skin and returning to its starting point to grasp the next strand of molten metal.

The continuous casting machine has been substantially redesigned since it was introduced commercially in the 1960s. Design and operating changes have helped improve performance, quality and cost savings.

Table 6.1 lists the main features that have helped lower energy use, better product quality, and raise steel yield for continuous casting of billets. Machine design changes and operating technique improvements have lowered failure rates, shortened set-up times, simplified operations, increased casting speeds, and cut costs; the result has been higher casting productivity and lower man-hours per ton. Techniques aimed at improving quality have reduced nonmetallic inclusions, stabilized the flow of steel and improved the surface finish.

Table 6.1: MAJOR MACHINE DESIGNS & PRACTICES INTRODUCED IN CONTINUOUS BILLET CASTING

FEATURE	BENEFITS
Machine Design and Equipment	
Slidegates for ladles and tundishes with high-performance refractories	Lower failure rate, simple operation, shorter set-up time, faster turnaround time
Cold tundish lined with prefabricated disposable boards	Rapid tundish change and energy savings
Top inserted dummy bar	Shortened caster preparation time
Multistage mold Water spray for secondary cooling zone Supporting rolls to prevent bulging of billets	Higher casting speeds Lower failure rate
Compact billet caster Rapid mold and roll changing	Higher productivity Manpower reductions
Operating Techniques	
Extended sequence casting, which requires: - Rapid changing of the ladle during casting - Employment of a large ladle and tundish - Fast removal and replacement of the mold - Restranding during casting	Higher productivity and yield, reduced production costs, prevention of start-up trouble, energy savings
Coupling technique	Steel from the next heat can be cast onto the tail end of the previous heat
Round billet caster	Billets can be direct rolled to seamless tubes
Direct hot billet charging into the reheating furnace	Energy savings
Quality Improvement Techniques	
Protection of the ladle and tundish stream from oxidation Use of filter	Steel cleanliness improved by reduction in nonmetallic inclusions and a better surface finish
Electromagnetic stirring (EMS)	Avoid nozzle blockage, prevention of central segregation and inclusion control
Automatic metal level control	Maximum metal yields, reduced labor force and numbers of breakouts
Liquid steel flow control by integrated flow control system	Stabilization of steel flow from ladle-to-tundish and tundish-to-mold
Addition of mold powder (especially Ca-Si powder injection)	Better surface finish Casting smaller sections
Argon injection through the tundish stopper and sub-entry nozzle	Prevention of alumina buildup at nozzle
Computer or microprocessor-based control and automation	Higher productivity, labor savings and improved working conditions

Additional efforts to improve the "conventional" continuous caster are being made in the following areas (Teoh (B) 1988):

- Slag detection and control
- Tundish flow modeling for optimized design
- Mold powder control
- Automatic mold process control
- Enhanced stability of strand guide alignment
- Automatic hot surface inspection
- Increased hot direct charging
- Development of special shape, high-speed casters

Thin slab casting and strip casting are two technologies that might offer mini-mills the chance to exploit demand in the lucrative flat-rolled market. Both these technologies potentially allow sharp reductions in capital investment, energy, processing time and manpower. Steelmakers have for decades tried to develop techniques to cast steel at sizes nearer the end product, and the folklore of steel manufacturing is full of near-misses (Preston 1991). The key, it appears, has been the design of an appropriate funnel into which the molten material is poured. Finally, however, thin casting is moving from the domain of experimentation to commercial use.

Several viable processes for thin slabs, i.e., slab ranging from 20 to 40 mm in thickness and 1,500 to 2,000 mm in width, are in various stages of development (Teoh (B) 1988). Thin slab casting does not eliminate hot rolling; however, it greatly lowers the amount of reduction necessary to produce hot band. The thin slab caster, together with the simplified hot strip mill, have a lower investment and operating cost than the conventional casters and strip mills (Cramb 1988).

Last year Nucor Steel became the first mini-mill in the world to adopt the thin slab caster in its estimated $264 million flat-rolled mill in Crawfordsville, IN, with an annual capacity of 800,000 tons. The plant's startup was difficult (narrated dramatically by Preston 1991). However, most process problems have apparently been ironed out and an acceptable quality product is being produced. Over the next few years, it is expected that the quality of steel produced will further improve as surface blemishes are eliminated. Nucor estimates that its final product will be $50 to $100 per ton cheaper than the conventional integrated product (see Box 6.1).

Armed with the thin slab caster, Nucor is entering the flat products area, long considered the preserve of integrated mills. Other mini-mills have been more cautious, but the move towards flat products is clearly gathering momentum. Birmingham Steel Corporation, in partnership with Proler International Corporation and Danieli & C. Officine Meccaniche S.p.A, is setting up a mill expected to cost $200 million, with an annual capacity of 800,000 tons of thin slab, flat-rolled steel (Wartzman 1989).

Strip casting will be even more dramatic than thin casting, when it becomes technically feasible. In the most optimistic scenario, rolling mills would be completely eliminated as strips of less than 5 millimeters would be directly cast. When available, strip casting machines are expected to be small, inexpensive and cost-efficient. However, many problems must be solved before the process can be commercialized. The serious commercial use of thin-casting machines for low carbon, aluminum-killed strip is at least 5 to 10 years away (Cramb 1988).

BOX 6.1: THE FUTURE IN FLAT-ROLLED STEEL

The sixth mini-mill for Nucor Steel, the Crawfordsville, IN, plant will compete head-on with integrated steel producers in the United States and abroad. Nucor, the seventh largest U.S. steel producer, is intent on being the lowest-cost manufacturer--a strategy it expects to implement in the flat-rolled market it is entering through the thin slab caster.

In adopting a thin-caster that had never been commercially tested before, Nucor took the type of risk that has become the hallmark of mini-mills worldwide, though the scale of investment and potential implications may be unprecedented.

The potential is enormous. Flat-rolled products are a high value-added item with sizable profit margins, and a larger range of applications than any other steel product. The mill will initially target appliance manufacturers, and may later try to sell to the automotive industry.

Made by SMS Schloemann-Siemag, the continuous caster has a capacity of 150 tons per hour. It is designed so that the mold can be changed quickly, in about 45 minutes. The caster produces five to six slabs--40 to 50 mm thick, roughly 4,000 mm long--per heat.

Nucor believes the process will allow it to be more responsive than the integrated steelmakers. The company hopes to move to made-to-order production runs rather than selling from inventory. Lead time for hot band coils is projected at two weeks, and for cold rolled output at three to five weeks. The industry's averages are four weeks for hot and six weeks for cold.

Nucor certainly is pleased with what it sees in its Crawfordsville plant. A new $300 million plant is being built in Arkansas, and industry analysts predict that other steel producers will have little choice but to follow the leader.

Summary

Improvements to machine design and operating techniques for the "conventional" continuous caster have lowered failure rates, shortened set-up times, simplified operations, increased casting speeds and lowered costs. The result has been higher casting productivity, better product quality and fewer man-hours per ton. While the advent of the thin slab caster has opened up a new market for the EAF steel producer, strip casting needs further development before it can be commercialized.

7. CONCLUSIONS

7.1 Competitive Position of Nations

We have demonstrated the following propositions regarding costs of producing steel in mini steel mills:

(1) Total cost of production tends to be most sensitive to costs of electricity and scrap, and less sensitive to capital and labor costs.

(2) Differences in production efficiency using a given technology can account substantially for production cost variations between firms.

(3) Differences in use of various modern technologies that enhance the "standard" furnace also account for a large part of cost variations. Most of the newer technologies dominate the old, inasmuch as they lower costs of production irrespective of country type.

A developed country mill that started with a benchmark furnace in the 1983-85 period and steadily added the innovations described in this report would have lowered costs by a maximum of $45 per ton (if all the effects were additive). On a base cost of $180 per ton, that represents a 25 percent decline. For a mature industry, this pace of change is rapid indeed.

The technological and cost strengths of the U.S. mini-mills make them formidable competitors in their domestic market, particularly while the dollar is weak; at current exchange rates, operating costs in U.S. steel mills make them very competitive. Even at extremely low wages, less developed countries (LDCs) currently cannot easily compete for U.S. customers with the highly efficient American producers.

Still, the substantial steel purchases by the U.S., Europe and even Japan suggest that there is a potential overseas market for LDCs and newly industrializing economies (NIEs) if they can develop the right products at low cost and reliable quality. Additional markets may be provided by LDCs and NIEs that have failed to develop a strong steel industry. But steelmakers in LDCs and NIEs can no longer rely merely on low-cost labor; they must become the technological rivals of steelmakers in the developed countries.

The news for LDCs is, therefore, mixed. Mini-mills are increasingly a viable alternative for many varieties of steel and hence LDCs have a small-scale, low-investment cost alternative to the big integrated mill. However, success in mini-mill production does not come easy. The many metallurgical innovations, past and ongoing, plus the increasing computerization of production require a trained labor force quick to respond to technological challenges.

7.2 Players: Old and New

Trade in steel has followed the classic product cycle trajectory. In the 1960s, Japan took away market share from the Western industrialized nations; in the late 1970s and early 1980s, Korea, Taiwan and Brazil did the same to Japan. These transitions were largely associated with low wages in the emerging nations.

How well will Korea, Taiwan and Brazil survive? Will developing countries with even lower wages now become increasingly important exporters of steel? In particular, will the technology embodied in mini-steel mills allow easier entry for the latecomers?

A few new entrants are surfacing. The most promising of these is Turkey. China, Indonesia and Mexico could also make a mark on international trade. However, it is important to note that the reason for the success of Turkey (and earlier of Korea, Taiwan and Brazil) is due much more to their capability for efficient manufacturing than merely to low wages. For China and others to enter international markets in any substantial way, they must invest in improving process capability and keep pace with the evolution of technology internationally.

Even as the product cycle is moving to lower-wage countries, certain forces are reversing the process. In the United States particularly, but also in Europe and Japan, mini-mills have become increasingly competitive. These nations have the advantage of low scrap costs and electricity prices. Even more importantly, they are pioneering with new generations of technology that are changing both the nature of the final product and the underlying process.

Certain developing countries could choose to stop making steel, given their inherent disadvantages, which are magnified by the new technologies. A U.S. firm that adopts all the technologies described in this report can produce at a cost that is about $45 lower than the benchmark cost of $180. At that cost, it is just about ready to ship steel competitively to an LDC that is using a "standard" furnace. The product quality advantage enjoyed by U.S. firms further reinforces their competitive strength.

However, it is worth noting here that at least some developing countries are betting that adopting modern technologies will pay off. Korea, Taiwan, Singapore and Turkey are among a select group of countries taking this route. In terms of the technologies described in this report, the NIE firm visited was the most progressive of the sample, more so than some of the most innovative U.S. firms that were also interviewed.

"Intra-industry" trade, or the import of certain varieties and qualities and the export of other varieties and qualities, is a growing trend. Countries investing in new technologies could increasingly participate in international trade on this basis. The most plausible scenario is that developed country mini-mills will focus increasingly on higher-quality steels within their current product range and gradually move into areas that have been the preserve of integrated producers. Supplying semi-finished and low-quality steel and buying higher-grade steel is likely to be a serious option for low-wage countries upgrading steel technology.

It should be re-emphasized, though, that the "lower-quality" steels are a moving target. New technologies render the lowest-quality steels obsolete by simultaneously lowering cost and raising product quality. Those who do not continually adopt such emerging technologies will have nothing to sell.

7.3 Technical Change

> "With the latest technology to enhance their competitive position, it is likely that the modern mini-mills will become the dominant, all-purpose steel producer in all parts of the world; the very large integrated steelworkers will exist only in those areas that can offer specially advantageous operating benefits and a reasonably stable market of the appropriate size" (Teoh (B) 1988).

Other experts have voiced similar views, although the prognosis is not uniformly held. What is clear is that the mini-mill has come a long way from being a curiosity that catered to geographically narrow and specialized markets, to being a major competitor shipping products all over the world. Many technological advances are on the anvil and are likely to further reinforce the position of the mini-mill.

Despite the striking progress made by the industry, especially in the last decade, it is worth remembering that change occurred incrementally. Starting from small furnaces that were generally black boxes, often spewing out unusable output, mini-mill operators have succeeded in enhancing the furnace so that it can be controlled to produce many different grades of steel. In the process, the industry has also evolved in ways that are likely to change competition significantly. Scales of production are larger than they once were. Entry costs are about $100 million, and rising, for internationally competitive mills.

The steel plant of the future could produce iron directly from iron oxide without the annoyance of coke and coke ovens; it will melt iron in an arc furnace followed by ladle refining and cast steel in strips close to the final shape required. The entire process will be monitored by intelligent computers ever vigilant of changing temperatures and chemical compositions. Optimists believe that this vision can be realized within a decade. Realists expect a "host of incremental improvements in basic steelmaking over the 1990s" (*Iron Age*, January 1990, p. 17).

These changes in technology will drive and are being driven by changes in industry structure. Smaller mini-mills are likely to merge with the larger ones as greater investment is made in developing and keeping pace with technology. Vertical relationships with suppliers, processors and final customers will increase in length and depth as products are tailored to end-user needs.

Developing country mini-mills will need to adopt the innovations described here to stay competitive. In fact, these mills stand to gain more than developed country mills since the innovations substantially reduce capital, energy and material costs, all of which are relatively high in developing countries. The greater the cost of electricity and the interest rate, the greater the savings.

This report also suggests a sequence in which innovations should be adopted. Control over the melting process (through oxy-fuel burners and preheating with slag foaming), followed by ladle refining, leads to greater output and quality consistency. Once these are in place, computerization of materials management and process control result in further increases in efficiency.

All technologies discussed in this report require additional capital investment, ranging from very small amounts for oxy-fuel burners to preheating equipment which increases capital costs by 15 percent or more. Computerized process control and materials management fall at the low end of the incremental investment range. Though the consequent increase in output reduces capital costs per ton of steel produced, the capital/labor ratio rises in all cases. It can be anticipated that, as newer technologies emerge, the capital/labor ratio will rise further.

Does the greater investment give the newer technologies a bias toward developed countries? In the long run, the answer seems to be: Yes. Current trends in technology and industry structure will not make business easier for developing countries as efficient scales of production rise and capital/labor ratios increase.

7.4 Management Practices

Mini-mill competitiveness will be determined not only by low costs but also by the ability to find a market niche and produce steel with consistent properties. This will require efficient management operating practices.

Finding a Market Niche

Mini-mills will continue to concentrate on a particular group of consumer products, rather than attempt to be mini-integrated steelmakers. In the past, they have either established a dominant position for a wide range of products within a particular geographical area (neighborhood mill) or limited their range of products and sought a wider marketplace (market mill) (Teoh (B) 1988). The trend is now towards greater product specialization, and most leading mills are market mills. Product focus will, therefore, be a key ingredient of success.

Basic advances and emerging technology will allow mini-mills to continue to enter new market areas and grow in market share and annual capacity. The advent of the thin slab caster has opened up a whole new market for the EAF steelmaker. Producing a steel sheet a few millimeters thick, offers mini-mills a cost-effective way to enter the lucrative flat-rolled market.

The Importance of Quality

Mini-mills in all country types will need to address the importance of a high-quality product. Both ladle refining and computerized process control will help steelmakers control variability within the steelmaking process. Unless LDC mills embark on programs aimed at total quality control, they will find themselves unable to compete with mini-mills in both NIEs and DCs. Some LDC mini-mills have shown themselves capable of adapting to greater international competition and to the more stringent demands of customers. See Box 7.1.

BOX 7.1: CUSTOMER SERVICE IN MEXICO

Quality and customer service have made the crucial difference for Acero Solar, a mini-mill in Mexico that produces specialty steel mainly for commercial use. The steelmaker lost 40 percent of its sales of finished products in 1986, when Mexico joined the General Agreement on Trade and Tariffs (GATT); Acero Solar could not match the prices for imported specialty steel. Now the company is regaining some of that business. But while the steelmaker is more price-competitive these days, what it sells primarily is quality and service.

In specialty steel, chemical and physical properties are critical to the product's application. Acero Solar has a certified testing laboratory where it can determine within 26 seconds 28 different elements in a sample of steel. Its lab is the only one in Mexico that can test for the presence of oxygen in steel. For the finished product, the company's quality control program is also exacting; it tests for internal and surface imperfections, strength, chemical content, length and thickness.

Quality aside, Acero Solar goes far to satisfy its customers. It produces virtually any specialty steel, in particular lengths and sizes, that its customers demand--and it delivers on time. Also, Acero Solar's customers pay only half the bill in advance, and the remaining half on delivery. Such liberal terms are not available to buyers of imported steel.

A Lean, Highly-Motivated Work Force

Although the share of labor in total cost is small, the role of labor continues to be pivotal in ensuring competitive performance. Product quality depends heavily upon the quality of the work force. Workers who have direct shop floor experience embody substantial knowledge of the steelmaking process. Many US mini-mills have already worked hard to improve incentives and labor relations, and those in LDCs will have to follow suit. Many mills will need to improve traditional management methods, labor incentives and labor relations. That in turn will require a great deal of training, education, employee involvement in process decisions, promotion programs and other infrastructure development.

As modern technologies are being introduced, factory workers are being called upon to take up new and more integrative functions. We have stressed the growing importance of multiskilled employment and flexibility in the steel industry, a trend that is consistent with our findings in other sectors. In the future, the steel labor force will need to be better "educated." However, education within the factory will be at least as important as formal education, if not more so. The process by which multiple skills and flexibility are acquired cannot be replicated in classrooms. Some developing and newly industrializing economies are well-positioned in this regard. The NIE firm visited had developed all its automation software internally.

The Cost of Electricity and Scrap

As the focus of this report is manufacturing practices, two important areas of cost reduction were not discussed. High electricity costs are a feature of many developing countries and competitive mini-mills clearly need access to inexpensive electricity. However, any examination of electricity generation and pricing would require a separate study.

The continued availability of scrap at relatively low prices is also critical for mini-mills to compete with integrated producers. In addition, developing countries, relying primarily on imported scrap, need efficient mechanisms to import scrap. Turkish firms have apparently dealt with this need through cooperative arrangements, whereby one major firm has undertaken the task of importing substantial quantities of scrap from the United States for its own use and for distribution to other mills. (See Appendix B.)

APPENDIX A: MINI-MILLS VS. INTEGRATED PRODUCERS

Mini-mills have been limited to relatively low-quality steel products because the electric arc furnace (EAF) has only coarse refining capabilities. Table A.1 shows for 1986 the steel shipped by U.S. mills, integrated and mini; an expert's estimate of how much the mini-mill sector could technically have produced; and how much was actually produced by mini-mills. It is clear that mini-mill strength lies in the production of bars (for reinforcement in construction and other uses) and rods (for making nails, fine wire, staples, springs, mesh). Increasingly, mini-mills are producing tubular products, light shapes and sections (channels and beams). Flat-rolled sheets are the next target. Nucor Corporation, a leading U.S. mini-mill, is pioneering the use of thin slab casting which, as the terminology suggests, permits the steel to be formed in thin layers requiring much less rolling than otherwise and hence vastly increasing the efficiency of producing flat-rolled sheets.

Table A.1: ESTIMATE OF TECHNICALLY FEASIBLE MARKET AND SHIPMENTS IN THE U.S., 1986

(thousand tons)

Product	Steel Shipped by U.S. Integrated and Mini-Mills	Technically Feasible Market for Mini-mills	Mini-mill Shipments
Reinforcing bars	4,229	4,229	4,229
Bars (excluding rebar)	7,816	7,425	3,301
Wire rods	3,464	3,464	2,900
Wire products	1,080	1,080	900
Structural shapes	4,233	1,904	1,200
Plates	3,565	2,496	600
Pipe and tubing	2,836	2,836	300
Strip (cold rolled)	920	736	240
Strip (hot rolled)	635	476	0
Sheet (cold rolled)	13,250	736	0
Sheet (hot rolled)	12,167	7,950	0

Source: McAloon, 1988.

A comparison of costs for an EAF and a conventional oxygen furnace used by an integrated steel producer suggests that carbon steel can be made competitively in an EAF in the United States (see Table A.2).

The estimated investment range for a mini-mill is \$150 to \$320 per ton of capacity and for an integrated mill is between \$1000 and \$1500 (Miller 1984). The far lower investment cost of mini-mills has allowed producers to revise and update their process continually by adding such innovations as continuous casters and ladle furnaces.

A few important features of the cost structure should be noted (Table A.2). The EAF relies more heavily on purchased inputs (and correspondingly adds less value). Energy costs are a substantial 19 percent of EAF steelmaking costs. Labor accounts for only 8 percent of the liquid steel cost, two percentage points less than in an oxygen furnace. Costs of production are therefore even more insensitive to wage rates than in an integrated mill. Materials management and electricity rates are the two dominant factors affecting competitiveness.

Other important distinctions give mini-mills their advantage. Particularly in developed countries, they have escaped the bitter labor history and high wage rates of the unionized integrated firms.

The mini-mill's cost advantages should not be exaggerated. Integrated producers have made heroic efforts in the past several years to lower costs through reduction of labor force. Integrated producers have also gained from retrofitting existing equipment and keeping depreciation costs at a low level. From a developing country's viewpoint, the mini-mill suffers further in comparison with the integrated mill. Scrap is almost always imported and is, therefore, more expensive than in a developed country, often reducing the cost advantage of the mini-mill. That is one major reason why Venezuelan mini-steel producers use directly reduced iron as feedstock.

Mini-mills in the U.S. have also benefitted from the protection from imports accorded the industry.

Table A.2: BREAKDOWN OF STEELMAKING COSTS PER LIQUID TON: ELECTRIC ARC VERSUS BASIC OXYGEN FURNACE

Input	Electric Furnace	Oxygen Furnace*	Electric Furnace	Oxygen Furnace*
	(Unit Cost in US$)		(Cost Structure %)	
Materials (ore, scrap, fluxes, etc.)	$102.35	$83.26	59.3	43.7
Energy (coal, electricity, oxygen, oil, etc., gas credits	$32.84	$31.60	19.0	16.6
Maintenance (materials and services)	$4.00	$9.40	2.0	4.9
Labor	$13.44	$19.13	7.8	10.1
Capital (interest and depreciation)	$20.00	$47.02	11.6	24.7
Total Liquid Steel Cost	$172.63	$190.41	100.0	100.0

* Oxygen furnace costs include components in coke and hot metal.
Source: Center for Metals Production 1987.

APPENDIX B: TECHNOLOGY PIONEER ON THE AEGEAN

Production of steel has grown faster in Turkey than in any other major steel producing country. Mini-mills have flourished while the state-dominated integrated sector has struggled.

Turkish mini-mills have been in the vanguard of the country's export drive in the 1980s (Table B.1). They are models of cost efficiency and ever on the watch for innovations that could reduce costs or improve product quality. However, like the rest of the Turkish export sector, their progress has been punctuated by sudden and sharp setbacks. Collapse of the Middle Eastern market, shifts in the real exchange rate, and changes in export subsidies have been among the factors causing booms and busts.

Table B.1: PERFORMANCE OF LEADING TURKISH MINI-MILLS*
(in million US$)

	1986	1987	1988
Sales	689.4	770.4	1,042.8
Profit	20.6	37.1	65.5
(% of sales)	(3)	(5)	(6)
Exports	196.1	218.7	441.8
(% of sales)	(28)	(28)	(42)

* The mini-mills included here are:
Cukurova Celik Endutrisi (Cukorova Group)
Colakoglu Metalurji (Colakoglu Group, AF)
Izmir Demir Celik Sanayii
Metas Izmır Metalurji Fabrikasi
Icdas Istanbul Celik Ve Demir Izabe Sanayaii
Diler Demir Celik Endustri Ve ticaret
Cemtas
Orpas

Source: Journal of the Istanbul Chamber of Commerce, October 15, 1989 Issue Number 284.

Turkey's first private-sector mini-mill, Metas, on the Aegean coast, began in 1956 as a 30,000-ton capacity rolling mill making reinforcing bars for the domestic market. But expansion and modernization have been continuous at Metas, and it has brought along Turkey's steel industry in its wake. Today, with rolling mill capacity of 360,000 tons, Metas accounts for 5.5 percent of total Turkish steel production and 10 percent of its EAF steel production.

In 1964 Metas introduced continuous casting to Turkey; other manufacturers soon followed, such that continuous-casting technology has reached a level of penetration in Turkey matching that of the European Community and other industrialized countries. During the early 1980s, Metas adapted the latest technological improvements for arc furnaces, increased melt shop capacity to 480,000 tons per year, and decreased its tap-to-tap time to 70 minutes. In the latter half of the decade, Metas established a five-year investment package to develop higher value-added quality steels. It added a state-of-the-art oxygen plant and two ladle furnaces, and the world's first

Krupp scrap preheating system. These innovations offer Metas cost savings as well as the capability of producing higher-quality steel. Its product line now includes wire rod materials, reinforcing concrete steel bars, carbon steel bars and low-alloy steel bars.

Extensive capital commitments coincided with withdrawal of export subsidies in line with GATT commitments, causing the firm to shut down in 1990. In early 1991, however, Metas was rescued, thanks to a 1985 decree which obliges banks to bail out troubled companies. Creditor banks agreed to restructure Metas' $68 million debt, converting part into equity and rescheduling the rest; the government is also injecting substantial new capital. As a result, Metas has resumed operations and even announced plans for expansion.

Other major mini-mill producers have continued to perform well and, despite setbacks, plans to invest in new equipment and technology continue unabated. Borcelik (with capacity of 300,000 tons per year of cold rolled products) and Cukurova (a strip mini-mill with 1.5 million tons capacity, one of Turkey's largest) plan to diversify into flat products. Cemtas is expanding capacity. In 1989, two new mini-mills (Ekinciler and Cebitas) were established, increasing the industry's annual capacity by 750,000 tons.

With its almost total dependence on imported scrap, the Turkish steel industry has evolved an unusual cooperative method for scrap import. The Cukurova Group has a subsidiary specializing in scrap imports. Based in New York, Equipment and Parts Export Inc. has a highly professional staff dealing in scrap and demolition vessel trading. It accesses worldwide markets for scrap and is the third largest exporter of scrap from the United States. Half of Turkey's scrap is imported through this company, supplying not just the Cukurova mini-mill but also other steel producers.

Such arrangements are not atypical of Turkey's close-knit steel industry. Most Turkish mills are parts of large conglomerates that support their activities, through purchases of manufactured steel or other involvement. Furthermore, as in the United States, steelmakers have formed trade associations to lobby for their own interests, such as lower electricity rates. The associations also get more directly involved in production - for example, coordinating the sharing of inputs produced by the state-owned integrated mills. It is through such networks - within and between corporations - that the industry has been able to thrive.

APPENDIX C

Mini-Mill Steelmaking Technologies

C.1 Parameters for a Benchmark Electric Arc Furnace

The "benchmark" EAF is equipped with water-cooled panels, an industry-wide norm. After the scrap is charged into an empty furnace, the arc melts a hole down through the scrap while using the remaining scrap charge to shield the furnace walls from arc flare. Once the scrap is completely melted, the refining and super heating begins. At this point the voltage is lowered to reduce the arc length and consequently the power, to protect the walls and roof from excessive radiant heat (Center for Metal Production 1987).

The parameters of a benchmark EAF are summarized in Table C.1. In chapters 4 to 6, we retain the same furnace, but change its operating parameters through the introduction of new technologies.

Table C.1: PARAMETERS FOR BENCHMARK MODEL

EAF Parameters	Units	Parameters
Furnace size	tons	150
The tap weight	tons	150
Arc furnace transformer	MVA	90
Charges per heat	charges/heat	2
Total energy consumption	kWh	500
Charging loss time	minutes	10
Refining time (20-40 minutes)	minutes	25
Tapping time (5-10 minutes)	minutes	10
Meltdown time	minutes	68
Tap-to-tap time	minutes	113

Source: Center for Metals Production 1987.

The reasons for choosing a 150-ton furnace as the benchmark are discussed in the main text. The choice is consistent with a widespread move to upgrade the first generation of mini-mills, by replacing two or more smaller furnaces with a larger furnace.

The scrap is fed into the EAF through a door, or an opened roof. Ideally, the blend of scrap densities should be fed to the furnace in a single operation while providing maximum protection of the refractory walls. This is seldom realized. Our model therefore assumes two charges are required during each heating cycle.

Melting and refining a ton of cold scrap steel requires, theoretically, 330 kilowatt hours (kWh). The actual amount is greater due to thermal and electrical losses (Ciotti & Pelfrey 1985). The "benchmark" furnace therefore assumes that 500 kWh per ton of power consumption is required during meltdown and refining.

Charging loss time is assumed to be five minutes per charge. Since the benchmark model has two charges per heat, the total time loss to charging is ten minutes per heat.

The refining time for plain carbon steel is normally 20 to 40 minutes, depending upon the grade of scrap steel used and the final metallurgical requirement. The user can assign a longer refining period for cheaper grades of scrap, to compensate for higher levels of impurities found in the charge. The "benchmark" furnace assumes a rather high grade of scrap, requiring a refining time of 25 minutes.

The tapping time depends upon the tap weight and the tap design of the furnace. The "benchmark" furnace time delay for tapping is assumed to be 10 minutes.

The tap-to-tap time (sometimes referred as the heat cycle) is defined as the time lapse between tapping the furnace and the next tap. It is used in determining the annual capacity of the benchmark mill, based on 7760 hours of operation per year. The annual capacity is used to allocate fixed costs on a per-ton basis.

The tap-to-tap time can be written as:

$$\text{tap-to-tap time} = \text{charging time} + \text{melting time} + \text{refining time} + \text{tapping time}$$

The **charging time** is the time period to transport and dump raw material in the form of scrap metal, or other iron-bearing material, and additives into the furnace prior to melting.

The **melting time** is the time period required to transform the charge material into a liquid state.

The **refining time** is the time period of a melting cycle during which the furnace charge is converted to molten metal.

The **tapping time** is the time period for emptying the molten steel from the furnace into a ladle or continuous caster.

The melting time is determined by the following equation:

$$\text{melting time (minutes)} = \frac{\text{tap weight} \times \text{kWh} \times 1.08 \times 60}{\text{arc furnace transformer rating} \times 0.8 \times 1000}$$

where,

tap weight	=	150 tons (model parameter)
kWh/ton	=	meltdown power consumption, 500 kWh (model parameter)
1.08	=	yield factor due to presence of residual elements in scrap and yield loss
60	=	hours to minute conversion
arc furnace transformer	=	90 MVA (model parameter)
0.8	=	operating power factor due to thermal and electrical equipment
1000	=	power units conversion

Source: Ciotti & Pelfrey 1985.

The annual capacity of the "benchmark" furnace is determined as follows:

$$\text{capacity} = \frac{\text{furnace size}}{\text{tap-to-tap time}} \times \frac{\text{60 minutes}}{\text{hour}} \times \frac{\text{7760 hours}}{\text{year}}$$

The benchmark mini-mill facility can produce 620,800 tons of carbon steel per year.

The model assumes a $100 million investment is required to build such a facility. The fixed costs of the investment arise from three sources (Table C.2).

Table C.2: SOURCES OF FIXED COSTS
(percent)

	DC	NIE	LDC
Interest rate	8	10	12
Depreciation rate	10	10	10
Maintenance rate	4	4	4

* Maintenance expenditure per $100 of capital equipment.

C.2 Material Costs

The material costs section of the spreadsheet allows the user to analyze the effect of variations in the price of scrap, fluxes, and alloys as they relate to the final cost of liquid steel, on a per ton basis (see Table C.3).

Table C.3: VARIABLE INPUTS

Input	Input per ton of liquid carbon steel	Price of input (US$)		
		DC	NIE	LDC
Benchmark FURNACE				
Scrap (tons)	1.03	90.00	115.00	115.00
Flux (ton)	0.03	55.00	55.00	55.00
Alloy (pound)	10.00	0.30	0.30	0.30
Refractory & panel ($/ton)	4.00	1.00	1.00	1.00
Others ($/ton)	1.00	1.00	1.00	1.00
Electricity (kWh)	500.00	0.03	0.050	0.080
Electrodes (pounds)	7.50	1.25	1.25	1.25
Lance: oxygen (mcf)	0.32	3.00	3.00	3.00
Labor (manhours)	0.64	21.00	5.00	3.00
ALTERNATIVE PRACTICES				
Lance: oxygen	1.13	3.00	3.00	3.00
carbon	20.00	0.04	0.04	0.04
Burners: oxygen (mcf)	0.36	4.00	4.00	4.00
natural gas (mcf)	0.18	4.00	4.00	4.00
Aux. preheat natural gas	1.06	1.25	1.25	1.25

The model assumes an average price of scrap of $90/ton in a DC, and $115/ton in both an NIE and an LDC. The "benchmark" furnace requires 1.03 tons of scrap to produce one ton of liquid steel, resulting in a total scrap cost of $92.70 per ton of liquid steel in a DC and $118.45 per ton in both an NIE and an LDC. The scrap price for each country type was established from information we gathered in 1988.

It is important to note, however, that the cheapest scrap does not necessarily lead to the lowest steelmaking cost. Better grades of scrap have fewer residual elements and therefore cost more. The residual elements normally reduce the melting yield and increase the materials cost (scrap, fluxes, alloys, etc.) because of the loss of iron into the slag and the additional requirement for fluxes and alloys (Teoh (A) 1988). The model compensates for this situation by allowing the user to allocate a higher material unit requirement for scrap and fluxes when using cheaper grades. Because the refining time is also longer for lower grades, the model allows the user to assign a longer refining period (refining range is 20 to 40 minutes).

The current cost of the necessary fluxes is $55/ton in a DC, and assumed to be the same in both an NIE and an LDC. Flux is added to a charge to promote dephosphorization and desulfurization of the metal, and to lower the fusion temperature of the slag. The "benchmark" furnace requires .03 tons of flux to produce one ton of liquid steel, res lting in a total flux cost of $1.65 per ton.

The cost of the required alloys is currently $.30 per pound, and is also assumed to be the same in each country type. Alloys are added to steel for a variety of reasons: improvement in physical properties, cleanliness, grain refinement, recovery of valuable elements from slag, and corrosion resistance. Since the "benchmark" furnace requires 10 pounds of alloys to produce one ton of liquid steel, the cost for alloys is $3.00 per ton.

Also included in the material cost per ton is $1.00 for other materials, such as cooling water and catalysts, and $4.00 for refractory and panel material-lining loss.

C.3 Energy Costs

The energy costs section of the spreadsheet covers the effect of price variations for electricity, carbon, natural gas, and oxygen as they relate to the final cost of liquid steel (see Table C.3). The benchmark model uses an industry average power consumption of 500 kWh per ton (I&SM 1988). Of this amount, 450 kWh per ton is necessary for meltdown and refining of the charge, while 10 and 40 kWh per ton energy losses are absorbed by water-cooled panels and slag, gas, etc., respectively. The benchmark furnace requires 0.32 mcf per ton of oxygen to decarburize the steel. Lastly, 7.50 pounds of electrodes are lost per ton of liquid steel produced. Note that the benchmark furnace does not require additional burners or auxiliary preheat, as these inputs will be used later in the evaluation of alternative technologies.

In a DC the average cost for electricity is assumed to be $0.035 per kWh, though the price varied significantly within countries. The electricity cost in an NIE and an LDC is assumed to be $0.05 and $0.08 per kWh, respectively. Electricity prices were established from information gathered during our interviews in 1988.

In each country type the cost for oxygen is assumed to be $3.00 per mcf, while the cost for electrodes is $1.25 per pound. The "benchmark" EAF requires 0.32 mcf of oxygen and 7.50 pounds of electrodes to produce one ton of liquid steel. Therefore, the total cost of oxygen and electrodes is $0.96 per ton and $9.38 per ton, respectively.

C.4 Labor Costs

Labor rate, in dollars per hour, should include salary, incentives, and any benefits paid. The "benchmark" furnace assumes that 0.64 manhours are required per ton of liquid steel. Given existing labor rates per hour of $21.00 in a DC, $5.00 in an NIE, and $3.00 in an LDC, the total cost of labor is $13.44, $3.20, and $1.92 per liquid ton, respectively. The labor rate for each country type was established from information gathered during our interviews in 1988.

C.5 Oxygen-Fuel Burners

Oxy-fuel burners supply additional energy source for melting low-alloy and non-alloy scrap. Melting aids such as oxygen and extra burners are unsuitable for high-alloy chrome-nickel, chromium, and manganese scrap, since the possible savings in time would be offset by loss of chromium or manganese. Nor should oxygen be used to remelt low-carbon, high-alloy scrap (Plockinger & Etterich 1985).

Oxy-fuel burners use natural gas, light oil or kerosene as fuels. An oxygen-fuel burner system with a capacity of about 300 cf/min (500 m^3/hour) natural gas and 600 cf/min (1000 m^3/hour) of oxygen used for 10 minutes at the beginning of each charge in a 50-ton UHP furnace will save about 35 kWh/ton) of oxygen (Center for Metal Production 1987).

In the case of kerosene, fuel is used at a rate of 6 to 10 l/ton together with twice the volume of oxygen. The thermal efficiency is said to be 60 to 70 percent, with a saving in electricity up to 70 kWh per ton (Plockinger & Etterich 1985).

C.6 Oxygen Lancing and Added Carbon (Foamy Slag Practice)

Mills use either consumable or water-cooled permanent lances. Consumable lances can be fed manually or mechanically into the bath. Water-cooled lances use oxygen rates of up to 1200 cf/min (2000 m^3/hour) with a total consumption of up to 1280 cf/min (40 m^3/hour).

Oxygen lancing with carbon as fuel is more efficient than the oxygen-fuel burner alone in melting steel. Mills have cut heat times significantly by using oxygen and substantial amounts of extra carbon, either injected into or supplied with the charged pig iron. For example, an extra 19.8 lb/ton of carbon and 353 cf/ton of oxygen has reduced electricity use by about 45 kWh/ton (Center for Metal Production 1987). Oxygen lancing plays a key role in foamy-slagging because it provides a controllable evolution of gas to maintain the foam.

BIBLIOGRAPHY

Adolph, H., G. Paul, K.H. Klein, E. Lepoutre, J.C. Vuillermoz, and M. Devaux. 1989. Iron and SteelMaker February. pp. 29-33.

Barnett, Donald F. and Robert W. Crandall. 1986. Up From the Ashes: The Rise of the Steel Minimill in the United States. Washington D.C.: Brookings Institution.

Business Week, June 13, 1988.

Center for Metals Production. 1987. Technoeconomic Assessment of Electric Steelmaking Through the Year 2000. Principal Investigators, Clark J.P., Dancy T.E., Fruehan R.J., McIntyre E.H., EPRI EM-5445, Project 2787-2.

Ciotti, Jon A. and Pelfrey, Donald L. 1985. "Electrical Equipment and Operating Power Characteristics." in Electric Furnace Steelmaking. Iron and Steel Society.

Collier, Andrew J. 1990. "Europe's Small Steelmakers Face Hurdles," Iron Age January. pp. 43-44.

Cotchen, J.K. 1988. "Analyzing Ladle Furnace Performance." Iron and Steel-Maker November. pp. 52-58.

Cramb, Alan W. 1988. "New Steel Casting Processes for Thin Slabs and Strip - A Historical Perspective." I&SM July. pp. 45-58.

Hess, George W. 1989. "Electric Furnace Steelmaking Hits New Peaks." Iron Age October.

Hock K.E. and Schroeder D.L. 1988. Iron and SteelMaker February. pp. 32-40.

Horne, David. 1988. Mechanical Engineering March. pp. 40-44.

International Iron and Steel Institute. 1990. The Electric Arc Furnace - 1990. Committee on Technology, Brussels.

Iron Age "Steel in the 90s." January 1990, pp.17-32.

Klein, Karl-Heinz and Paul, Gunter. 1988. Paper presented at the ISS 46th Electric Furnace Conference, Pittsburgh, PA December.

Marcus, Peter F. and Karlis M. and Kirsis. 1989. World Steel Dynamics. New York: PaineWebber.

McAloon, T.P. 1988. "Electric Furnace Steelmaking - The Next Decade." I&SM August. pp. 15-17.

McManus (A), George J. 1988. "Electric Furnaces Turn Up the Power." Iron Age November. pp. 14-23.

McManus (B), George J. 1988. "Getting Down to One Manhour Per Ton." Iron Age October. p. 52.

McManus (C), George J. 1988. "Nucor-Yamato Gets on the Beam." Iron Age October. pp. 17-24.

Plockinger, Erwin and Etterich, Otto. 1985. "Melting Techniques." in Electric Furnace Steel Production. Wiley Heyden.

Preston, Richard. 1991. American Steel: Hot Metal Men and the Resurrection of the Rust Belt. New York: Prentice Hall Press.

Schroeder, David L. 1985. "Computer Applications." in Electric Furnace Steelmaking. Iron and Steel Society.

Sheridan, A. 1989. "Arc furnace development and ladle and tundish practice." Paper presented at the Energy Technology Support Unit, Harwell, in association with the Institute of Metals, November 2-3, West Bromwich; Ironmaking and Steelmaking 16 (1): 11-19.

Steel Times. 1988. pp. 346-356.

Teoh (A), L.L. 1988. "Prospects for Mini-Mills - Part I." I&SM, May. pp. 45-50.

Teoh (B), L.L. 1988. "Prospects for Mini-Mills - Part II." I&SM, June. pp. 26-31.

von Hippel, Eric. 1988. The Sources of Innovation. New York: Oxford University Press.

Wartzman, Rick and Hymowitz, Carol. 1988. "Big Steel is Back, But Upturn is Costly and May Not Last." The Wall Street Journal November.

INDUSTRY SERIES PAPERS

No. 1 Japanese Direct Foreign Investment: Patterns and Implications for Developing Countries, February 1989.

No. 2 Emerging Patterns of International Competition in Selected Industrial Product Groups, February 1989.

No. 3 Changing Firm Boundaries: Analysis of Technology-Sharing Alliances, February 1989.

No. 4 Technological Advance and Organizational Innovation in the Engineering Industry, March 1989.

No. 5 Export Catalyst in Low-Income Countries, November 1989.

No. 6 Overview of Japanese Industrial Technology Development, March 1989.

No. 7 Reform of Ownership and Control Mechanisms in Hungary and China, April 1989.

No. 8 The Computer Industry in Industrialized Economies: Lessons for the Newly Industrializing, February 1989.

No. 9 Institutions and Dynamic Comparative Advantage Electronics Industry in South Korea and Taiwan, June 1989.

No. 10 New Environments for Intellectual Property, June 1989.

No. 11 Managing Entry Into International Markets: Lessons From the East Asian Experience, June 1989.

No. 12 Impact of Technological Change on Industrial Prospects for the LDCs, June 1989.

No. 13 The Protection of Intellectual Property Rights and Industrial Technology Development in Brazil, September 1989.

No. 14 Regional Integration and Economic Development, November 1989.

No. 15 Specialization, Technical Change and Competitiveness in the Brazilian Electronics Industry, November 1989.

INDUSTRY SERIES PAPERS *cont'd*

No. 16	Small Trading Companies and a Successful Export Response: Lessons From Hong Kong, December 1989.
No. 17	Flowers: Global Subsector Study, December 1989.
No. 18	The Shrimp Industry: Global Subsector Study, December 1989.
No. 19	Garments: Global Subsector Study, December 1989.
No. 20	World Bank Lending for Small and Medium Enterprises: Fifteen Years of Experience, December 1989.
No. 21	Reputation in Manufactured Goods Trade, December 1989.
No. 22	Foreign Direct Investment From the Newly Industrialized Economies, December 1989.
No. 23	Buyer-Seller Links for Export Development, March 1990.
No. 24	Technology Strategy & Policy for Industrial Competitiveness: A Case Study of Thailand, February 1990.
No. 25	Investment, Productivity and Comparative Advantage, April 1990.
No. 26	Cost Reduction, Product Development and the Real Exchange Rate, April 1990.
No. 27	Overcoming Policy Endogeneity: Strategic Role for Domestic Competition in Industrial Policy Reform, April 1990.
No. 28	Conditionality in Adjustment Lending FY80-89: The ALCID Database, May 1990.
No. 29	International Competitiveness: Determinants and Indicators, March 1990.
No. 30	FY89 Sector Review Industry, Trade and Finance, November 1989.
No. 31	The Design of Adjustment Lending for Industry: Review of Current Practice, June 1990.

INDUSTRY SERIES PAPERS *cont'd*

No. 32 National Systems Supporting Technical Advance in Industry: The Brazilian Experience, June 26, 1990.

No. 33 Ghana's Small Enterprise Sector: Survey of Adjustment Response and Constraints, June 1990.

No. 34 Footwear: Global Subsector Study, June 1990.

No. 35 Tightening the Soft Budget Constraint in Reforming Socialist Economies, May 1990.

No. 36 Free Trade Zones in Export Strategies, December 1990.

No. 37 Electronics Development Strategy: The Role of Government, June 1990

No. 38 Export Finance in the Philippines: Opportunities and Constraints for Developing Country Suppliers, June 1990.

No. 39 The U.S. Automotive Aftermarket: Opportunities and Constraints for Developing Country Suppliers, June 1990

No. 40 Investment As A Determinant of Industrial Competitiveness and Comparative Advantage: Evidence from Six Countries, August 1990 *(not yet published)*

No. 41 Adjustment and Constrained Response: Malawi at the Threshold of Sustained Growth, October 1990.

No. 42 Export Finance - Issues and Directions Case Study of the Philippines, December 1990

No. 43 The Basics of Antitrust Policy: A Review of Ten Nations and the EEC, February 1991.

No. 44 Technology Strategy in the Economy of Taiwan: Exploiting Foregin Linkages and Investing in Local Capability, January 1991

No. 45 The Impact of Adjustment Lending on Industry in African Countries, June 1991.

No. 46 Banking Automation and Productivity Change: The Brazilian Experience, July 1991.

No. 47 Global Trends in Textile Technology and Trade, December 1991.

Note: For extra copies of these papers please contact Miss Wendy Young on extension 33618, Room S-4101

ENERGY SERIES PAPERS

No. 1 Energy Issues in the Developing World, February 1988.

No. 2 Review of World Bank Lending for Electric Power, March 1988.

No. 3 Some Considerations in Collecting Data on Household Energy Consumption, March 1988.

No. 4 Improving Power System Efficiency in the Developing Countries through Performance Contracting, May 1988.

No. 5 Impact of Lower Oil Prices on Renewable Energy Technologies, May 1988.

No. 6 A Comparison of Lamps for Domestic Lighting in Developing Countries, June 1988.

No. 7 Recent World Bank Activities in Energy (Revised October 1989).

No. 8 A Visual Overview of the World Oil Markets, July 1988.

No. 9 Current International Gas Trades and Prices, November 1988.

No. 10 Promoting Investment for Natural Gas Exploration and Production in Developing Countries, January 1988.

No. 11 Technology Survey Report on Electric Power Systems, February 1989.

No. 12 Recent Developments in the U.S. Power Sector and Their Relevance for the Developing Countries, February 1989.

No. 13 Domestic Energy Pricing Policies, April 1989.

No. 14 Financing of the Energy Sector in Developing Countries, April 1989.

No. 15 The Future Role of Hydropower in Developing Countries, April 1989.

No. 16 Fuelwood Stumpage: Considerations for Developing Country Energy Planning, June 1989.

No. 17 Incorporating Risk and Uncertainty in Power System Planning, June 1989.

No. 18 Review and Evaluation of Historic Electricity Forecasting Experience, (1960-1985), June 1989.

No. 19 Woodfuel Supply and Environmental Management, July 1989.

No. 20 The Malawi Charcoal Project - Experience and Lessons, January 1990.

No. 21 Capital Expenditures for Electric Power in the Developing Countries in the 1990s, February 1990.

No. 22 A Review of Regulation of the Power Sectors in Developing Countries, February 1990.

No. 23 Summary Data Sheets of 1987 Power and Commercial Energy Statistics for 100 Developing Countries, March 1990.

No. 24 A Review of the Treatment of Environmental Aspects of Bank Energy Projects, March 1990.

No. 25 The Status of Liquified Natural Gas Worldwide, March 1990.

No. 26 Population Growth, Wood Fuels, and Resource Problems in Sub-Saharan Africa, March 1990.

No. 27 The Status of Nuclear Power Technology - An Update, April 1990.

No. 28 Decommissioning of Nuclear Power Facilities, April 1990.

No. 29 Interfuel Substitution and Changes in the Way Households Use Energy: The Case of Cooking and Lighting Behavior in Urban Java, October 1990.

No. 30 Regulation, Deregulation, or Reregulation--What is Needed in LDCs Power Sector? July 1990.

No. 31 Understanding the Costs and Schedules of World Bank Supported Hydroelectric Projects, July 1990.

No. 32 Review of Electricity Tariffs in Developing Countries During the 1980s, November 1990.

No. 33 Private Sector Participation in Power through BOOT Schemes, December 1990.

No. 34 Identifying the Basic Conditions for Economic Generation of Public Electricity from Surplus Bagasse in Sugar Mills, April 1991.

No. 35 Prospects for Gas-Fueled Combined-Cycle Power Generation in the Developing Countries, May 1991.

No. 36 Radioactive Waste Management - A Background Study, June 1991.

No. 37 A Study of the Transfer of Petroleum Fuels Pollution, July 1991.

No. 38 Improving Charcoaling Efficiency in the Traditional Rural Sector, July 1991.

No. 39 Decision Making Under Uncertainty - An Option Valuation Approach to Power Planning, August 1991.

No. 40 Summary 1988 Power Data Sheets for 100 Developing Countries, August 1991.

No. 41 Health and Safety Aspects of Nuclear Power Plants, August 1991.

No. 42 A Review of International Power Sales Agreements, August 1991.

No. 43 Guideline for Diesel Generating Plant Specification and Bid Evaluation, September 1991.

No. 44 A Methodology for Regional Assessment of Small Scale Hydro Power, September 1991.

No. 45 Guidelines for Assessing Wind Energy Potential, September 1991.

No. 46 Core Report of the Electric Power Utility Efficiency Improvement Study, September 1991.

For copies, please call extension 33616.