CHAPTER 6

New Technologies for the Steel Industry

Contents

List of Tables

List Of Figures

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Summary

Steel technology has entered a period of particular vitality, Whether new processes are being stimulated by raw material and energy changes or whether they are creating opportunities to use new raw materials and energy sources is not important: the technology of the industry is not static. Relatively small integrated systems based on coal reductants and electrical energy are feasible now, and the opportunity to add capacity in small increments, where it is needed, can lower the industry's capital intensity. Large existing integrated systems can adopt new technologies that will increase efficiency, productivity, and product quality. The roots of the steel industry have also spread; the diversity and wide geographical distribution of steel plants in the United States are strengths with which the industry can face the changing conditions of the coming decades.

It is expected that changes in the availability and cost of raw materials, fuels, and energy sources will provide impetus for building new steel plants and modifying existing ones. Integrated companies face some difficult decisions about replacing or drastically altering operating systems; about using new raw materials, fuels, and energy sources; and about how to fulfill often noncomplementary objectives. But for the industry has a whole, the rich variety in plant size, location, and character will ease the industry’s adjustment to new raw materials and energy sources and its adoption of new technologies.

Technological developments that offer flexibility in the choice of inputs are more attractive than those that depend on single sources. Also, new technologies that can be adopted rapidly in efficient-sized modules, that can be constructed in a variety of locations, and that can fulfill regional market requirements, will receive more attention than larger, less flexible systems.

The following technological developments appear to offer particular promise for the steel industry:

- alternatives to metallurgical coke as a blast furnace feed material;
- continuing improvement in coal-based direct reduction (DR) systems, including those that utilize coal gasification and those that use coal directly:
- continuing development of DR systems that allow for the use of alternate fuels and energy sources, including biomass, hydrogen, and nuclear sources;
- improved methods of increasing scrap and sponge iron use;
- increased availability of direct reduced iron (DRI) as a substitute for scrap;
- increased availability of suitable iron oxide/carbon composites (pellets, briquettes) as “self-reducing” materials;
- continuing development of systems for solid-state processing (the direct conversion of metallic powders into structural forms);
- alternate electric furnaces such as plasma systems;
- continuing development of high-speed melting, refining, processing, and transfer equipment;
- secondary or ladle steelmaking processes that allow separation of melting and/or primary refining from final composition control;
- improved instrumentation and control procedures;
- continuous casting and direct rolling; and
- improved methods for using waste materials and heat.

Several of these technologies are explored in this chapter to illustrate the range of opportunities available to the steel industry.

Introduction and Background

Steel Industry Technology

"The steel industry" is composed of those companies that produce steel products from ferrous raw materials including ore, pellets, sinter, sponge iron and other DRI, pig iron, * recycled iron and steel scrap, and a variety of waste products. Conventionally, the iron and steel foundry industry is considered separate from the steel industry, although substantial overlap occurs in many technical areas. Differences in scale and product make it possible to distinguish the two industries clearly. In 1978, the steel industry had approximately 156.9 million tonnes of annual capacity, and the foundry industry 18.1 million tonnes.[1] The foundry industry produces only about 1.8 million tonnes of steel castings per year, about 2 percent of the total national steel production; its remaining capacity is used to produce iron castings.[2]

In 1978, the steel industry was composed of 93 companies operating 158 individual plants.[3] The industry may be divided into three categories, based on the type of primary operations, products, and marketing approach of the individual companies: integrated companies, alloy/specialty companies, and nonintegrated companies.

Integrated companies have primary raw material and ironmaking facilities (blast furnaces), ** steelmaking units, and finishing mills. Alloy/specialty companies produce alloys and special products from steelmaking units; usually they do not deal with primary raw material or engage in ironmaking activities. Nonintegrated companies operate melting and casting units and fabrication mills, and produce a limited range of products for a regional market. The term "minimill" is used to describe some of these nonintegrated activities, although it is now conventional to restrict that term to plants with capacities less than 544,200 tonne/yr.

Table 67 shows that the majority of integrated plants are in the size range of 0.9 million to 8.2 million tonne/yr; most nonintegrated plants are in the 90,700- to 907,000-tonne range; and most of the specialty plants in the range of 9,070 to 108,840 tonne/yr. The final column of the table lists the total number of plants in each size range operated by all three categories of companies.[4] The United States does not have a single steel plant with a capacity of 9.1 million tonne/yr, although two are between 7.3 million and 8.2 million tonnes. In contrast, Japan has eight post-World War II steel plants with capacities of about 9.1 million tonne/yr.[5] The heaviest concentrations of U.S. steel mills are in the Pittsburgh and Chicago areas; only three fully integrated plants are in the Western States.

Although plants vary widely in character and size, it is helpful to use current integrated plants to describe steelmaking technology. Figure 22 shows a flow line of steelmaking. All of the major material inputs and operations are indicated, but many of the secondary operations, materials-handling operations, and environmental control operations are not, nor are any of the inspection and quality control operations. An integrated

*DRI designates the metallized products that come under the general heading of direct reduced iron. The term "sponge iron" describes a common type of DRI, DRI is formed from iron oxide without fusion. Frequently, such iron is porous and appears spongelike under the microscope. Pig iron is solidified blast furnace iron: the term originates from the appearance when cast from a common feeder of liquid iron and one or more rows of small castings result.

[1]Institute for Iron and Steel Studies. "Plant Locations and Capacities. " 1978: D. H. Desy, "Iron and Steel."' Mineral Commodity Profiles. MCP-15, U.S. Bureau of Mines, July 1978; American Iron and Steel Institute, "Annual Statistical Report,"' 1978.

[2]Institute for Iron and Steel Studies, op. cit.; American Iron and Steel Institute, op. cit.

[3]Institute for Iron and Steel Studies, op. cit.

**A new class of integrated plant is emerging based on direct reduction. as discussed later.

[4]Additional discussion of the characteristics and distribution of steel plants is contained in a report prepared for OTA in July 1979: G. R. St. Pierre, C. E. Mobley, C. B. Shumaker, and D. W. Gunsching. "Impacts of New Technologies and Energy/Raw Material Changes on the Steel Industry," July 17, 1979.

[5]K. L. Fetters, "Innovation-The Future of the Iron and Steel Industry," Journal of Metals, June 1979, pp. 7-13.

Table 67.–Capacities of Steel Plants in the United States, 1978

Size range raw steel capacity tonnes/yr	Number of plants operated by the— 17 integrated companies	33 specialty companies	43 scrap/DRI companies	Total number of plants in size range
7,256,000-8,162,999	2	0	0	2
6,349,000-7,255,999	1	0	0	1
5,442,000-6,348,999	1	0	0	1
4,535,000-5,441,999	3	0	0	3
3,628,000-4,534,999	4	0	0	4
2,721,000-3,627,999	9	0	0	9
1,814,000-2,720,999	11	0	1	12
907,000-1,813,999	15	3	0	18
816,300- 906,999		0	0	1
725,600- 816,299	1	1	1	2
634,900- 725,599	0	0	1	1
544,200- 634,899	1	3	3	7
453,500- 544,199	1	1	3	5
362,800- 453,499	1	1	4	6
272,100- 362,799	2	1	5	8
181,400- 272,099	2	2	14	18
144,190- 181,399	1	2	6	9
126,980- 144,189	0	2	4	6
90,700- 126,979	0	10	9	19
68,025- 90,699	0	3	2	5
45,350- 68,024	2	10	9	19
22,675- 45,349	0	5	0	5
0- 22,674	0	3	0	3
Total number	57	47	54	158

SOURCE Institute for Iron and Steel Studies

plant would have many of the indicated operations; a nonintegrated plant would have only a few. A nonintegrated steel plant might have electric furnaces for melting scrap, continuous casting units to produce slabs or billets, and rolling mills. A specialty steel plant might have only electric furnaces with some secondary steel-refining equipment such as vacuum degassing units, electroslag remelting equipment, argon-oxygen decarburization (AOD) units, in addition to special forming and rolling facilities. Most of the various operations can be performed on a widely varying scale, but several are inefficient and costly on a small scale. Blast furnaces and sheet-rolling mills are examples of units that cannot be scaled down economically. Where product demand or capital availability is too low to justify constructing a blast furnace, scrap-based electric furnace steelmaking or DR ironmaking can be used.

Steelmaking, even in the simplest form, consists of a number of processes. Iron from the mine may go through more than 20 processing steps and transfers before it becomes a finished product. Ore is ground, beneficiated, reconsolidated into pellets, indurated, reduced, desulfurized, refined, cast, and finally subjected to a series of forming and heat-treating steps. Technological developments that can eliminate these operating steps or establish a more continuous flow clearly have the greatest potential benefits.

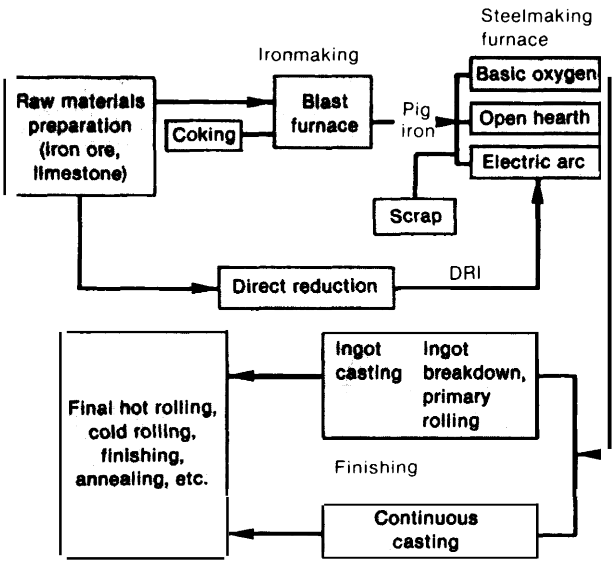
Technological Change in the Industry

Major developments in ironmaking and steelmaking include:

1. pneumatic steelmaking—first the Bessemer process, and more recently the basic oxygen converters;*
2. hot-blast techniques that permit “continuous” production of liquid iron in the blast furnace;
3. the electric arc furnace (EAF);
4. continuous casting; and

*These processes are discussed inch. 9.

Figure 22.—Schematic Flow Chart for Integrated and Nonintegrated Steelmaking



Possible major routes:

Integrated:	coking-blast furnace-basic oxygen-ingot casting-finlshlng.
Non integrated:	scrap-electric furnace-continuous casting finishing,
Semi.integrated:	direct reduction + scrap-electric furnace-continuous casting-finishing.

SOURCE Off Ice of Technology Assessment

5. continuous rolling facilities to produce a wide range of flat and structural products.

Very recently, DR processes have also taken on importance.

The 20th century has seen many lesser developments in steelmaking as well: coking procedures, low-cost systems for producing oxygen, ore beneficiation and pelletizing procedures, rapid analytical and control techniques, and a host of others. Along with these process developments came a multitude of product developments based on a fuller understanding of the relationships between composition, microstructure, and properties of steel. Of necessity, steelmaking also became more sophisticated in the areas of composition and structure control.

A review of technological change in the steel industry during the period 1963-76 reveals the adoption of more than a hundred different developments during a 10- to 15-year period.’ Although this information must be interpreted carefully, two conclusions are evident:

- information on technological developments in the steel industry is transmitted very rapidly; and
- each new technology has characteristics that provide opportunities in markedly varying degrees to individual companies.

Impacts of Changes in Raw Materials, Energy Sources, Environmental Requirements, and Capital Requirements

The overall conversion or dissociation of iron ore (hematite, Fe_2O_3), to metallic iron (Fe) may be represented as, Fe_2O^3- $2Fe + 3/2O_2$. The minimum theoretical energy requirement to convert Fe_2O_3 to Fe is about 7 million Btu per tonne Fe. Expressed in another way, the conversion of Fe_2O_3 to Fe represents the formation of a new “fuel” by a matching consumption of another fuel or energy source. The replaced fuel might be coal, oil, natural gas, hydrogen, combustible biomass, combustible wastes, another metal (e.g., aluminum in the thermite process), or combinations and derivatives of all of these. Potential energy sources include electrical energy introduced by a variety of techniques (electric arc, plasma, high-frequency induction, etc.) and obtained from a variety of sources (fossil fuels, hydro systems, wind, solar, nuclear, etc.).

The conversion of Fe_2O_3 to Fe cannot be accomplished with energy alone—the thermodynamic stability of iron oxide is too great. A temperature of several thousand degrees Celsius is required to bring about spontaneous dissociation to form metallic iron. Material reactants must be used to drive the dissociation at moderate or practically attainable temperatures. All of the common fossil fuels and their derivates can act as suitable reduc-

“R. K. Pitler,“Worldwide Technological Developments and Their Adoption by the Steel Industry in the United States, ” American Iron and Steel Institute, Apr. 13, 1977.

ing agents; however, there are strict thermodynamic requirements that limit the efficiency with which C, CO, and H_2 can be used. For example, the value of CO as a reducing agent is practically exhausted when the CO_2/CO ratio is about three to one. * The minimum material requirement of CO corresponds to an equivalent carbon requirement of about 0.43 tonne of carbon per tonne of Fe.**

One common procedure for assessing the combined requirements is called "thermochemical balancing."' For any particular system, thermochemical balancing can be used to find optimal operating modes for the lowest possible energy and material consumption.

Changing conditions stimulate the development of new processes and the adoption of new technologies, Examples may be found among changes in raw materials, energy sources, environmental requirements, and capital availability.

Raw Materials.— Iron ore and scrap are the two major sources of iron units for steelmaking, As scrap availability increases, incentives are created for adopting technologies that use more scrap. The replacement of open hearth with basic oxygen furnaces permitted an expansion of scrap-based electric furnace steelmaking. On the other hand, a limited supply of high-quality scrap may lead a scrap-based steel company to seek sources of DRI of known quality or to construct new DR facilities of its own. Future developments in the area of amorphous materials may create situations in which entirely new steelmaking and casting sequences will be needed.

Coal, coke, and natural gas are the principal reductants available for the conversion of iron ore. If coking coal is not readily available and natural gas is, there is clear incentive to adopt gas-based DR processes in place of blast furnace ironmaking. Current blast furnaces also depend in part on injected oil to achieve high production rates and low coke-consumption rates. If oil is in limited supply or very expensive, alternatives must be considered.

Energy Sources.— If the availability of conventional fuels is limited, development of new processes such as those using plasma and magnetohydrodynamics (MHD), which make direct use of electrical energy, becomes important.

Environmental Requirements.—As pressure to meet stringent environmental constraints increases, processes are needed that are more amenable to physical enclosure and require lower volumes of waste discharge. For example, dry methods can replace aqueous methods, as they have in coke quenching, and countercurrent flow processes like cascade rinsing become attractive. The need to produce low-sulfur steel can foster changes in the mode of operation of an integrated steel plant, External desulfurizers can be installed, secondary steelmaking units can be added, and blast furnace practices can be altered drastically.

Capital Requirements.—For a new technology to be adopted it must represent a sound use of limited financial resources. Processes that have high throughputs per unit volume and that depend on a minimum of auxiliary support equipment may meet such requirements.

International Comparisons of Production and Energy Consumption

Tables 68 through 71 contain information on raw material, energy, and labor consumption in the international steel industry. The data in these tables represent a composite for integrated plants and do not reflect the wide differences in process configurations, age of plant, available raw materials, and product requirements of individual plants. Table 68 presents unit inputs per tonne of U.S. steel shipped in 1977. Table 69 compares product

*To fix the precise value, one must consider the individual reduction steps (Fe_2O_3 - Fe, O_4, FeO - Fe) and the effective temperature of each.

**This is surprisingly close to recent record coke consumptions in ironmaking: however, those records are achieved through the injection of otherr reductants (tar, oil, etc.).

Table 68.—Unit Material and Energy Inputs per Tonne of Steel Shipped, United States, 1977[a]

Unit input (tonnes or as noted)	Data source AISI[b]	WSD[b]
Iron ore	1.33	1.68
Coking coal	0.7666	1.01
Noncoking coal	0.033	0.033
Coke[c]	0.538	0.643
Scrap	0.292	0.14
Natural gas ($10^3 ft^3$)	6.96	6.17
Fuel oil (U.S. gallons)	20.50	21.13
Electricity (kWh)	537.00	452.00
Oxygen ($10^3 ft^3$)	3.04	NA
Fluxes and alloys	0.304	NA

NA = not available.
a113,939,091 tonnes raw steel produced; 82,860,909 tonnes raw steel shipped, yield (shipments/production) = 72.7%.
bAmerican iron and steel Institute, actual operating data for entire US. industry, World Steel Dynamics idealized model based on 10° tonne/yr integrated plain carbon steel plant
cCoke is produced from coking coal, and thus represents a double counting of inputs in this table Coke usage is included for comparison with data in subsequent tables

SOURCE: G. St. Pierre for OTA.

mixes for major steel-producing countries, * table 70 provides country comparisons on a wide range of operating parameters for several types of steelmaking units, and table 71 deals with energy consumption per tonne of steel shipped. All these data point to technological opportunities for the domestic steel industry, but without full investigation of capital requirements and return-on-investment factors for both replacement and expansion, information of this type can be badly misinterpreted. A clear distinction must be made between technological opportunity and feasibility.

*Product mix for any nation varies with time. For the United States, there is a trend toward making fewer flat products, which are very energy and capital intensive.

Table 69.—Steel Product Mixes for Various Countries, 1976 (percentage of total shipments)

Product type	Country: United States	Japan	United Kingdom	West Germany	France
Hot-rolled sheet, under 3mm thick	51.9	43.1	28.6	22.3	34.9
Light sections	15.9	19.1	19.4	14.0	16.0
Heavy plate	8.0	15.5	11.0	11.0	8.7
Strip	6.5	2.1	7.4	7.6	6.9
Wire rods	4.9	8.2	9.0	10.3	11.6
Heavy sections	4.7	7.1	11.2	6.3	6.1
Semis for sale		—	5.3[a]	9.2	6.2
Medium plates	(b)	1.7[c]	2.2	11.1	3.7
Percent total production	94.6	96.8	94.1	91.8	94.1
Sheets (< 3mm) and strip	58.4	45.2	36.0	29.9	41.8

[a]Deliveries [b]Included in heavy plates. [c]From 3 to 6 mm.

SOURCE: Annual Bulletin of Sfeel *Statistics for Europe, vol.* V, 1977, U.N. Economic Commission for Europe

Table 70.—Comparison of Operating Parameters, 1976

	Country: United States	Japan	United Kingdom	West Germany	France	Brazil
Raw steel produced, million tonnes	116.4	107.4	22.3	42.4	23.2	9.2
Apparent yield[a]	69.9%	84.%	76.80/o	80.7%	83.8%	81 .8%
Average blast furnace Coke rate (tonne coke / tonne pig iron)[b]	0.60	0.43	0.60	0.48	0.52	NA
Steelmaking process[c]						
BOF	62.50/o	80.9%	51.47%	73.3%[e]	80.1%	NA
OH	18.2	0.5	18.1	14.3	5.6	NA
EF	19.2	18.6	30.3	12.4	14.2	NA
Continuous casting of raw steel	10.5	35.1	9.4	28.3	18.0	12.1

NA = not available.
aApparent yield is the ratio of steel shipments to raw Steel production. This ratio is dependent on the range and type of final products shipped, The relatively low apparent yield value for the United States is associated, in part, with its relatively large fraction of thin products and limited use of continuous casting.
bThis coke rate (tonnes coke/tonnes pig iron) reflects only the actual coke charged to the blast furnaces and is not the blast furnace fuel rate (i.e., tonne fuel/tonne pig iron). It is estimated that the fuel rates for the non-U.S. countries are about 0.05 units greater than the coke rates cited
c1975 world steel production by process was 51 1 percent by BOF, 17.1 percent by EF, 305 percent by OH, balance (1 3 percent) by Thomas and other processes
d 0.1 percent of steel made by "other" unspecified Processes
eIncludes 14 percent steel production by Thomas (airblown) converter process.
fIncludes 11.8 percent steel production by Thomas (airblown) converter process.

SOURCE: G. St Pierre for OTA.

Table 71 .—Aggregated Industry Apparent Energy Consumption for Steel making by Country, 1976 (million Btu/tonne steel shipped)

Fuel	United States	Japan	United Kingdom	West German y	France	Brazil
Coking coal.	24.62	20.02	23.85[a]	22.22'	23.22[a]	21.91
Steam coal	1.01	—	—	—	—	0.98
Natural gas....	6.64	—	2.57	4.00	1.92	6.96
Fuel oil	2.71	3.99	6.63	4.07	5.13	3.08
Electricity	1.86	1.61	1.95	1.14	1.67	1.83
Total	36.84	25.62	35.00	31.44	31.94	34.76
Total[b]	25.75	21.52	26.88	25.37	26.77	25.27
Relative energy consumption.	100	84	104	98.5	104	98

United States, 1976 = 100
aCokinq coal consumption is estimated from known coke consumption. Typically 1.45 tonne of coking coal is used to produce 1 tonne of coke.
bThe total energy per tonne of steel produced is the product of the total energy per tonne steel shipped and the apparent yield for each country

SOURCE: G. St. Pierre for OTA.

Energy Consumption in the Domestic Steel Industry

Tables 72 through 74 summarize energy consumption in the U.S. steel industry. Although the industry consumes about 4 percent of the total U.S. domestic energy, most is in the form of coal. Steel processing accounts for only about 0.6 percent of total domestic petroleum consumption and about 3.2 percent of domestic natural gas consumption. However, the trend is toward increasing the use of petroleum (from 6.2 percent of steelmaking energy in 1972 to 11 percent in 1979) and decreasing the use of coal (from 69 percent in 1972 to 63 percent in 1979). After adjusting for the decrease of 8 percent in total energy use, the petroleum energy used in steel production increased by 63 percent during this period while coal energy use decreased by 16 percent.

Table 72.—The American Steel Industry and the Nation's Energy Consumption

Year	Consumption (quadrillion Btu)		Steel industry as percentage of total domestic economy
	Steel industry	Total domestic	
1972	3.13	71.63	4.4%
1973	3.45	74.61	4.6
1974	3.42	72.76	4.7
1975	2.94	70.71	4.2
1976	3.05	74.51	4.1
1977	2.91	76.54	3.8
1978	2.98	78.15	**3.8**
1979	2.88	NA	NA

NA = not available

SOURCES. American Iron and Steel Institute, *Annual Statistical Report* Depart. ment of Energy, "Monthly Energy Review "

Table 73.—Steel Industry Energy Consumption by Source

Source of en erg y	Percent from each source							
	1972	1973	1974	1975	1976	1977	1978	1979
Coking coal.	64.0%	64.50/.	62.1 %	66.8%	65.7%	62.4°10	56.30/o	NA
Other coal.	3.5	3.4	2.9	2.6	2.4	2.9	2.4	NA
Outside coal	1.3	1.7	2.8	(1 .5)	(0.9)	0.9	5.8	NA
Subtotal from coal.	68.8	69.6	67.8	67.9	67.2	66.2	64.5	63.0
Natural gas.	**20.7**	**19.0**	**20:0**	**20.0**	**19.9**	**19.9**	**20.5**	**21.0**
Petroleum	**6.2**	**6.9**	**7.6**	**7.3**	**7.8**	**8.6**	**9.4**	**11.0**
Liquid petroleum gas.	**—**	**—**	**—**	**0.1**	**0.1**	**0.1**	**0.1**	**NA**
Purchased electricity	**4.3**	**4.5**	**4.6**	**4.7**	**5.0**	**5.2**	**5.5**	**5.0**
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

NA = not available

SOURCE American Iron and Steel Institute, *Annual Statistical Report.*

Table 74.—The Mix of Energy Sources

Energy source	Total domestic 1978	Steel industry 1972-78 average	
		Direct	Adjusted
Coal	18.20/o	67.5%	69.6%
Natural gas	25.3	20.0	20.8
Petroleum	48.6	7.7	8.5
Nuclear	3.8	—	0.4
Hydro and other		—	
Electricity	(a)	4.8	(a)
Total.	100.0	100.0	100.0

alncluded in sources above. The adjusted mix for the steel Industry distributes the 48 percent purchased electricity to the primary fuels in proportion to primary fuels consumed by the electric utility industry during the 1972.78 period.

SOURCES. American Iron and Steel Institute, Annual *Statistical Report,* Department of Energy, "Monthly Energy Review."

Characterization of New Technologies

Definitions

Developments in the steel industry can be divided into four broad groups:

- radical and major technologies;
- incremental technology developments;
- regulatory technology developments; and
- developments from other industries.

The term "radical" is used to describe a process modification that eliminates or replaces one or more of the current steelmaking processes or creates an entirely novel option for ironmaking and steelmaking.[7] DR is thus a radical ironmaking change because it is an alternative to the traditional coke oven-blast furnace sequence. Direct steelmaking processes are radical changes because they combine several processes into a single reactor. Continuous casting is radical because it replaces ingot casting and shipping, reheating, and blooming mill operations. Rolling of powders to strip is also radical.

"Incremental" technology developments include process modifications that improve efficiency, increase production, improve product quality, or lower operating costs. Energy conservation measures and the recycling of waste materials fall into this category. So too does external desulfurization of blast furnace iron, although it involves adding a new operating unit. Secondary steelmaking processes including AOD also are incremental technologies. * The economic impact and technological significance of incremental developments may be great.

Developments in environmental technology include add-on systems that do not alter the steelmaking process. Examples are biological treatment of waste waters, pipeline charging of coke ovens, and fugitive particulate collectors.

Developments from other industries can be used in many ways. Analytical and control techniques are transferred to the steel industry on a broad basis. The adoption of coal gasification processes in conjunction with DR might represent a type of technology transfer, although the steel industry has had long experience with generating, cleaning, and using fuel gases in coke oven operations, in the recycling of blast furnace top gas, and more recently in the collecting of carbon monoxide from steel convertors.

Pitler, op. cit.: J. Szekely, "Toward Radical Changes in Steelmaking. Technology Review, Massachusetts Institute of Technology, February 1979, pp. 23-29.

*AOD is a case study in ch. 9.

Potential Technological Changes and Opportunities

Table 75 lists potential technological changes to steelmaking identified in OTA workshops, seminars, and reports and in the current technical and commercial literature.[8] The entries in the table represent different process designs such as DR. The adoption projections in the table should be interpreted

[8] St. Pierre, et al., op. cit.; OTA workshop on “Radically Innovative Steelmaking Technologies, Massachusetts Institute of Technology, (J. Szekely, chairman), Apr. 24-25, 1978: OTA seminar on “New Technologies in Steelmaking, ” Washington, D. C., (J. Hirschhorn, chairman), May 2-3, 1979; S. Eketorp and M. Mathiesen, “Direct Steelmaking—A Review of Processes Under Development. ” report to OTA, 1979: J, T. Strauss and T. W, Heckel, “Future Potential of Ferrous Powder Metallurgy.” report to OTA, August 1979.

Table 75.—Potential Technological Changes in the Steel Industry

Technological process[a]	Category	Significant adoption possible within: 5 yr	10 yr	20 yr	Principal features
Plasma arc steelmaking[a]	1	—	—	?	Fast reactions, small units.
Direct steelmaking[a]	1	—	?	?	Eliminates cokemaking.
Liquid steel filtration	2	?	?	?	Improves product quality.
Continuous steelmaking[a]	1	—	?	?	Conserves energy and reduces number of reactor units.
Secondary refining systems[a]	2	x	x	x	Improves product quality.
Hydrometallurgy production of iron	1	—	?	x	Low-temperature processes.
Nuclear steelmaking[a]	1	—	—	?	Alternative energy source for steel making.
Hydrogen systems[a]	1	—	?	x	Alternate fuel/energy source.
Direct reduction processes	1	x	X	X	Low-temperature solid-state reduction of iron ore to iron.
Coal gasification	4	?	x	x	Alternate fuel/energy source.
Preheating of coking coal/ pipeline charging	2,3	x	x	x	Reduces pollution and conserves energy in cokemaking operation.
Dry quenching of coke	2,3	x	x	x	Reduces pollution and conserves energy in cokemaking operation.
BOF/Q-BOP off gas utilization	2,3	x	x	x	Energy conservation measure.
High top pressure BF electricity generation	2	?	?	x	Energy conservation measure.
Evaporative cooling	2,3	x	x	x	Improved cooling system, saves water usage.
External desulfurization[a]	2	x	x	x	Allows improved product quality and increased blast furnace productivity.
Induction heating of slabs/coils	2	x	x	x	Reduces scale formation, increases yield, and conserves energy.
Catalytic reduction process	2	—	?	x	Used with coal-based reduction processes to increase reaction rate.
Blast furnace fuel injection	2	x	x	x	Use of alternative fuels to replace coke (possible energy conservation).
Direct casting of steel	1	—	?	x	Eliminates mechanical forming and heating.
Continuous casting	1	x	x	x	Direct conversion of liquid steel to solid slabs and squares. Major energy conservation measures and increased yield.
Formed coke	1	—	?	x	Replaces metallurgical coal/coke.
Biomass energy systems	2	—	?	x	Alternate fuel source.
Self-reducing pellets and briquettes	2	—	?	x	Iron ore/carbon flux is intimately mixed to allow reduction in the pellet.
Powder metallurgy steel sheet	1	?	x	x	No melting or reheating required, mini mill concept.
Direct/inline rolling	2	?	x	x	Eliminates holding and reheating steps.
Computer modeling/control	2,4	x	X	x	Applies to any unit/process operation.
High-temperature sensors	2,4	x	x	x	Units to measure and control high-temperature iron making and steel making process variables.

Categories l-radical, 2-incremental 3-environmental, 4-transfer ?-significant adoption possible if pilot efforts show promise. X-significant adoption possibl.
[a] Includes a variety of processes

SOURCE: G. St. Pierre for OTA.

with care: a question mark indicates that a significant adoption is possible within that time period if current pilot efforts show promise; an X-entry, that the technology should be significantly adopted within the time period; a dash, that adoption within the time period is improbable. A number of the technologies are currently adopted or near adoption.

Radical and Major Technologies

Four major new technologies-direct reduction, direct steelmaking, plasma steelmaking, and direct casting—are described and assessed in this section. * These technologies are in markedly different stages of research, development, demonstration, and adoption. The first process is in use throughout the world; the last three have not advanced beyond the R&D stage.

Direct Reduction

Description.— DR processes convert iron ore (fines, pellets, sinter, etc.) into sponge iron at temperatures well below the melting point of iron.** These processes distinctly differ from the conventional blast furnace process in two major respects: solid metallized product is produced, rather than molten iron;*** and a wide variety of reductants may be used in place of metallurgical-grade coke. DRI is normally porous, or in some cases has a filamentary form, and must be processed in steelmaking units that convert it into a usable product. If the starting oxide material is finely divided, the resulting DRI does not have the characteristic spongelike structure but consists instead of finely divided particles of iron. Subsequent processing involves consolidating the reduced or metallized powders by either compression and sintering into finished forms, as in the powder metallurgy industry, or direct rolling of these powders into sheet products.

Another type of DR process is based on combining the reducing agent with the iron oxide as a charge material. For example, it may use a self-reducing pellet or briquette in which finely divided iron ore or mill scale is mixed with a carbonaceous reductant material and fluxes. This pelletized or compacted mixture contains all of the reactants for DR, and it is only necessary to provide the heat for metallization. If the particles are very finely divided and well mixed in the pellet or briquette, reactions can be very fast; for example, a number of reports indicate that under favorable heat transfer conditions 95-percent metallization can occur within 4 to 5 minutes at temperatures of about **1,3000** C.

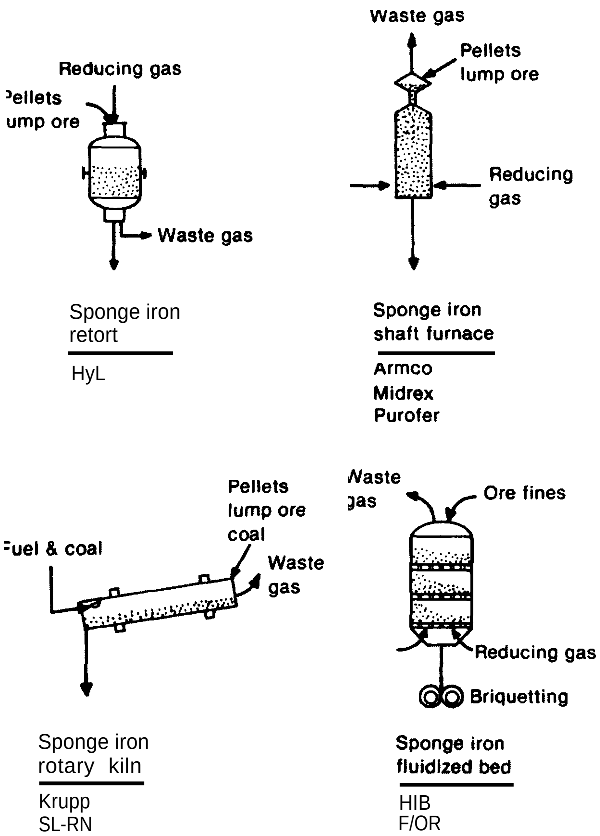
The fuel requirements in the DR processes are very different from those in conventional blast furnace ironmaking. Current blast furnace practices require high-grade metallurgical coke, which is produced in coke ovens from selected blends of coal. Current DR processes use a variety of fuels and reductants, including coal without prior coking, natural gas, oil, or gases produced from any of these fossil fuels. DR processes also maybe of many mechanical designs: there are batch-type processes in which preheated, preformed reducing gases are passed over a static bed of iron oxide material; other designs are based on concurrent or countercurrent flows of gases and solids in a shaft. Fluidized beds have also been used for DR, as have rotary kilns with countercurrent or concurrent flows of gases and solids. Figure 23 is a schematic diagram of several of the principal DR systems.

*TWO other major changes, formcoke and continuous casting, are fully described and discussed in ch. 9.

**The principal concepts of DR were presented by William Siemans in 1869; however, elementary direct reduction using char was practiced by ancient ironmakers,

***The degree of metallization describes the fraction of the iron content of the ore which is converted to metallic iron.

Figure 23.—Schematic Diagram of Direct Reduction Processes



SOURCE: K.H. Ulrich, "Direct Reduction by Comparison With Classical Method of Steel Product Ion," *Mefallurgical Plant and Technology, No.* 1, 1979.

In all of these systems, the operating temperatures must be controlled so that the material moves uniformly through the system without sticking, agglomerating, or clinkering; the gases and solids must have adequate contact for fast reactions and heat and mass transfer; and the design must allow the materials to be discharged and cooled properly.

About 20 different DR processes are in use throughout the world.[9] (See table **76.) Most** of the processes have not spread widely: only three processes have been adopted in more than four plants. The most prevalent process, the Midrex, was first built at Oregon Steel Mills in **1969**; the remaining **16** Midrex plants are widely scattered and include several 2.3-million-tonne/yr plants in the U.S.S.R. The **14** HyL plants are also widely dispersed. All of the Midrex and HyL plants use natural gas as a reductant. The coal-based SL-RN process has been adopted at six plants. Additional information on the distribution of operating DR plants is given in table 77. A number of U.S. steel companies are showing substantial interest in adopting DR: at least six plants have been constructed, and at least another four are planned.

Tables **76** and **78** show that most of the current DR systems, whether based on coal or gas, have been built in units of less than 362,800 tonnes nominal capacity; however, several larger units are being planned and modules of 1.2 million tonne/yr are probable in the next decade. Several DR plants have individual capacities in excess of 907,000 tonne/yr.[10] Some representative characteristics of major DR processes are shown in table 79.

Energy consumption figures for the four major natural gas DR processes vary significantly, as table 80 shows. The lower energy processes are the more prevalent ones.

Table **78** presents general information on three categories of operating coal-based DR processes: direct use of coal, coke breeze, and gasified coal. The third category is really a separate breed, because the coal gasification processes can, in principle, be coupled with any of the gas-based processes.[11] Such a

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[9] J. R. Miller, "Use of Direct Reduced Iron Ore and Balanced Integrated Iron and Steel Operations,"' *Ironmaking and Steelmaking*, 1977, No. 5, pp. 257-264; "The Inevitable Magnitudes of Metallized Iron Ore,'" iron ond *Steel* Engineer, December 1972.

[10] "Saudi Resources and Korf Technology Combine to Create a Dessert Steel Mill, "" *33 Metal* Producing, May 1979. pp. 54-57: W. Loewe, "DR Unit Construction Due in Six Months, " *Washington Post*, May 31, 1979.

[11] J. W. Clark, "Integrated Steelmaking Based on Coal Gasification and Direct Ore Reduction," Westinghouse R&D Center. Pittsburgh, Pa., Dec. 8, 1979; OTA seminar. May 2-3, 1979.

Table 76.—Direct Reduction Plants Constructed or Scheduled for Completion by 1980

Process	Number of plants	Year of original plant	Year of last plant	Countries[a]	Reductant	Capacity, 10^3 tonnes	Type[b]
Hoganas	3	1954	1954	1,2	Coke breeze	63-154	—
Wiberg	4	1954	1964	1,3	Coke breeze	9-82	—
Rotary kiln	1	1957	1957	3	Coal	22	R.K.
HyL	14	1957	1980	4, num.	Natural gas	91-1,905	St. B[c]
Highveld kiln	2	1968	1977	5	Coal	272-907	R.K.
Midrex	17	1969	1980	2, num.	Natural gas	272-2,268	S.F.
Kawasaki	3	1969	1977	3	Coke breeze	65-227	R.K.
SL-RN	6	1970	1978	6, num.	Coal	54-327	R.K.
Purofer	4	1970	1980	7, num.	Natural gas, CO	136-726	S.F.
Koho	1	1971	1971	3	Coke breeze	44	—
Armco	1	1972	1972	2	Natural gas	300	S.F.
Krupp	1	1973	1973	5	Coal	136	R.K.
HI	1	1973	1973	8	Natural gas	590	Fl. B.
Sumitomo	1	1975	1975	3	Coal	218	—
Kubota	1	1975	1975	3	Coal	190	—
ACCAR	2	1975	1976	9	Coal, oil, gas	45-218	R.K.
FIORD	1	1976	1976	8	Natural gas	363	Fl. B.
NSC	2	1976	1977	3	Oil	136-218	—
Kinglor-Metor	1	1976	1976	10	Coal	36	
Azcon[c]	1	1978	1978	2	Coal	91	R.K.

a1-Sweden, 2-united States, 3-Japan, 4-Mexico, 5-South Africa, 6-New Zealand, 7-West Germany, 6-Venezuela, 9-Canada, 10-Italy.
bR, K, = rotary kiln, St.B. = static bed, S F = shaft furnace, Fl. B. = fluidized bed (See text)
cNow known as Direct Reduction Corp. (DRC).

SOURCE: G. St. Pierre for OTA.

Table 77.—Distribution of World Direct Reduction Capacity, 1980

By process	
Midrex	38.5%
HyL	38.1
SL-RN	5.6
Purofer	4.2
Others	13.6

By reductant source	
Natural gas	87.40/~
Coal	11.1
Gas/fuel oil	1.5

By process type	
Shaft furnace	44.6%
Static bed	38.9
Rotary kiln	12.6
Fluidized bed	3.9

By country	
Venezuela	24.8%
Iran	14.2
Mexico	10.7
Canada	8.7
United States	6.1
Japan	6.1
Others	29.4

SOURCE: R.J. Goodman, "Direct Reduction Processing—State. of-the. Art," *Skillings Mining Review, vol. 68, No* 10, March 1979

coupling would involve producing clean fuel and reducing gas by pressurized gasification of nonpremium, high-sulfur coal; using the gas as a reductant in the chemical reduction of iron ore; using the offgas from ore reduction either as a fuel for combined-cycle power generation or as an auxiliary energy source for gasification and reduction plants; and then melting and refining the DRI in an electric furnace with electricity from the combined-cycle powerplant. Several coal gasification processes might complement other steel processes.[12]

Table 81 summarizes energy consumption in coal DR kilns. There is a wide range in the energy consumption figures for coal-based rotary kiln DR because of the flexibility in the operation of rotary kilns. In particular, coals of varying ash and moisture content and ores of varying quality can be processed. The low consumption figures are for coals of low moisture and ash content with ores [pellet, lump, fines) of low gangue and moisture and high iron content. Energy consumption in shaft units is about the same as in rotary kilns.[13] The consumption in static beds is almost 50 percent greater, and in fluidized beds may be 75 percent greater, than in kiln and shaft systems.

Total consumption of energy in coal gasification processes might be as low as 12.1 mil-

[12] E. J. Smith and K. P. Hass, "Present and Future Position of Coal in Steel Technology,"' *Ironmaking and Steelmaking*, 1979, No. 1, pp. 10-20,

[13] D. S. Thornton and D. I. T. Williams. "Effects of Raw Materials for Steelmaking on Energy Requirements, *Ironmaking and Steelmaking*, No. 4, 1975, pp. 241-247.

Table 78.—Operating Direct Reduction Plants Based on Coal or Coke Breeze

Process	Location	Company and country	Capacity (tonnes)	Startup	Product use[a]
Plants-using-coal **directly**					
SL-RN.	N.W. Ontario	Steel Co. of Canada	362,800	1975	A
SL-RN.	Arizona	Hecla Mining, United States	54,420	1975	c
SL-RN.	Rio Grande	Aces Fines Pir., Brazil	58,955	1973	A
SL-RN.	Fukuyama	Nipon Kokan, Japan	317,450	1974	B
SL-RN	Glenbrook	New Zealand Steel	108,840	1970	A
SL-RN/Krupp.	Benoni	Dunswart, South Africa	90,700	1973	A
Azcon–DRC, ...	Tennessee	Azcon Corp., United States	90,700	1978	A
Kinglor-Metor	Cremona	Danieli, Italy	36,280	1976	A
Kinglor-Metor ...	Monfalcone	Danieli, Italy	9,070	NA	A
Sumitoma	Kashima	Sumitoma, Japan	195,912	1975	B
Highveld .	Witbank	Anglo-Am. Corp., South Africa	907,000	1968	B
ACCAR.	Ontario	Sudbury, Canada	226,750	1976	NA
Plants **using coke** breeze					
Hoganas	Hoganas	Hoganas AB, Sweden	136,050	1954	c
Hoganas	Oxelosund	Granges AB, Sweden	32,652	1954	c
Wiberg	Sandriken	Sandrik AB, Sweden	21,768	1954	c
Kawasaki	Chiba	Kawasaki, Japan	54,420	1969	B
Kawasaki.	Chiba	Kawasaki, Japan	54,420	NA	B
Sumitomo	Wakayama	Sumitomo, Japan	217,680	1975	B
Rotary kiln.	Muroran	Nippon, Japan	43,536	NA	B
Plants using gasified coal					
NSC	Hirohata	Nippon, Japan	136,050	1977	B

NA = not avaflable
aProduct use: A = steel making feed B = ironmaklng feed C = specialty product

SOURCE Department of Commerce 'Production of Iron by Direct Reduction,' May 1979

Table 79.—Characteristics of Direct Reduction Processes and Electric Furnace Consumption

	SL-RN	Armco	Midrex	Purofer	HyL	HIB	FIOR-ESSO
Furnace ., . .	Kiln	Shaft	Shaft	Shaft	Retort	Fluid bed	Fluid bed
Reductant source .	Coal	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas or oil
Energy, 10^6 Btu/ tonne DRI. . .	13.1	13.1	11.9	13.1	15.5	17.9 -19.9	15.1
Feed, type . .	Coarse ore, pellets	Pellets	Pellets	Coarse ore, pellets	Coarse ore, pellets	Ore fines	Ore fines
Product metallization.	900/o	90%	92-960/0	95°/0	85-900/0	90%.	920/o
Elect ric-f urn ace consumption charge							
Sponge . . .	75%	200/0	700/0	500/o	600/0	—	75%
Scrap	25	30	30	50	40	—	25
Hot metal.	0	50	0	0	0	—	0
Power, kWh/tonne.	555	272	550	583	625	—	535
Yield. .	91 %	84%	93°/0	—	92.40/.	—	—

SOURCE: E.J. Smith and K.P. Hass, Present and Future Position of Coal in Steel Technology." *Ironmaking and Steelmaking,* 1976, No 1, pp. 10-20

lion Btu/tonne of DRI. The most favorable energy consumption figures for blast furnaces are about 14.3 million Btu/tonne of iron. The high efficiency of modern blast furnaces is undisputed, and it is unlikely that any DR system will consume less energy when proper account is taken of all inputs and outputs.[14] Waste heat losses are **0.5** million to 5.0 million Btu/tonne for steel production by the coke

“Clark, op. cit.; R. S. Barnes, “The Current State of Iron and Steel Technology. ” *Ironmaking and Steelmaking.* 1975, No. 2, pp. 82-88: Thornton and Williams, op. cit.

Table 80.—Energy Consumption in Gas Direct Reduction Processes

Type	Reductant energy 10^6 Btu/tonne	Electricity consumption kWh/tonne	Total 10^6 Btu/tonne
Shaft	10-12	33-135	11.1 -12.8
Retort.	12.5	20	136
Kiln.	13-20	35-45	13-20
Fluidized bed .	15-18	40	14.7

SOURCE G St Pierre for OTA

Table 81 .—Energy Consumption of Direct Reduction Rotary Kilns

Item	Consumption Low	High
Coal, Btu/tonne	14.3 x 1 o'	22.0 x 10'
Electricity, kWh/tonne.	38.5	49.5
Total energy, Btu/tonne. . . .	14.4 x 10'	22.2 x 10'

SOURCE: G St Pierre for OTA

oven-blast furnace-basic oxygen furnace (CO-BF-BOF) sequence and **11.8** million Btu / tonne for the direct reduction-electric arc furnace (DR - EAF) sequence using **20** percent scrap.[15] The latter figure is likely to improve as technological advances occur, but for energy consumption from ore to metal it will be difficult to better the performance of a modern blast furnace system; however, capital and operating costs may be improved with DR systems.

[15]Barnes, op. cit.

A comparison of coal-based DR system energy costs with other types of DR systems has been prepared using OTA energy prices and projected rate of increase, (See ch. 5.) The results are presented in table 82 by specific process and in figure **24** by type of process. A favorable situation is predicted for coal-based DR systems in the United States.

New DR Processes.— A number of new DR processes are under development. In the United States, the Midrex Corp., originator of one of the two leading natural gas DR processes, has also developed a direct coal DR process. It is fundamentally different from the coal kiln processes in use for some years. The principle of the electrothermal process is electrical resistance heating of the iron ore and coal mixture; this is shown in figure 25A. This process is now in the pilot stage and is expected to be marketed for plant sizes of 181,400 tonne / yr within the next 5 years. Because of its relatively simple design, the process appears to offer good process control and reliability, with a relatively low capital cost.

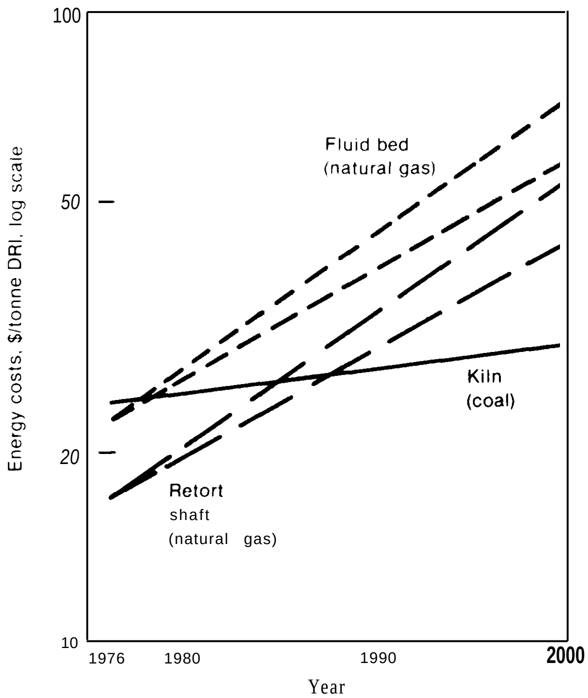
Table 82.—Energy Costs for Direct Reduction Processes Based on OTA Energy Costs

Energy source[a]	OTA energy cost and annual cost increase	Allis-Chalmers kiln	Armco shaft	FIOR fluid	HIB fluid	HvL retort	Krupp kiln	Midrex shaft	Purofer shaft	SL-RN kiln	Cost averages: Fluid bed	Retort shaft	Kiln
Electricity 10° Btu/tonne ., ...	—	0.17	'0.12	0.15	(d)	0.08	0,15	0.51	0.38	(d)			
$ in 1976	$5.57	0.95	0.67	0.84	(d)	0.45	0.84	2.84	2.12	(d)	–	–	–
Low $ in 2000	1.0%	1.22	0.84	1.04	(d)	0.57	1.04	3.60	2.71	(d)			
High $ in 20()().	4.7%	2.88	2.01	2.49	(d)	1.38	2.49	8.55	6.39	(d)			
Natural gas 10^6 Btu/tonne			12.65	16.06	19.86	13.75		11,90	1320	(d)			
$ in 1976	$1.27	(b)	16,07	2040	25.15	17.46	—	15.11	16.76	(d)			
Low $ in 2000"	4.0%		41.18	52.58	64.46	4476		37.87	42.97	(d)			
High $ in 2000. .	5.0°10		51.81	65.78	81.10	56.32		48.73	54.07	(d)			
Coal 10° Btu/tonne.		18.O[c]					18.O[c]			18.O[c]			
$ in 1976 ... .,	$1 31	23.8	–	–	–	–	238	–	–	23.8	–	—	
Low $ in 2000	1.0%	30.2					30.2			30.2			
High $ in 2000. .	5.0%	76.7					76.7			76,7			
Total energy costs per tonne													
1976. , ...	($)	24.8	16.7	21.2	25.2	17.9	24.6	18.0	15.3	25.8	23.2	16.7	24.4
2000; all low increases, ...	($)	31.4	42.0	53.6	645	45.3	31.2	41.5	45,7	30.2	59.1	43.1	30.9
2000; low electricity, high natural gas, low coal.	($)	314	52.7	66.8	81.1	56.9	31.2	52,3	56.7	30.2	74.0	53.9	30.9

a1976 dollars, no coke or 011 used; energy consumptions from R.J. Goodman, "Direct Reduction –State-of-the-Art, " Skillings Mining Review, Mar. 10-17, 1979
bAllis-Chalmers unit can use natural gas, oil, and coal. Coal used here
cAn average value of 18 10^6 Btu/tonne was used to represent a readily available coal Typical of kiln processes and assumed to be used in each Process
'Data not available

SOURCE: G St Pierre for OTA (see tables 54 and 55)

Figure 24.—Projected Energy Costs to Produce a Tonne of Direct Reduced Iron



Key,

High-curve: 5 percent Increase natural gas costs, 1 percent coal, 1 percent electricity

Low-curve 4 percent Increase natural gas costs. 1 percent coal, 1 percent electricity

Reactor type

Fluid bed: average of FIOR & HIB process data

Kiln average of All Is-Chalmers, Krupp, and SL-RN data

Shaft furnace and retort: average of Armco, HyL, Midrex, and Purofer.

SOURCE G St Pierre for OTA

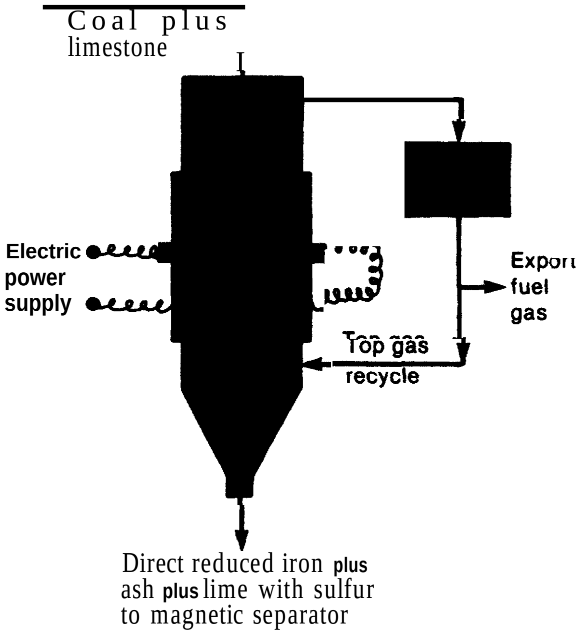
A rather ingeniously designed coal-based DR process has recently been described by its American inventor. ” (See figure 25 B.) Although pilot testing has not yet been carried out, the proposed process uses well-accepted chemical reactions, simple design, and already proven technologies and materials for its components. It is a good example of designing a new technology to suit contemporary concerns, constraints, and opportunities. The basic features of the Calderon Ferrocal ironmaking process are:

- any grade of coal is mixed with any type of iron ore, including domestic low iron content taconite ores;
- the mixture is put through a heating-reduction vessel consisting of a vertical tower made up of several cells, each insulated from the others and tapered downward;
- the inside of the cells are made of alloy steel which serves as a susceptor for induction heating, with the induction coils surrounding the outside of the tower;
- induction heating of the cells leads to a temperature at which there is combined coal gasification and solid-state reduction of the iron ore; the hot gases rise through the tower and preheat the next batch of the ore-coal mixture before being collected, processed, and used for heating, electrical generation, or sale;
- a portion of the solid metallic iron is periodically pushed out of the bottom of the tower into an induction-heated holding vessel of liquid iron, in which slag is formed and removed and desulfurization is accomplished; and
- molten iron is periodically removed and delivered to either a basic oxygen or electric arc steelmaking furnace in the same way that pig iron is delivered in a conventional integrated plant.

This process has several advantages that make it highly attractive, It could be adopted by present scrap-based nonintegrated plants, but it can also use the raw material and steelmaking facilities in existing integrated plants, It uses low-cost iron ores and coals, but unlike conventional DR processes it produces hot liquid iron which can be used in existing integrated facilities. It is a closed system with minimal environmental problems. It has high thermal efficiency, and, because it produces enough medium-Btu gases to generate electricity in considerable excess of the demands of its induction units, it is adaptable to the cogeneration of electricity. Present cost estimates also indicate considerable savings:

11A. Calderon, “Program for Reconstruction of U.S. Steel Industry,” Calderon Automation, Inc., Cleveland, Ohio, February 1980. (Patents applied for.)

Figure 25.—Two New Coal Direct Reduction Processes

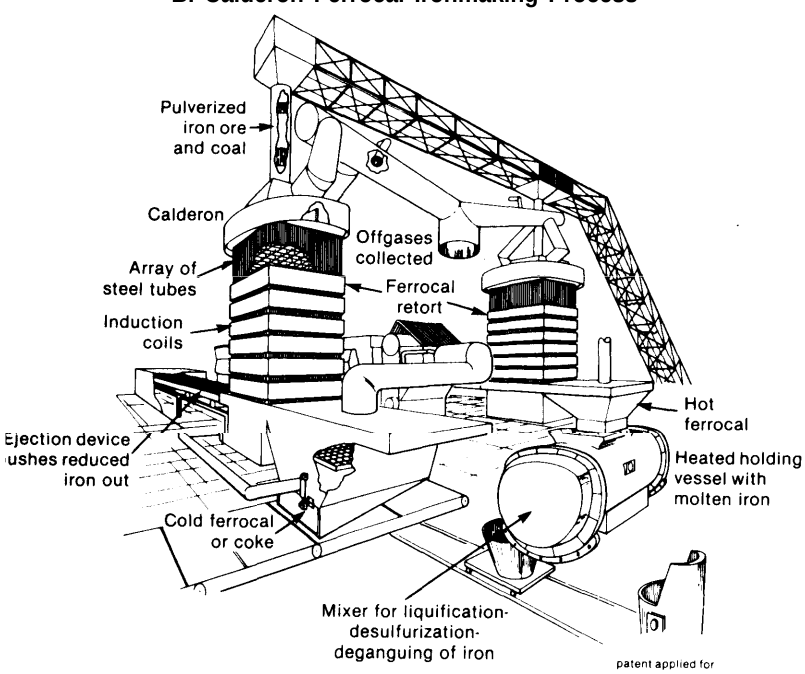


SOURCE: Midrex Corp.

capital costs (exclusive of electricity cogenerating facilities) may be only one-half those of coke ovens and blast furnaces; the modular design allows higher utilization rates at lower capacity levels; and there might also be savings in both construction time and maintenance costs. Return on investment could be as high as 25 percent.

A pilot plant has been designed to produce 4.5 tonne/hour. It would cost approximately $5 million to construct and operate for at least several months. Since the process has been invented by someone outside of a steel company, although with considerable experience with the industry as a designer and builder of steelmaking facilities, pilot evaluation which requires a steelmaking plant may prove to be difficult. At this stage the technology provides an excellent example of the problems facing the introduction of major innovations into the steel industry. This American invention or something similar to it could become the most important innovation for domestic integrated steelmaking in the coming decades.

B. Calderon Ferrocal Ironmaking Process



SOURCE: Calderon Automation, Inc.

A number of new ironmaking processes are also being developed in Sweden, All are based on the concept of using partial (low degree of metallization) DR followed by a smelting operation that melts and further refines the material to produce the equivalent of the pig iron. Descriptive information on three of these processes is given in table 83. Some of them appear to offer a potential for considerable energy savings, both in energy units and in costs. This results from the use of low-grade coals rather than coke. All produce less environmental pollution because of their relatively simple design (figure 26). Several processes and plants based on the same approach of prereduction and smelting were developed in the United States; but for many reasons, including the difficulty and expense of testing new steelmaking technology in pilot and demonstration plants by firms that are not steelmaker themselves, they were not successful. 17

Apparently the Hofors plasma process is related to a recently announced, more traditional DR process producing DRI rather than pig iron. The DR process, called Plasmared, uses plasma heating and can burn oil, gas, or coal as the energy source.[18] A small plant is now under construction in Sweden.

Costs.—An important aspect of evaluating new DR processes is their capital costs. Reported capital costs for a number of DR processes are given in table **84.** The cost for presently used natural gas processes is relatively low, generally about $110 per annual tonne of DRI capacity. This compares to two to three times that cost for coke ovens and blast furnaces to produce pig iron. The capital costs of using coal gasification, direct coal, or coke oven gas are higher than those for natural gas, but they are still quite competitive with the conventional coke oven-blast furnace route. The capital costs for the new Swedish processes that produce pig iron are also quite competitive with the conventional route (see table 83).

More detailed data for a particular direct coal, kiln DR process and a typical gas-based process as a function of plant size are shown in figure **27.** This illustrates the savings re-

"See, e.g., T. E. Ban. "Effective Energy Utilization Through Direct Electric Smelting of Hot Prereduced Iron Ore, " Skillings Mining Review, Sept. 14, 1974.

[18] *American Metal Market*, Sept. 21.1979, and Aug. 8, 1979.

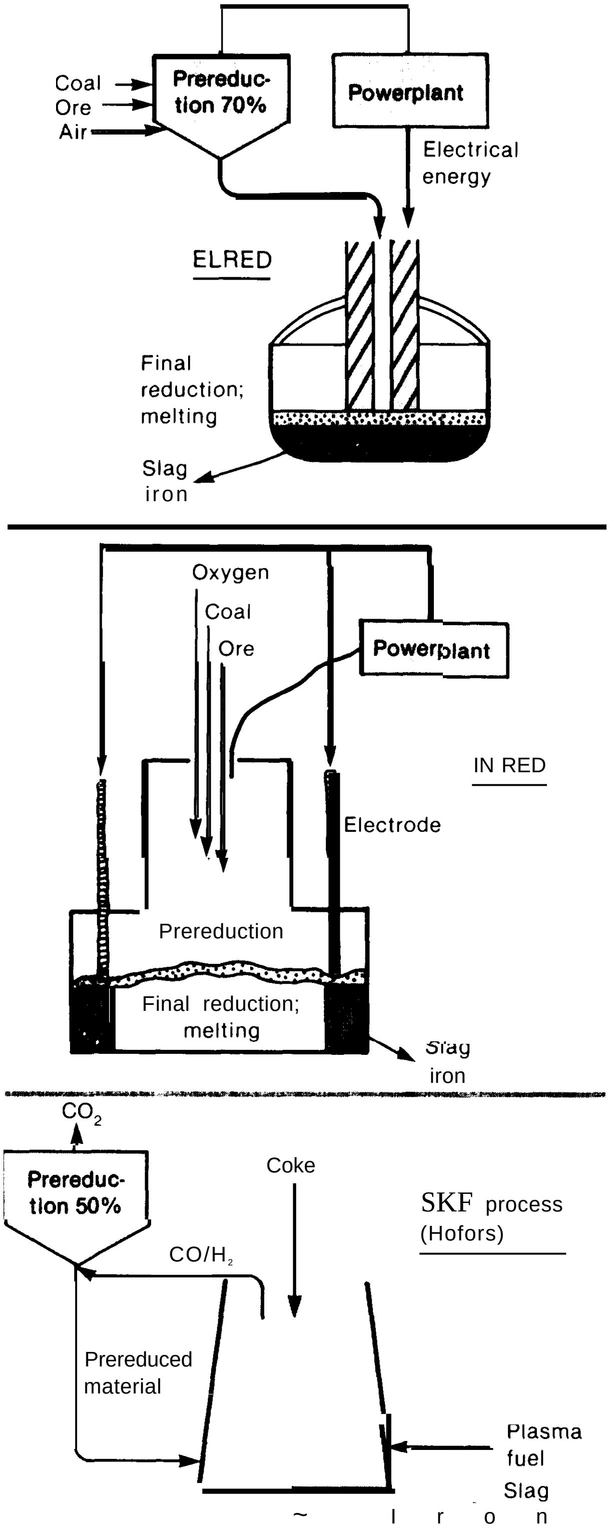
Table 83.—Three New Swedish Steelmaking Processes

Process	Capital costs ($1979)/tonne annual capacity	Production costs ($ 1979)/ tonne pig iron	Energy use 10^6 Btu/tonne pig iron[a]
ELRED.—Reduction stage uses coal in a fluidized bed. Final smelting-reduction stage is in an electric arc furnace. Flue gases from both stages generate electricity.	NA	NA	15
Hofors. —Reduction in fluidized beds followed by smelting reduction in a plasma-heated shaft furnace. Gas for first-stage reduction from smelting operation using coke. Outlet gas from first stage used for drying and preheating of materials. The plasma-heating requirement can be reduced by injection of oxygen or oxygen-hydrocarbon mixture in second stage.	$140	$116	
Low- and high-electricity versions within about 3 percent of each other.			10
INRED. -First-stage reduction-smelting using coal which is partially burned, the remainder forming coke. Second-stage uses coke from first-stage and prereduced iron in an induction-heated furnace. Electricity is produced from steam formed by cooling of first stage furnace. Coal is sole energy source.	178	125	16

NA = not available
aFor comparison purposes the energy for a blast furnace ranges from 11.8 10^6 Btu/tonne of pig iron for a new blast furnace to 15.4 10^6 Btu/tonne for an existing one.

SOURCES: ELRED from P. Collin and H Stickler. "EL RED-A New Process for the Cheaper Production of Liquid Iron, " provided by ASEA Corp. Others from S Eketorp, et al "The Future Steel Plant—A Study of Energy Consumption," Nat tonal Swedish Board for Technical Development, 1979

Figure 26.—Three New Swedish Ironmaking Processes



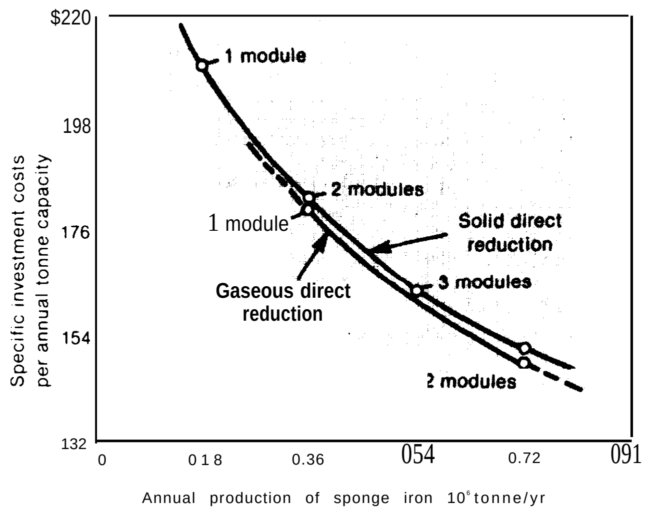
SOURCE S Eketorp for OTA

Table 84.—Capital Costs of Direct Reduction Processes (1979 dollars per tonne of DRI)

Process	cost
Natural gas plants	
Typical gas process in the United States[a]	$120
Typical gas process in the United States[b]	100
HyL process[c]	100
Midrex process in Venezuela[d]	110
Unstated in Italy[e]	200
Coal oven gas (existing coke plant)[f]	190
Coal gasification	
Midrex process with either Lurgi or Texaco gasifiers[f]	300
Unstated DR process with Koppers-Totzek gasifier in Brazil[g]	200
Direct coal	
Midrex electrothermal[f]	200
Tata iron and steel process in India[h]	182
Accar process in India[i]	167
Swedish Plasmared process[j]	135
Azcon—DRC in South Africa[k]	150

[a]H. W. Lownie, Jr., "Cost of Making Direct Reduced Iron," 1978 SME-AIME Fall Meeting, 1978.
[b]J. W. Brown and R. L. Reddy, "Electric Arc Furnace Steelmaking With Sponge Iron," *Ironmaking and Steelmaking*, No. 1, 1979, pp. 24-31
[c]*33 Metal Producing*, July 1979, p. 27.
[d]*The Washington Star*, Oct. 1, 1979.
[e]*American Metal Market*, Nov. 13, 1979.
[f]From Midrex Corp.
[g]*American Metal Market*, Oct. 19, 1979.
[h]*American Metal Market*, Oct. 30, 1979.
[i]*American Metal Market*, Sept. 26, 1979.
[j]*American Metal Market*, Sept. 21, 1979.
[k]*American Metal Market*, June 12, 1980.

Figure 27.—Specific Investment Costs per Tonne of Direct Reduced Iron (Krupp coal process, price basis, 1978)



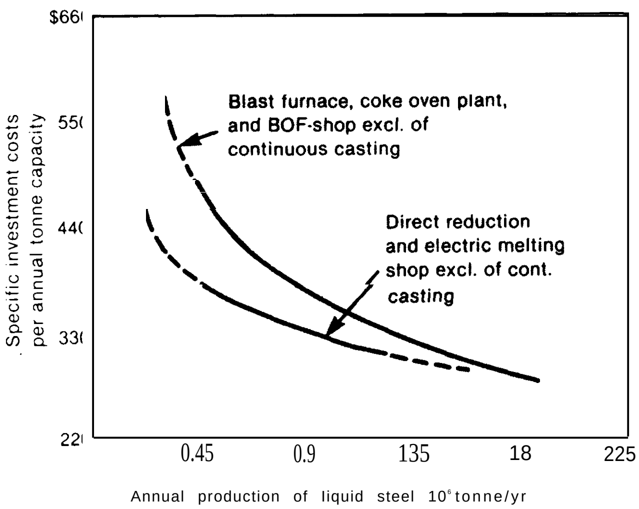
SOURCE: K.H. Ulrich, "Direct Reduction by Comparison With Classical Method of Steel Production," *Metallurgical Plant and Technology, No 1, 1979* suiting from scaling up DR processes, which is just now beginning.

Another way of examining the potential economic advantages of new processes is to consider the costs to produce steel rather than DRI, Capital costs as a function of annual capacity for a direct coal, kiln DR process and conventional blast furnace based on steelmaking are shown in figure 28. For capacities less than 907,000 tonne/yr, DR appears to have a distinct capital cost advantage. A similar result holds for production costs, as shown in figure 29.

A comparison of both capital and production costs for conventional steelmaking with several variations of a coal gasification steelmaking process, shown in figure 30, shows considerable savings possible.

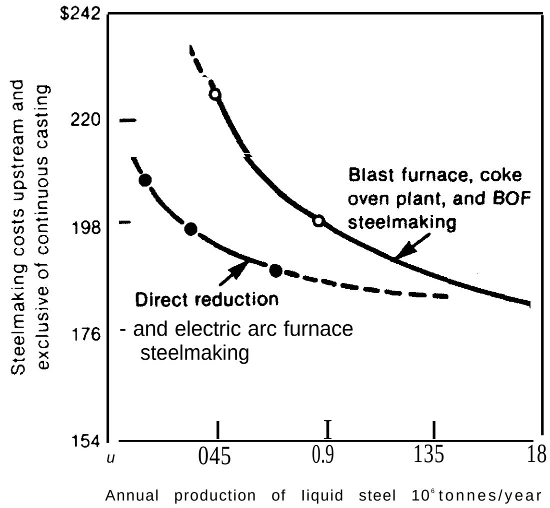
A comparison of the Swedish ELRED process production costs with both conventional blast furnace steelmaking and a typical natural gas DR system is shown in table 85. The comparison with the conventional route is valid, and it shows a saving with the ELRED process at this relatively low annual capacity, but the comparison with the gas DR plant

Figure 28.—Specific Investment Costs for Different 'Routes of Steelmaking per Tonne of Raw Steel Capacity (price basis, 1978)



SOURCE K H Ulrich, "Direct Reduction by Comparison With Classical Method of Steel Production," Metallurgical *Plant and Technology, No* 1, 1979

Figure 29.—Steelmaking Costs Upstream and Exclusive of Continuous Casting for Different Production Routes per Tonne of Raw Steel (price basis, 1978)



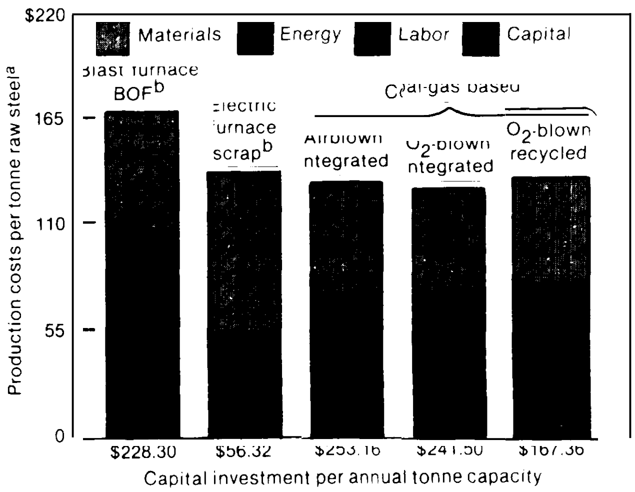
Coking coal: $72/tonne (respective coke price depending on size of coke oven plant)

DR-coal: $33/tonne
Oil: $72/tonne
Electric power. $0.02/kWh

SOURCE K H Ulrich. "'Direct Reduction by Comparison With Classical Method of Steel Product Ion," *Mefallurgical Plant and Technology No* 1, 1979.

Figure 30.—Comparison of Coal Gasification Direct 'Reduction Steelmaking to Conventional Blast Furnace and Nonintegrated Steelmaking

Coal-gas processes yield steel at $128to$134/tonne



[a]Costs in 1978 dollars.

[b]Scrap at $81.68/tonne.

SOURCE: Westinghouse Research and Development Center.

Table 85.—Total Steelmaking Costs in 1978 Dollars per Tonne of Raw Steel (for 050,000 tonne/yr of raw steel)

	Blast furnace (sinter) + BOF	ELRED + BOF	Shaft furnace (sponge iron) + arc furnace
Iron raw material[a] . . .	$51.6	$33.5	$60.0
Energy[b]	54.4	16.8	47.6
Processing.	37.5	38.0	51.6
Capital costs[d]	39.0	45.7	44.3
Unforeseen costs . . .	—	11.0	—
Total steel making costs.	$182.5	$145.0	$203.5
Relative total costs as a percentage. . .	100%	80%	112%

aConcentrates and pellets, respectively, alloying element, cooling pellets,

bCoke, coal, oil, minus energy credit plus electricity in steel mill ($181 tonne)
CLabor operation, repairs, and maintenance), electricity, electrodes, lime, oxygen. refractories, desulfurizing (for ELRED)
dFor the ironmaking and steelmaking plants Plants assumed to be in Europe.

SOURCE P. Collin and H. Stickler, "EL RED-A New Process for the Cheaper Product Ion of Liquid Iron, " ASEA Corp.

Table 86.—Capital Costs for Different Steelmaking Routes (1979 dollars per annual tonne steel product capacity)

Process route	cost
Conventional new plant (greenfield).	$1,320
Integrated blast furnace[a].	275
Nonintegrated scrap-electric furnace[a].	275
Combined scrap non integrated with coal DR[b]	
Direct coal	385
Coal gasification.	418
Integrated gas DR[c]	
0.45 million tonne/yr, Midrex process Argentina . .	660
1 million tonne/yr, unstated process and location[e].	550
0.85 million tonne/yr, Midrex process, Saudi Arabia[f].	814
0.6 million tonne/yr, unstated process, Egypt[g]	725
Coal gasification-DR integrated	
Unstated DR with Koppers-Totzek gasifier in Brazil[h].	1,011

aFrom ch. 10 Value for nonintegrated plant IS for a broader product mix than is currently true for most such plants
bAssumes 50-percentt use of DR plant to produce 1 tonne of steel Less then 50 percent of DRI would be used with scrap, but because of Incomplete metallization of the ore and yield uncertainties extra DR capacity IS accounted for The unit cost for direct coal DR IS $220/tonne and for coal gasification $3301 tonne The value for the base steelmaking plant IS $2751 tonne
CAssumes a product mix corresponding to a domestic nonintegrated producer
dAmerican *Metal Market, Aug 281979*
e*American Metal Market,* Aug. 21, 1979 (by French Society of Steel Studies)
f33 Metal *Producing,* May 1979
gArnerican Metal Market, June 11 1980.
hAmerican Metal *Market,* Aug. 19, 1979.

is not quite so meaningful because the cost of gas purchased in Europe would be high.

To help put the potential capital cost advantages of DR in better perspective, cost data for steelmaking capacity for a number of different process routes, including conventional steelmaking, are given in table 86. Although steelmaking based entirely on natural gas is not likely to be practicable for the United States, it is being adopted by foreign nations with domestic sources of gas and without large supplies of scrap. The costs are less than for blast furnace technology. The two more likely cases for the United States are the use of a combination of coal DR and scrap-based steelmaking and the use of coal gasification DR ironmaking. Because coal gasification is just now being commercialized, there are no reliable cost data for the United States. However, the data for a Brazilian plant based totally on coal gasification, and the data shown in figure 30, suggest that this is a viable option for future domestic steelmaking. The most intriguing possibility for the near term (within 5 to 10 years) is the combination of scrap-based steelmaking with either direct coal or coal gasification. A greenfield plant using a combination of scrap and DRI (discussed more fully in ch. 8) would cost much less than expanding an existing integrated plant or constructing a new integrated plant. Costs for the latter are discussed in chapter **10.**

Labor requirements for DR systems range from 0.4 to **0.6** employee-hours per tonne.[19] For DR with EAF, the range is **1.6 to 1.9** employee-hours per tonne.[20] In contrast, the CO-BF-BOF sequence uses around 2.6 employee-hours per tonne.

Product Use.— In the steel industry DRI has three major uses:

- feed to ironmaking units (BF, cupola, electric smelting);
- feed to steelmaking units (BOF, EAF); and
- feed to metal powder processes.

In addition, DRI may be used for a variety of special applications such as the recovery of copper from water streams. DR processes may be used to recover other constituents in

[19]H. W. Lownie, Jr., "Cost of Making Direct Reduced Iron,"' SME-AIME Fall Meeting. Florida, Sept. 11.1978,
[20]Clark, op. cit.

an ore feed, and in the extreme case DRI may be a lesser value byproduct.

The composition of DRI determines its suitability for various applications. Some DRI products have relatively low degrees of metallization (less than 90 percent, and even 80 percent in a few cases); these are suitable only for ironmaking. Other DRI products have a relatively high carbon content. Frequently, DRI is marketed on the basis of its carbon-tin oxygen ratio, which—depending on the particular steelmaking operations—is a very important factor in the selection among available DRI products.

One advantage of DRI is that it is free of the so-called "tramp" elements that often appear in recycled scrap. Recycled scrap contains a variety of alloying elements, including copper from copper-bearing alloys, tin and zinc from coated products, and many others, all of which can pose problems in steelmaking. On the other hand, DRI can have the disadvantage of a high sulfur content.

Desirable composition specifications of DRI are given in table **87.** It must be recognized, however, that off-specification material may be used in blending batches of DRI. DRI is normally used in conjunction with scrap, and an optimal ratio of DRI to scrap can be established for any particular situation.[21] In one estimate of EAF energy consumption, it was found that energy consumption decreased linearly from about 770 kWh/tonne at 80-percent metallization to 500 kWh/tonne at 96-percent metallization.[22] Most studies have shown that EAF productivity peaks at an optimal ratio of DRI to scrap corresponding to about 45 percent DRI.[23]

Table 87.—Typical Specifications for Direct Reduced Iron Used in Steelmaking

Item	Specification (by weight)
Metallization	More than 95%
Total iron	More than 93%0
Metallic iron	More than 88%
Gangue [a]	Less than 6%
Sulfur	Less than 0.03°/0
Phosphorus	Less than 0.05%
Carbon	Between 0.8 and 1.7°A
Size [b]	Variable
Strength and density	Variable

aThe gangue specification would take into account the balance of basic oxides (CaO, MgO, etc) over acidic oxides (SiO^2, Al^2O_3. etc). The former are desirable, while the latter are undesirable from the standpoint of slag formation and refractory lining life in steelmaking

bFor example, for Midrex processes. 100 percent less than 0.75 inch and no more than 5 percent less than 0.13 inch

SOURCE G St Pierre for OTA

Siting.—The selection of optimal sites within the United States for coal-based DR plants is a complex problem. Site selection depends on whether the plant is to operate in association with contiguous ironmaking and steelmaking operations or is to transport and market DRI. In the former case, it is important to consider:

- distance from ore and coal sources;
- availability and price of scrap;
- site, labor, and environmental constraints;
- cost of electricity; and
- distance to steel product market centers.

In the latter case, important factors include:

- distance from ore and coal sources;
- labor, environmental, and climatic constraints; and
- distance from iron and steelmaking centers.

There is almost no region within the continental United States that would be entirely unsuitable for a DR operation in some form. Particularly attractive opportunities appear to exist in the Southwest and Gulf States, the Appalachian States, the Northern Great Lakes region, and the Canadian border States.

[21] "Ironmaking by Direct Reduction-A Review of the Detroit Meeting."' *Iron and Steelmaking*. May 1979, pp. 44-45; D. H. Houseman. "Direct Ironmaking Processes, " *Steel Times*. April 1978; B. Rollinger. "Steel Via Direct Reduction, " *Iron and Steelmaking*. January 1975, pp. 8-16: J. W. Brown and R. L. Reddv. "Electric Arc Furnace Steelmaking With Sponge Iron,"' *Ironmaking and Steelmaking*. No. 1, 1979, pp. 24-31: F. Fitzgerald, "Alternative Iron Units for Arc Furnaces, " *Ironmaking and Steelmaking*. No, 6.1976. pp. 337-442: K. Shermer. "Improved Technology for Processing Sponge Iron in the Electric Arc Furance,' '" *Ironmaking and Steelmaking*. No. 3. 1975, pp. 1 18-92; J. D. 1)' Entremont. Armco Steel Corp., paper presented a I 1979 conference.

[22] Brown and Reddv, op. cit.

[23] Rollinger, op. cit.

Alternate Energy Sources.—In addition to coal, other inexpensive solid reactants may be used for DR systems. These include biomass, peat, lignite, wood and paper wastes, and municipal and industrial wastes. Biomass, which embraces a large variety of vegetable and animal wastes, and the other materials have similar advantages and drawbacks as reactants. They cost little, are generally available, and are regenerable. They also contain little inorganic matter, such as ash, and few of the elements, such as sulfur and phosphorus, that are undesirable in steel. In addition, these materials frequently provide very reactive sources of carbon; biomass, for example, may consist of cornstalks, nutshells, and perhaps pulp and skin from a variety of food-processing operations.

The chief disadvantages of these materials are their high moisture content and low bulk density. The direct charging of wet, low-density materials into iron production units, such as rotary kilns, causes a substantial loss of productivity, which translates into higher energy, labor, and capital costs per tonne of product. Both problems can be overcome by pretreating (drying, carboning, etc.) and compacting the materials, although this too takes energy. Ironmaking operations present an attractive site for processing these materials. Most large steelmaking plants have low-temperature waste heat available. Transferring that heat is not very efficient, however, and the bulky equipment is costly.

If inexpensive methods can be found to convert all of these materials into a product roughly equivalent to sub-bituminous coal in moisture, density, and transportability, then their use by DR plants within a reasonable distance might follow. The pretreatment technologies are broadly recognized and are under intensive investigation throughout the country; significant advances should occur during the next decade.

Advantages of DR Systems.—DR systems offer an advantageous alternative to the blast furnace process for the production of iron from iron ore and recycled iron oxide, and to scrap in the manufacture of steel products in the electric furnace. Not all of the potential advantages of using DR would apply to every economic or regional enterprise. Further, it is apparent that there is a wide variety of DR processes from which to choose, and each has its particular advantages and disadvantages. The following advantages, then, should be treated as opportunities presented by the development of DR systems:

- DR units can be built on a variety of scales, to use a variety of charge oxides and reductants, and in a variety of locations;
- scrap-based companies can manufacture high-grade steels from DRI, which, unlike scrap, has a known, uniform composition;
- DRI can be transported and handled easily and can be charged to furnaces on a continuous basis;
- DRI can be used as a feed material for blast furnaces and basic oxygen steelmaking units;
- DR processes do not require metallurgical-grade coke;
- DR systems do not pose environmental problems as severe as those of coke oven-blast furnace systems;[24]
- DR processes can be coupled with several energy-generation systems (nuclear, MHD, etc.);
- DR processes can be coupled with coal gasification systems;
- DR systems can be constructed with comparatively low capital costs; and
- DR systems have competitive operating costs.

The DR processes provide attractive opportunities for all three segments of the steel industry. The integrated segment could increase ironmaking capacity in increments much smaller than is economical for the blast furnace, and could do so without the need to build additional coke capacity or purchase coke. Both integrated and particularly scrap-

[24]L. G. Twidwell, "Direct Reduction: A Review of Commercial Processes,"' Environmental Protection Agency, 1979.

based producers would benefit from having DRI as an alternative to purchased scrap. * Nonintegrated plants using DRI could produce higher grade steels and control their operations more readily. In addition, DR facilities would allow this segment to integrate operations from ore to steel product. The alloy / specialty steel companies, too, would benefit to some extent by the opportunity to substitute high-grade DRI for scrap.

In general, the substitution of DRI for scrap lowers residual element ("tramp") levels, facilitates material handling and charging, and enhances product quality. In addition, DRI enables steelmaker to write tighter specifications for iron units than is usually possible with scrap. Although DRI use does not require special arc furnaces, many developments are likely in electric furnace design for adaptation to DRI.

Difficulties With DR Systems.—Like DR's advantages, not all of its disadvantages apply to each DR system or economic region:

- DR processes have higher energy and material requirements than blast furnaces;
- DR processes cannot be built on a scale equivalent to a large modern blast furnace;
- DRI is a solid product that cannot substitute significantly for "hot metal" as a feed to BOFs;
- DRI must be handled, stored, and charged in a different manner from scrap;
- in coal-based DR processes, special provision must be made for sulfur control;
- solid waste materials (lime, ash) from coal-based DR processes must be disposed of in a different manner than slag from a blast furnace;
- the variety of DR options, many not yet proven on a commercial scale, makes it difficult to select an optimum process for a given set of conditions;
- off-specification DRI (high-oxygen, alkali, silica contents, fines) can damage electric furnaces;
- without special provisions, DRI use might increase the generation of fugitive particulate emissions around electric furnaces; and
- some coals are not suitable for direct use in coal-based DR systems and must be gasified in separate units.

*Also discussed in chs. 7 and 8.

Forecast.—The capacity of DR plants throughout the world has grown at a rate of about 30 percent per year since 1965; however, this growth rate has been achieved in a relatively early stage in the technology's development and adoption, when DR capacity is still less than 5 percent of total world steel production. Nevertheless, forecasts of future growth in DR plant capacity have used rates as high as 13 percent per year for the period 1980-85 and 4.7 percent per year for the period 1990-2005.[25] The latter may still be too low, in view of expected steel production growth rates of 7.5 percent in the developing countries and 3.2 percent in the developed countries for the same period.

Worldwide, it is estimated that about 40 new DR units are planned for operation between 1981 and 1985. About one-half will use natural gas, one-quarter will use coal directly, and the remainder will use liquefied natural gas, gasified oil, gasified coal, or byproduct gas.

The figures shown in table 88 are conservative estimates for the growth of DR capacity. All of these projections might be influenced markedly by shifting practices in the United States and Japan or by industrial activity in China. The table also shows data on actual production of DR plants and it can be seen that production has been far below capacity. This has resulted from a depressed world steel market, startup problems in developing nations, and a combination of high natural gas costs and low scrap prices in the industrialized nations.

[25] H. W. Lownie, Jr., "Prospects for the Future," draft of ch. 13 for forthcoming book on direct reduction edited by J. R. Miller: Lownie's estimate agrees closely with the median estimate established by the Hamersley Delphi study.

Table 88.—Projections for Direct Reduction Growth (millions of tonnes)

Year	Capacity[a]							Production	
	Rate*	North America	Japan	EEC	Third World	Mid East	Free world	Free world[b]	Free world[c]
1975	27.8	2.0	1.2	0.7	4.0	0.0	8.0	2.7	2.7
1979	NA	NA	NA	NA	NA	NA	NA	7.2	9.0
1980	13.1	2.9	4.1	3.6	11.2	4.4	27.3	10.1	14.4
1985	9.3	5.3	6.3	6.6	21.2	9.6	50.6	19.0	NA
1990	5.7	9.5	7.7	9.4	33.9	15.3	78.9	NA	NA
1995	2.4	13.3	9.0	11.9	45.2	20.3	104.1	NA	NA
2000	–	15.3	9.7	13.2	51.2	22.9	117.2	NA	NA

"Annual compound growth rate (%) projected for succeeding 5 years

SOURCES [a]G. St. Pierre for OTA
[b]A.B. Jensen, "New Alternates for Charge Metal lie," Ferrous Scrap Consumers Coalition Symposium, February 1980
[c]Department of Commerce, "Production of Iron by Direct Reduction, " May 1979

Direct Steel making

Description.— Direct steelmaking is the conversion of iron ore to steel in a single reactor system. This would represent a radical or major technological advance, because it would replace several operations in either the CO-BF-BOF or DR-EAF sequences.[26] Included in this class of technology are continuous steelmaking systems and plasma steelmaking systems The latter are described separately in a later section of this chapter.

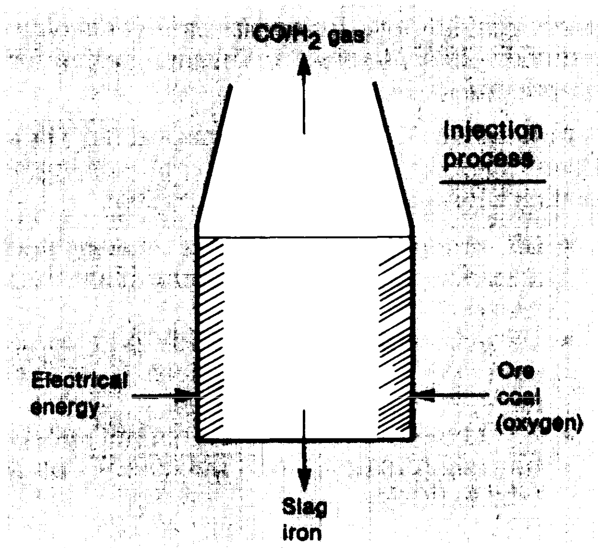
In essence, direct steelmaking allows the reduction, melting, and refining functions to occur and be controlled in a single (perhaps divided) reactor. Figure 31 is a schematic diagram of a proposed system, which has not advanced beyond pilot-plant exploratory work. Furthermore, none of the proposed systems represents the application of new basic principles.

Advantages of Direct Steelmaking.—The advantages of direct steelmaking may be summarized as follows:

- ore is converted to steel in a single reactor, rather than first making iron and then making steel;

[26]S. Eketorp, "Decisive Factors for the Planning of Future Steel Mills, " *Iron and* Steelmaker, December 1978, pp. 37-4 1; D. H. Houseman, "Continuous Steelmaking Processes,"' *Steel* Times, May 1978, pp. 457-462; A. K. Syska, "The S-Process,"' OTA seminar, May 2-3.1979.

Figure 31 .—Schematic Diagram of Direct Steelmaking System



SOURCE S. Eketorp for OTA

- consolidation of fumes, transfer of liquid products, and environmental problems are reduced;
- less land area, equipment, and capital are required; and
- a variety of raw materials (iron oxide and reductant) may be used.

Suitability for Industry Segments.—Direct steelmaking processes provide an opportunity for integrated steel plants; however, it is unlikely that significant adoption by alloy/ specialty or scrap-based companies would occur rapidly.

Disadvantages of Direct Systems.—None of the pilot-plant efforts on direct steelmaking has yet been successful. Specific technical problems exist that require major research, development, and demonstration efforts, such as:

- wall refractories are needed that can withstand severe chemical and mechanical erosion;
- procedures are needed for controlling steep chemical potential gradients (e.g., simultaneous injection of reductant and oxygen);
- injection refractories that can operate continuously must be developed;
- uniformity of product must be maintained over a significant period; and
- steel output per unit of reactor volume must be increased to compete with alternative routes to steel.

Forecast.—The idea of going from oxide concentrate directly to steel in a continuous, smooth operation has excited imaginations for many years. Europeans, Americans, and many others have spent a great deal of money on small pilot efforts, but none of these efforts, has been particularly successful from a research standpoint, and none has been carried to commercial scale. The problem has been that the different functions cannot be isolated properly: all the equipment must be tied up in a single strand, and the system has little flexibility with respect to either process variables or product requirements.

The major recent gains in improving the speed, efficiency, and productivity of steelmaking systems have been accomplished by separating rather than combining the different parts of ironmaking and steelmaking. In integrated systems, for example, substitution of a desulfurization station between the blast furnace and the steelmaking units can result in the increased productivity of each at a relatively low capital cost. In the development of the AOD system, adding another unit to separate the melting function from the refining function has markedly increased the productivity of stainless steel and high-alloy production systems.

Although major advances in the rates of reduction, melting, and refining and in the throughput per unit volume of equipment must be made, it is very unlikely that any direct, continuous single-reactor process will assume commercial significance in the next decade.

Plasma Steelmaking

Description.— Plasmas are already used commercially for steel melting and refining, but they can also be used for reduction reactions.[27] A plasma is generated in a steelmaking reactor either from “inert” gases like argon or nitrogen or from reactive gases like hydrogen or methane, and fine iron oxide particles and solid reductant are then fed into the plasma. While most plasma smelting systems use the plasma as an intense and efficient source of energy, some experts now think that the plasma also participates in unique reactions with the oxide undergoing reduction. Figure 32 is a schematic diagram of a plasma smelting (reduction) system for steel production. Bench-scale and small pilot systems have been operated, and several are reported in the literature. These systems include:

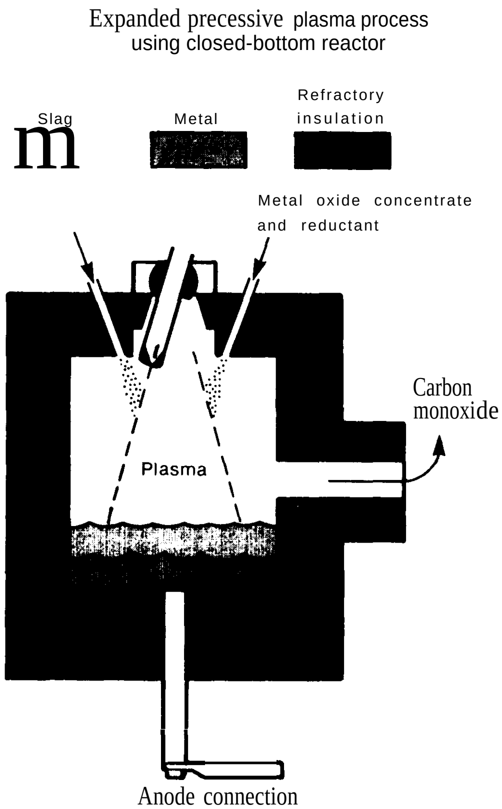
- the extended arc flasher at the University of Toronto;
- the falling film reactor at Bethlehem Steel Corp.;
- the SKF Hofors plasma reduction process;
- the rotating plasma process; and
- the expanded precessive plasma furnace.

Advantages of Plasma Steelmaking.—The advantages of the plasma steelmaking systems are similar to those of the direct steelmaking processes, but with several additional advantages:

- the plasma provides an intense, concen-

I’, L. Gulliver and P. J. F. Gladman, ‘‘F’l:]sm:] Furnace Processing,”’ OTA seminar, May 2-3. 1979; 1). R. McRae, ‘‘Plasrni] Reduction of Iron Ores to Raw Steel.”’ OTA seminar, May 2-3, 1979, paper No. 15; K. J. Reid, ‘‘Direct Steelmaking Based on Solid-Plasma Interact ions,”’ OTA seminar. May 2-i. 1979. paper No. 16.

Figure 32.-Plasma Steelmaking System



SOURCE. Tetronlcs Research & Development Co., Ltd, United Kingdom and foreign patents pending.

trated source of energy for endothermic reactions;

- the plasma system is ideally suited for the conversion of finely divided solids;
- plasma processes may involve some unique gas-solid-liquid reactions that are not encountered during conventional processing; and
- plasma "reactions" may be very fast.

Suitability for Industry Segments.—If successful development of the plasma steelmaking processes occurs, they could provide major opportunities for all three segments of the industry. Alloy/specialty companies might benefit in a most significant manner by being able to produce highly alloyed steels directly from oxide charge materials rather than from ferroalloys.

Disadvantages.— All of the disadvantages of the direct steelmaking processes apply to some degree to the plasma systems. An additional difficulty is that the engineering developments and control procedures for plasma systems are still in an early stage. Also, the reported power requirements and of fgas volumes are very high.

Forecast.—Some commercial development of plasma steelmaking systems is likely to occur by 2000. The first adoptions are likely to be for the manufacture of alloy steels.

Direct Casting

Description.— Direct casting is the pouring of liquid steel directly into thin solidified sections suitable for conversion into strip products. While continuous casting produces slabs that must be hot and cold rolled into thin-gauge products, direct casting would produce a thin product ready for final rolling into suitable gauges.

Advantages of Direct Casting.—Direct casting would eliminate the necessity to produce slabs for hot rolling. Some unique properties might be developed, particularly if an amorphous material can be produced in the casting step.

Suitability for Industry Segments.—All three segments of the industry would benefit from the development of this technological opportunity.

Disadvantages.— Flexibility in the control of properties and gauges of sheet products might be lost.

Forecast.—The need for development and demonstration is so extensive and costly that it will take many years to bring such a technique to the point of adoption on a significant scale.

Incremental Technologies

From literally thousands of advanced incremental technological opportunities that are or will be available to the steel industry, a few have been selected for illustrative purposes, These have particularly wide applicability during the next 10 years.

External Desulfurization

External desulfurization refers to all processes that lower the sulfur content of hot iron after it leaves the blast furnace and before it enters a steelmaking unit. It may be accomplished in torpedo cars or in ladles by introducing a sulfur-capturing reagent through plunging or lance injection. Many reagents have been used, including calcium oxides, calcium carbides, soda ash, and magnesium-impregnated coke (mag-coke). Special handling, injection, or plunging equipment must be used to provide a fast, efficient reaction. In addition, pollution abatement equipment is usually required.

The principal advantages of external desulfurization are that:

- the blast furnaces can be operated with less basic slags and at higher production rates;
- lower sulfur-content hot metal can produce low-sulfur steels in BOF processes; and
- capital requirements are modest compared to the alternatives.

External desulfurization is a proven technology available to the steel industry in a variety of engineering "packages. " It benefits integrated and alloy/specialty steel companies that use the CO-BF-BOF sequence. Continuing adoption by integrated steel companies is expected through the early 1980's.

Self= Reducing Pellets

Self-reducing pellets are prepared from a finely divided iron oxide concentrate, a solid reductant such as char, and lime (for sulfur absorption).[28] They contain all required reactants for iron production. The pellets may be cold- or hot-bonded, but heat is required for the endothermic reduction reaction. In addition, porosity is required to eliminate gaseous reduction products (Co, Co_2).

The principal advantage of self-reducing pellets is that no gaseous reactant is required. It is only necessary to establish suitable heat transfer in a reactor to produce sponge iron. In addition, the pellets could be used as supplemental feed to a BF system. The principal disadvantages are that the production, handling, and conversion techniques are unproven commercially, although some limited tests appear promising. Abrasion and impact resistance is important from both a handling and a processing standpoint. Another disadvantage is that the sponge iron quite readily absorbs sulfur from the carbonaceous reductant.

The development of self-reducing pellets could benefit all segments of the industry, and it is likely that development will proceed as an adjunct to DR developments during the next decade.

[28] E. M. Van Dornick, "Furnace Reduction of Pelletized Ferriferous Materials,"' U.S. patent No. 3,340,044, Sept. 5, 1967; G. D. McAdam, D. J. O'Brien, and T. Marshall, "Rapid Reduction of New Zealand Ironsands," *Ironmaking ond Steelmaking*, No. 1, 1977, pp. 1-9; K. Schermer, "Improved Technology for Processing Sponge Iron in the Electric Arc Furnace, " *Ironmaking and Steelmaking*, No. 3. 1975, pp. 118-92.

Energy Recovery

Energy recovery technologies in the steel industry have advanced significantly during the past 10 years.[29] The pressures of rapidly rising energy prices and declining availability have served as major incentives. Energy now represents nearly 20 percent of the cost of producing steel; 10 years ago it was 10 percent. There are a number of energy recovery opportunities available to the steel industry, and some new ones may be on the way. Nippon Steel Co. of Japan has demonstrated the effectiveness of energy recovery and conservation. In 5 years (1974-78) they achieved a total energy savings of 11.4 percent. Of this total, 3 percent resulted from energy-saving equipment installation, 6 percent from changes in operation, and 2.4 percent from modernization of facilities such as the use of continuous casting. [30]

Various estimates have been made of the potential for energy conservation in the steel industry. A North Atlantic Treaty Organization study indicated a potential for energy savings of up to 40 percent.[31] A study in the United Kingdom concluded that a savings of 30 percent was possible.[32] This would be somewhat applicable to the United States. Another study indicated that 15 to 20 percent of present energy consumption could be saved within the next decade. That study noted that two-thirds of the heat input to an integrated plant is wasted: 13 percent in waste gases, 16 percent in cooling water, 13 percent in sensible heat in residual matter such as slag and coke, and 24 percent lost to the ambient atmosphere.

Electric power could be generated by gas-expansion turbine generators operating on high-pressure top gas from BFs. The technology has been demonstrated in Japan, but adoption is difficult and economically questionable for most older BFs. Similarly, hot off-gases from coal-based DR kilns are being used to produce steam for electrical generation.[34]

Another demonstrated technological opportunity is in BOF offgas collection.[35] Carbon monoxide is released intermittently from steelmaking units, and its collection and use for fuel purposes have been adopted by some European, Japanese, and American operators. Hood design is the most critical parameter in modification for this purpose.

Adoptions of this nature are likely to continue through the 1980's along with the development and demonstration of new concepts for recovery of sensible heat from process materials (coke, slag, sinter, and steel),

Continuous Rolling

If slabs from continuous casting units could be rolled directly without the necessity of reheating, a considerable amount of energy could be saved. However, the technology is difficult to develop and the capital costs could be high. In addition, the effect on cold-rolling operations and the ability to control final steel properties with such processing are unproven. Until research efforts show the feasibility of this technology, and until the composition and cleanliness of liquid steel fed to continuous casters are controlled more tightly, any major development effort is unlikely. With continued developments in secondary refining[36] and perhaps filtration, direct rolling may become an attractive technological opportunity.

%4. Morley, "Industry is Making Its Energy Work Harder, " *Iron* Age, Aug. 27, 1979.

"*Nippon Steel News*, December 1979.

"E. G. Kovach (ed.), *Technology of* Efficient Energy Utilization, Pergamon Press, 1974.

"G. Leach, "A Low Energy Strategy for the United Kingdom,'" *International Institute for the* Environment *and* Development, 1979.

"H. G. Pottken, et al., *Metallurgical Plant and* Technology, vol. 4, 1978, p. 47.

"*33* Metal Producing, February 1980.

"" Potential for Energy Conservation in the Steel Industry to Federal Energy Administration, " Battelle, Columbus Laboratories, May 30, 1975; U. K. Sinha, "Recent Developments in the Iron and Steel Industry in the Light of Energy Conservation," *Steel* Times, January 1978. pp. 61-71.

"J. C. C. Leach, "Secondary Refining for Electric Steelmaking, " *Ironmaking and Steelmaking*, No. 2, 1977, pp. 58-65.

'-R. L. Reddy, "Some Factors Affecting the Value of Direct Reduced Iron to the Steelmaker," 38th AIME Ironmaking Conference, Detroit, Mich., 1979.

High= Temperature Sensors

It is difficult to determine the composition, cleanliness, and temperature of liquid iron and steel on a continuous, reliable basis. Although immersion thermocouples and oxygen-potential probes have been developed for intermittent measurements, no instruments are available for long-term continuous control.[38] The difficulty lies not in the primary instruments but in the severe conditions under which they must operate. Under reactive conditions at 1,550° C, "protective" materials fail rapidly. Hence, developments in this area depend on the development of immersion materials and/or major innovations in remote sensors.

If continuous control measurements of temperature, composition, and cleanliness can be developed, significant increases in productivity and overall quality could be achieved. As is always the case, improvements of this nature lead to decreased energy and raw material consumption per tonne of steel product shipped. Contact and remote sensors for hot solid products in process are available and under continuing improvement. The major research problem is in the liquid steel processing area. All sectors of the industry would benefit, and the impact would be significant. Breakthroughs on a selective basis are expected during the next two decades.

Computer Control

This subject is very broad and complex. From a "black box" point of view, the steel industry appears no more complex than other basic industries. The complexities arise when the inputs must be fully characterized and the process mechanism (reaction and transformation rates, heat and mass transfer, electrical and electromechanical characteristics, and process variables) must be fully described. Despite major effort, the surface has only been scratched.[39]

Processing of Iron Powders

The potential advantages of avoiding the very high temperatures associated with liquid steel processing and the potential opportunities for making difficult alloy components with iron powders have provided incentives for many ventures in iron powder processing. The powdered metal industry has developed proven technology for converting iron oxide to metallic products through powder processing,[40] but powder processing has not competed with liquid processing for major steel markets. Efforts to roll quality iron powder directly into thin-gauge steel sheet continue.[41] The technology must advance to the point where wide strip with a uniform thickness and structural quality can be produced before significant demonstration can occur. Cost competitiveness might be achieved through major energy and fuel savings in the 1990's.

Plasma Arc Melting

In the Soviet Union and East Germany, plasma melting of steel scrap has become an industrialized process.[42] Plasma arc furnaces with capacities of 27.2 to 90.7 tonnes are in operation there, replacing conventional EAFs used to melt and refine steel scrap. The furnaces may also be used for melting DRI.

In the conventional EAF, electric arcs are ignited between carbon electrodes and the furnace charge. Heat is transmitted by convection and radiation. Plasma arc furnaces

[38] J. P. Ryan and R. R. Burt. "Oxygen-Sensor Based Deoxidation Control," *Iron and Steelmaking*, February 1978, p. 28.

[39] C. L. Kusik, M. R. Mournier, and G. J. Kucinkas, "State-of-the-Art Review of Computer Control in the Steel Industry," A. D. Little, Inc., contractor report for the Department of Energy, June 1979; Central Intelligence Agency, "Foreign Development and Application of Automated Controls for the Steel Industry," S.K. 79-10010, January 1979; Iron Age, Feb. 4, 1980: H. Okada, "Background to 'technological Advance in the Japanese Steel Industry," Workshop on Innovation Policy and Firm Strategy, Dec. 4-6, 1979.

[40] Strauss and Heckel, op. cit.

[41] M. Ayers, "New Technology for Steel Strip Production," OTA seminar, May 2-3, 1979, paper No. 11: P. Witte, "An Energy Efficient, Pollution Free Process for the Production of Steel Sheet from Iron Concentrates," OTA seminar. May 2-3, 1979. paper No. 12.

[42] Eketorp and Mathiesen, op. cit.: A. S. Borodachev, G. N. Okorokov, N. P. Pozdev, N. A. Tulin, H. Fiedler, F. Muller, and G. Scharf, "Melting Steel in Plasma Electric Furnaces," *Stal*, 1979, pp. 115-17.

have bottom electrodes under the charge. The plasma arc is generated by forcing a stream of argon or nitrogen gas through an electric arc, which ionizes the gas and raises its temperature. The gas may reach temperatures as high as 13,7000 C. The arcs of injected gas throw plasma streams through ports in the furnace walls into the charge.

The advantage of the plasma arc furnace is that the plasma process transfers heat much more rapidly to the metal being melted and refined. Radiation and convection are much more efficient. According to reports, the power coefficient is 96 percent, which is considerably higher than in the EAF, where typical values are on the order of 75 percent.

Long-Range Opportunities

Perhaps the two most significant opportunities on the horizon for the steel industry are:

- complete elimination of the need for fossil fuels through the production of hydrogen by water hydrolysis; and
- adaptation of steelmaking to the potentials afforded by advanced nuclear reactors, high-temperature gas-cooled reactors, and, further off, fusion or MHD reactors .43

For the first opportunity to become a reality, energy from nuclear reactors must be available at costs well below those for fossil fuels. Hydrogen can then be used as a substitute for other gaseous reductants in most of the DR processes. For the second opportunity to emerge, the steel industry must work closely with the nuclear industry and take advantage of related developments in plasmas and MHD."[44] Although the Japanese have made the first major move, * a U.S. energy-chemical-steel consortium is underway. [45] By the turn of the century, experts expect a demonstration plant to be operating. By combining the best features of available technology, it might be possible to achieve very fast oxide reduction and melting in DR and melting units.

"J. Cushman, "Nuclear Steel: Long Wait for the Birth of an Industry," *Steel Week*, Nov. 26, 1979.

"R. W. Anderson, "Application of MHD Power and MHD Exhaust Gas Sensible Heat,<' OTA seminar, May 2-3, 1979,

*See ch. 9 for discussion of the Japanese nuclear steel making program.

[45] Cushman, op. cit.

Changes in Steel Products

Perhaps the major factor affecting the development of steel mill products is the energy shortage. Steel products play a large role in energy production (e.g., in tubing for petroleum production and transport and in materials for fossil fuel processing equipment and for electricity generation), and the increased needs of the energy sector will place greater demands on steel products. At the same time, the role of steel in the transportation industry will be one of helping to conserve energy (e.g., by decreasing vehicle weights to save fuel or by increasing the efficiency of electrical equipment such as motors and transformers). In these energy-related areas, steel products will have to achieve higher levels of performance in such characteristics as strength, toughness, corrosion resistance, fabricability, weldability, and formability. (See ch. 5 for a discussion of these properties.)

Such characteristics have always been considered in the development of steel alloy composition and processing. Except for the specialty steels (such as high-alloy steels, stainless steels, and tool steels), production costs, when weighed against properties, have generally led to the use of carbon as the major modifier of properties. That is, it has been possible to satisfy most markets by using the range of properties attainable from carbon steels in either the hot-rolled, cold-rolled, or heat-treated condition.

The combinations of characteristics that will be needed to meet future performance requirements are not readily attainable with the plain carbon steels. Consequently, steel metallurgists have been using a combination of strengthening mechanisms to develop materials with greater strength and toughness—a difficult combination. A number of new products have already been marketed to a limited degree or are in advanced stages of development. In some cases, barriers in processing technology are affecting or are likely to affect the product developments.

Incremental Product Developments

High-strength low-alloy (HSLA) steels are already marketed for energy production and automotive applications. In these steels, alloying elements such as titanium, vanadium, columbium, molybdenum, manganese, nickel, or cobalt are added. Carbon content is reduced in order to achieve high strength along with good toughness, better weldability, and better corrosion resistance. The precipitation of fine alloy carbides, which are smaller and better distributed than the carbide in commodity steels, improves the properties of the steel. This alloying effect and controlled rolling and heat treatment, which create small gains in strength and toughness, are the basis of the HSLA steels.

Dual-phase steels are on the market on a limited basis in automotive applications. These steels take advantage of the strength of a high-hardness crystalline form of iron (martensite) but use it in a mixture of very fine grains of relatively soft, virtually carbon-free iron. The combination of grain hardness and fine grain size, which can control the deformation pattern of the mixture, makes the dual-phase steels especially useful in sheet metal applications. The original material for sheet metal is relatively soft and easily shaped, but as it is being formed into shape, it attains the high strength needed for final service. This strengthening during the deformation process, or work-hardening, of a fine grain size material is a major alternative to the heat-treatment process for HSLA steels. The lack of carbide precipitates in the dual-phase steels generally gives them better weldability, formability, and corrosion resistance than conventional HSLA steels.

Superplastic ferrous alloys are less developed than superplastic nonferrous alloys, but there are some mainly small-scale test applications, primarily for the automotive and packaging industries. These ferrous alloys extend the concept that very fine-grained solids are both stronger and tougher than conventional steels by using ultrafine grains. The grains in these alloys are extremely fine (0.lμ to 5.0μ) mixtures of two crystalline phases, one iron (austenite) and the other a ceramic iron carbide (cementite). When this material is deformed at a moderately elevated temperature, it can be shaped, like a typical organic polymer plastic, into intricate patterns with very little applied force. The potential savings in design of dies and operation of presses for forming of sheet metal could be substantial. Moreover, by using such alloys in bulk form, such items as gears might be formed in a small number of simple extrusion steps with significant savings of energy and material compared to current machining practices.

One-side galvanized steel is described and discussed in chapter 9.

Major Product Developments

Amorphous ferrous alloys are under development in some small-scale test applications, primarily in electromagnetic devices. The amorphous ferrous alloys demonstrate the reduction of grain size taken to the limit, so that the aggregates of atoms no longer have any of the ordered characteristics of crystalline solids; they are amorphous solids like glass. Such materials have very useful properties, such as high strength, corrosion resistance (higher than ferrous alloys such as stainless steels), and easy magnetization (equal or better than materials such as permalloy).[46] The ferrous metallic glasses, as they are commonly called, can be obtained only by an extremely rapid cooling from the liquid to the solid state (10^{60} C/see). They do not have compositions typical of steels, although they have iron contents ranging from 3 to 93 percent. The greatest potential for these materials seems to be in transformer cores or in electric motors. The ease of magnetization would greatly increase transformer and motor efficiency.

According to a recent description of the potentially large impact of metallic glass:

> The random structure gives metallic glass unique magnetic properties that translate into vastly improved transformer efficiency, And, if scientists can learn to use this substance in the transformer's moving counterpart—the electric motor—Americans eventually could save up to $2 billion annually in energy costs.
>
> According to the U.S. Department of Energy, metallic glass will begin to tap enormous quantities of wasted electric energy before the decade ends.[47]

The National Academy of Sciences has noted that commercial exploitation of these materials will stimulate much R&D during the next 5 to 10 years.

Development Problems

These steel products or potential products face some common problems in further development and use, problems which reflect the higher quality level of those products. Two are general problem areas: control of melt chemistry; and ability to carry out complex and/or tight-specification thermomechanical processing.

The melt chemistry problem involves the control of both impurities and alloy additions. The role of impurities, such as sulfur, oxygen, nitrogen, hydrogen, and in some cases even carbon, in affecting the properties of further processing of steel is well known. Control of those impurities requires more extensive processing such as vacuum remelting, or degassing, as well as better process monitoring and control procedures [e.g., the use of solid-state oxygen detectors for rapid chemical analysis). The control of alloy additions requires similar attention. It is noteworthy that the newer low-alloy steels are called "microalloyed" steels, which reflects the low levels of alloy addition as well as the need to control those levels within narrow ranges.

The problem of thermomechanical processing is central to all the materials that have been discussed. Facilities to carry out such processing, or the lack thereof, will significantly affect the marketing of the new steel products. These facilities will affect the product costs in two ways: the more complex and more closely controlled processing that these materials require will raise operating costs; and the equipment and facilities for producing the higher quality products will not be part of the existing plant of most steel mills, so production will require investment in new facilities. It is reasonable to assume that those mills with the more sophisticated thermomechanical processing capability will be in the most competitive position to participate in the market for these products.

The new products also have some individual disadvantages:

- Both HSLA and dual-phase steels pose some problems in die design if they are to be properly formed. For HSLA, the major problem is that its great strength causes "spring-back;" that is, the steel deforms elastically, but then springs back after the die pressure is removed. For dual-phase steels, the problem is to have the die contour control strain distribution so that sufficient hardening occurs. In both dual-phase and HSLA steels, corrosion resulting from the use of thinner gauges of steel is of some concern. The use of more extensive corro-

[46] J. J. Gilman, "Ferrous Metallic Glasses." *Metals Progress*, July 1979, pp. 42-47.
[47] Freeman, "Science and Technology—A Five Year Outlook." National Academy of Sciences, 1979.

sion protection methods will probably compensate for that potential disadvantage.

- Superplastic ferrous alloys are as easy to form as plastics, but like plastics they also have a low forming rate: it takes longer to form one piece of the superplastic alloy than to form an ordinary steel sheet. Additionally, the fine grain size of the superplastic alloys is likely to lower their corrosion resistance.
- The amorphous ferrous alloys suffer from two significant disadvantages with respect to structural applications. They are relatively brittle (have very low ductility), and they are currently only available in very limited shapes and sizes. Perhaps the biggest potential problem in applying the amorphous alloys is that they are extremely susceptible to crystallization or devitrification if service is at elevated temperatures.

Summary

There are a number of steel mill product developments that indicate a continued competitiveness for steel products. Although product development continues to improve the applicability of the materials, there are needs to be met in the processing technology at the mills before full advantage of the potential markets can be realized, Of special note are the need to gain greater control over chemical composition and metallurgical structure in order to produce uniformly high-performance materials, and the need to develop the procedures and facilities to carry out the more complex processing needed to obtain the desired metallurgical structures. Mills that have the financial and technical resources to meet these needs should be at an advantage in developing the markets.

The steel industry has played the dominant role in the development of HSLA, dual-phase, and superplastic steels; but chemical companies, universities, electrical equipment firms, and commercial research organizations have been very active in innovating in the glassy steels. There is a high probability that new companies will become the dominant producers of glassy steels.