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Effects of Direct Reduction Upon Mineral Supply Requirements for Iron and Steel Production

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EFFECTS OF DIRECT REDUCTION UPON MINERAL SUPPLY REQUIREMENTS FOR IRON AND STEEL PRODUCTION

by

R. J. Leary[1] and G. M. Larwood[1]

ABSTRACT

The technologies of contemporary iron and steel production and of direct reduction processes have been studied to identify and estimate the potential effects of direct reduction on mineral consumption and the problems raised thereby for the Nation's mineral supply to the iron and steel industry.

Contemporary patterns of mineral raw material and energy consumption were determined from a study of the 1964-70 period. Major changes were observed in requirements for 14 of 20 principal commodities. Average practice in 1970 was compared to best practice to estimate the potential effects of implementing existing technology without recourse to direct reduction.

Potential effects of direct reduction were estimated by comparing the mineral requirements for 95 percent reduced pellets with 1970 best practice technology for two cases of use: (I) complete substitution for hematite pellets in blast furnace burdens, and (II) partial substitution (40 percent) for scrap in electric furnace steel charges. Effects upon mineral supplies are described; important collateral factors are analyzed, and the principal metallurgical, industrial, and environmental consequences of implementing direct reduction are discussed.

Major effects of direct reduction on the domestic steel industry and its mineral supply system are foreseeable. Direct reduction will (1) create a large demand for low-gangue iron ore; (2) relieve the dependence of the steel industry on coking coal, and (3) permit great increases in furnace productivity, both in blast furnace ironmaking and electric arc furnace steelmaking.

INTRODUCTION

The quest for better allocation of mineral resources never ends. A more efficient allocation, a better way, is signaled when a new process is adopted. New technology alters the proportions of materials, labor, or capital required for production. The usual result is a change in the mineral raw material and energy supply needs of the industry and the Nation.

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[1] Metallurgist.

A signal of change in the technology of iron reduction has been given by the steel industry of the United States. Direct reduction processes are, for the first time, being implemented by U.S. firms (21, 93, 100).[2] Four plants are building or in operation. Together they will supply nearly 2.2 million tons per year of metallized pellets and briquets to steel furnaces.

The Bureau of Mines has a special concern for and sensitivity to the issues for mineral supply raised by direct reduction. The Bureau is the Nation's agency concerned with problems of mineral supply. It perceives that change in the Nation's supply needs is an essential consequence of substitution, and that decisions are unlikely to be better than the foundation of information and foresight.

This is especially true for problems arising in iron and steel. An abundant and assured supply of steel is vital for the U.S. economy. Iron and steel manufacturing is a principal consumer of minerals. The supplying of ores, fuels, and fluxes to the iron and steel industry constitutes a large segment of the mining industry.

This study compares the mineral raw material and energy supply needs of contemporary iron and steel technology with an assumed future based on substitution of direct reduction for blast furnace reduction. The principles of direct reduction and a description of prominent processes are presented in Appendix A.

A four-stage comparison is developed, as follows: (1) Contemporary trends in mineral consumption, analyzing the two types of technologic change--improvements within a process, and substitution of one process for another; (2) between the contemporary average and the best contemporary practice, to measure the possibilities of further change in average usage based on the technologic possibilities of existing processes; (3) between best contemporary practice and direct reduction, the reduced iron being used entirely in blast furnace burdens, and (4) between direct-reduced iron used in blast furnaces to supply primarily basic oxygen process (BOP) steel furnaces and direct-reduced iron consumed in electric-arc steel furnaces. The extreme case, complete substitution by the new technology, is considered. Provision is made for interpolation to reflect intermediate conditions and to relate the findings to projections of future demands for iron. Effects on individual minerals are considered. Collateral factors are discussed. The metallurgical, industrial, and environmental consequences of direct reduction are identified and discussed.

ACKNOWLEDGMENT

The generous contribution of confidential information to this study by colleagues in private firms, trade associations, research groups, and the Bureau of Mines is gratefully acknowledged.

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[2] Underlined numbers in parentheses refer to items in the bibliography that precedes the appendixes.

MINERAL RAW MATERIALS AND ENERGY CONSUMPTION IN IRON AND STEELMAKING

Importance of Mineral Production and Trade

The iron and steel industry of the United States is a major consumer of minerals. In 1967 the principal mineral raw materials and fuels consumed by the iron and steel industry amounted to at least $4.7 billion, equivalent to about one-sixth of the total value of minerals available for consumption[3] in the United States that year (table 1). Principal items of consumption included iron ore and agglomerates, $1.6 billion; ferrous scrap, $1.0 billion; coal for coke, $0.9 billion; purchased fuel (and the fuel equivalent in purchased electric energy), $0.6 billion; fluxes $0.2 billion, and an additional $0.4 billion, the estimated value of the minerals consumed in manufacturing the nonferrous metals, ferroalloys, and refractories (table 2). Minerals amounted to one-fourth the value of iron and steel shipments; $19.6 billion in 1967 (10).

TABLE 1. - Value of mineral production and trade, 1967-70

(Million dollars)

Item	1967	1968	1969	1970	1967	1968	1969	1970
	U.S. production				Exports			
All minerals........	23,734	24,971	24,921	29,802	1,013	1,026	1,099	1,558
Mineral fuels.....	16,195	16,820	17,965	20,153	601	539	632	1,011
All, except fuels.	7,539	8,151	8,956	9,637	412	487	467	547
Metals..........	2,333	2,703	3,332	3,926	171	241	246	322
Iron ore[1].......	818	836	929	942	72	71	62	68
	Imports				Apparent U.S. supply			
All minerals........	2,820	2,960	3,014	3,270	25,541	26,905	26,836	31,514
Mineral fuels.....	1,289	1,309	1,428	1,460	16,883	17,590	18,761	20,602
All, except fuels.	1,531	1,651	1,586	1,810	8,658	9,315	10,075	10,900
Metals..........	1,117	1,161	1,094	1,252	3,279	3,623	4,180	4,856
Iron ore........	444	454	403	479	1,190	1,219	1,270	1,353

[1] Iron ore shipments.

Source: Bureau of Mines Minerals Yearbook.

Consumption Trends

Contemporary trends in mineral consumption provide the perspective for analyzing the effects of direct reduction. Short-term consumption statistics can be distorted by inventory differences; in the longer term, however, consumption data measure mineral raw material and energy requirements. Aggregate statistics sum up the tasks and issues of mineral supply to be faced by the industry and by Government as well.

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[3] Available for consumption = U.S. production less exports plus imports.

TABLE 2. - Value of principal minerals and energy consumed in iron and steel, 1967

(Million dollars)

	Blast furnaces and steel mills	Foundries			Total
		Iron		Steel	
		Gray	Malleable		
PRINCIPAL MINERAL MATERIALS					
Coal used in coke	879.8	-	-	-	879.8
Iron ore	1,596.6	-	-	-	1,596.6
Iron and steel purchased scrap	730.1	209.3	24.5	55.3	1,019.2
Nonferrous metals and alloys	315.4	10.7	1.2	2.7	330.0
Ferroalloys	446.9	46.0	8.9	24.7	526.5
Refractories	202.9	33.3	5.2	21.3	262.7
Fluxes	169.6	-	-	-	169.6
Total of principal mineral materials	-	-	-	-	4,784.4
Total consumption of materials, containers and supplies	-	-	-	-	8,419.5
PURCHASED FUELS AND ELECTRIC ENERGY					
Coal (anthracite, bituminous and lignite)	40.0	1.6	2.1	1.0	44.7
Coke, screenings, and breeze	170.7	42.3	4.8	0.5	218.3
Fuel oil, total	102.5	1.7	0.7	2.7	107.6
Gas, total	270.9	13.9	4.4	10.8	300.0
Other fuels	41.8	11.2	0.7	1.8	55.5
Gross consumption	-	-	-	-	726.1
Less: Value of coke, coke oven gas, and blast furnace gas consumed					-458.7
Net purchased fuels	-	-	-	-	267.4
Purchased electricity	293.8	32.0	7.7	26.2	359.7
Net purchased fuels and electric energy	-	-	-	-	627.1
Total consumption:					
Principal mineral materials	-	-	-	-	4,784.4
Net purchased fuel and electric energy	-	-	-	-	627.1
					5,411.5
Total energy used for heat and power (billion kw hr equivalent)	279.6	27.9	6.5	11.4	325.4

Source: Census of Manufactures 1967 (7, 9).

Limits of Coverage

Only the mineral requirements likely to be affected by direct reduction are included in this study. Minerals consumed in iron mining and associated beneficiation and agglomerating plants were not included because the trend to pelletizing seems likely to go to completion regardless of whether direct reduction is adopted. Ferroalloys and nonferrous metals and alloys were excluded because consumption would be independent of the reduction process. Minerals consumed subsequent to raw steel production also were excluded. Refractories were considered but were excluded because the statistics of refractories consumption were not sufficiently disaggregated to be useful.

The 1964-70 Period

The time period 1964-70 was selected to represent contemporary trends. Shipments from U.S. producers were remarkably stable despite great changes in market size and in technology. With regard to market size, in 1964 the demand for steel products in the U.S. economy surged upward to 137 million tons raw steel equivalent,[4] more than 10 million tons ahead cf any previous year. Growth has continued since, the market reaching 162 million tons in 1969. With regard to new technology, a generation of investment in research and development had accumulated a great reserve. This pattern of market growth coincided with a harvesting of technology to energize a wave of capital investment in steel for new and better methods of production; it also remotely set the stage for the contemporary interest in direct reduction. The market for domestic products remained essentially static because imports captured most of the growth in demand. Domestic shipments grew only 5 percent from 1964 to 1970 (table 3).

Differences in mineral consumption express the net result of three categories of change--growth of shipments; inventory difference, and technologic change. A growth of 5 percent would be expected, to keep pace with domestic shipments. Since allowance for inventory differences between any 2 years might be as much as 2 to 3 weeks consumption, say 5 percent, three times that quantity, 15 percent, was selected as the criterion of a major change in technologic requirements. The measure of a major gain from technologic change would be an increase of 20 percent or more in consumption, that is, 5 percent to reflect growth proportional to shipments, plus 15 percent, the measure of major change. A major decline in consumption would be at least minus 10 percent or more (+5, -15).

A major change in consumption was experienced in 14 of the 20 principal minerals between 1964 and 1970. The prevalence of major change in the needs for minerals signaled intense currents of substitution at work. It meant that comparisons of mineral requirements between contemporary technology and direct reduction have to be comprehended in the light of the contemporary trends and the datum year selected for the comparison. Although the 1964 and 1970 statistics in table 3 are accurate cross-sectional representations of mineral supply needs at those two points in time, the inferences to be drawn from the respective years would be quite different. For comparison with direct reduction the trends in iron and steel production have to be examined.

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[4] Demand is taken to be the sum of shipments by U.S. producers plus imports. Raw steel equivalent measures the total steelmaking activity, domestic and foreign, required to supply this demand. Imports are assumed to be produced from raw steel at the same yield experienced by U.S. producers. (See table B-4.)

TABLE 3. - Mineral raw materials and energy consumed in making iron and steel in the United States, and product shipments, 1964 and 1970

	Year		Difference, 1970 minus 1964[1]	
	1964	1970	Quantity	Percent
CONSUMPTION				
Ferrous inputs:				
Ore, iron...........million short tons..	59.0	41.1	-17.9	-30.4
Ore, manganese..............do..........	.1	.1	.1	102.0
Ore, total.................do..........	59.0	41.2	-17.9	-30.2
Pellets....................do..........	30.7	62.1	31.4	102.0
Sinter and others...........do..........	56.2	47.8	-8.4	-14.9
Total agglomerates..........do..........	86.9	109.9	23.0	26.5
Less: flue dust recovered....do..........	5.2	3.4	-1.8	-34.2
Net ore and agglomerates.....do..........	140.7	147.7	6.9	4.9
Iron and steel scrap.........do..........	31.8	33.0	1.2	3.9
Fuels and energy:				
Coal, bituminous............do..........	88.8	96.0	7.3	8.2
Coal, anthracite............do..........	1.5	.9	-.6	-37.8
Coal, total.................do..........	90.3	97.0	6.7	7.4
Coke........................do..........	59.9	64.2	4.3	7.2
Natural gas[2].............billion cu ft..	156.2	112.6	-43.7	-28.0
Fuel oil[2]..............million gallons..	1,068.0	582.7	-485.6	-45.5
Purchased electric power[2]..billion kwhr..	8.7	12.6	3.9	45.2
Byproduct fuels:[2]				
Coke breeze.......million short tons..	2.7	2.3	-.4	-16.3
Tar and pitch.........million gallons..	280.8	219.4	-61.4	-21.9
Coke-oven gas...........billion cu ft..	413.6	456.4	42.8	10.3
Blast furnace gas......trillion cu ft...	2.4	2.8	.4	16.9
Fluxes:[2]				
Limestone...........million short tons..	29.6	25.3	-4.2	-14.4
Lime.......................do..........	2.4	5.9	3.5	143.9
Fluorspar..................do..........	.3	.6	.3	82.0
Oxygen[2]....................billion cu ft..	99.5	199.7	100.2	100.7
PRIMARY METAL PRODUCT SHIPMENTS				
Total iron and steel...million short tons..	102.1	107.3	5.2	5.1

[1] Totals may not add owing to rounding. Percentages calculated from detailed statistics.

[2] Blast furnace and steel plants. Statistics on foundry industries consumption not available.

Source: Appendix tables B-3, B-8, and B-16-B-31.

Industrial Shares of Production Unchanged

The near-constant flow of product shipments in the 1964-70 period was matched by the flow proportions contributed by the four primary industries. The industry shipped 108 million tons per year on the average, divided about 83 percent in steel mill products, 14 percent in gray iron castings, 1 percent in malleable castings, and 2 percent in steel castings (table B-3). This distribution has remained essentially unchanged for nearly 20 years. Thus the industrial makeup of iron and steel production provides no clue to the shifting movements in mineral consumption.

Constant Proportions of Pig Iron and Scrap

In the aggregate there has been no substitution of pig iron for purchased iron and steel scrap. New iron minerals, smelted into pig iron, constituted about 73 percent of the total iron supply in both 1964 and 1970 (table B-8). Recycled iron, in purchased iron and steel scrap, provided the balance. The 1964-70 average was 72.5 percent, a proportion that has been maintained since the 1950's. Essentially there are two operations involved--one for smelting iron ore, the other for melting and refining iron and steel. About 99 percent of iron ore smelting is performed in blast furnaces; thus it can be said that blast furnace smelting of pig iron has contributed a steady 73 percent share of the total iron supply to an essentially steady flow of iron and steel products. The explanations of mineral consumption trends are to be found separately in the processes for iron ore smelting and iron and steel melting and refining.

Blast Furnace Smelting

Six of the nine major declines in minerals consumption between 1964 and 1970 (table 3) occurred in the blast furnace and its subsidiary processes for ore and coke preparation. Consumption in the blast furnace of iron ore, sinter, flue dust, anthracite, coke breeze, and limestone (including dolomite) decreased in that order during the period. Of the five major gains in minerals consumption, one occurred in the blast furnace--pellets. The currents of technologic change in mineral consumption are revealed by the trends of mineral usage per unit of pig iron production (tables 4-6).

Ferrous Inputs

Total usage of ferrous inputs per ton of pig iron produced remained unchanged from 1964 to 1970 but the shares contributed by iron ore and agglomerates changed greatly. Iron ore use tumbled from 36 percent of gross ferrous inputs in 1964 to 25 percent in 1970. Pellet usage spurted from 22 percent to 42 percent. Sinter usage slipped from 40 percent in 1964 to 31 percent in 1970.[5] These trends away from ores and toward manufactured agglomerates have been underway since 1950 or so; further substitution is inevitable on the basis of announced plans for increased agglomerate production (25). Sinter

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[5] Flue dust byproduct (including sludge) was netted out of tables 4-6 (this byproduct is sintered and recharged); however, flue dust production dropped from 122 pounds per ton of pig iron in 1964 to 75 pounds in 1970, primarily from substitution of agglomerates for natural ore.

led the way, but after 1957 the industry preferred pellets. The peak year for sinter usage was 1962 and its trend has been downward since. Pellets will provide essentially all of the expanded capacity for agglomerate production.

TABLE 4. - Ferrous inputs in pig iron production, 1964-70

(Pounds per short ton pig iron)

Year	Iron ore	Manganese ore	Agglomerates				Total ore and agglomerates		Iron and steel scrap
			Pellets	Sinter	Other	Total	Gross	Net of fluxes[1]	
1964..	1,186	1	698	1,287	13	1,998	3,185	3,092	113
1965..	1,131	3	785	1,201	20	2,006	3,140	3,049	115
1966..	1,048	2	908	1,195	21	2,124	3,174	3,070	114
1967..	975	3	999	1,187	41	2,227	3,205	3,096	109
1968..	985	2	1,143	1,121	43	2,307	3,294	3,179	96
1969..	896	2	1,231	1,051	33	2,315	3,213	3,102	101
1970..	835	2	1,346	1,004	34	2,384	3,221	3,111	116

[1] Flux used in agglomerate plants adjusted for calcination.

Source: Appendix tables B-9 and B-16.

TABLE 5. - Fuel usage in pig iron production, 1964-70)

(Quantities per short ton pig iron)

Year	Coke, pounds	Breeze, pounds	Total, pounds	Natural gas, cubic feet	Fuel oil, gallons
1964............	1,310	63	1,373	453	0.5
1965............	1,313	55	1,368	529	.6
1966............	1,273	54	1,327	563	.6
1967............	1,263	53	1,316	509	.8
1968............	1,248	51	1,299	524	.9
1969............	1,253	48	1,301	467	1.2
1970............	1,260	50	1,310	486	1.6

Source: Appendix tables B-20 through B-23.

TABLE 6. - Flux usage in pig iron production, 1964-70

(Pounds per short ton pig iron)

Year	In agglomerates	In blast furnaces	Total	Calcined flux in sinter, percent	Oxygen, cubic feet
1964.......	155	393	548	7.2	104
1965.......	151	407	558	7.6	108
1966.......	173	363	536	8.7	99
1967.......	182	332	514	9.2	100
1968.......	192	290	482	10.3	75
1969.......	185	303	488	10.6	96
1970.......	184	308	492	11.0	148

Source: Appendix tables B-28 through B-31.

Fuels

The 1964-70 period was one of slow improvement in fuel usage. Coke usage improved between 1964 and 1967 in continuation of a strong downward trend that had started in 1950. Beginning in 1960, natural gas and fuel oil had been adopted as supplemental fuels injected through the tuyeres wherever economical (34); together they accounted for the equivalent of 21 pounds of coke per ton of pig iron by 1964, and 29 pounds in 1970. On an equivalent coke basis, average fuel usage in blast furnaces declined from 1,331 pounds in 1964 to 1,289 pounds in 1970. The improvement has been a consequence of improved burden quality and better furnace technology. The principal technical improvement since 1964 has been higher blast temperature accompanied by increased injection of moisture for maximum productivity.

Fluxes

Total usage declined about 10 percent from 1964 to 1970. The lessened requirement for limestone (and dolomite) reflected higher grade ores, more agglomerates, and lower coke rates. Raw flux usage directly in blast furnaces dropped even more. The difference was made up by the increased use of raw flux in sinter making. During the years of the study period, the steel plants having sintering lines increased the average flux content of sinter by more than one-half, from 7 percent flux[6] in 1964 to 11 percent in 1970, and thereby cut back the heat-consuming flux calcination load upon their blast furnaces.

Summary

Materials substitution was the principal force of change in 1964-70. Improvements in furnace technology were a secondary factor. Both movements continue. In this shifting scene the latest year is the best estimate of contemporary best practice.

Melting and Refining

Upheavals in mineral consumption also have been experienced in the melting and refining stage. Three of the nine major declines (table 3) occurred in natural gas, fuel oil, and tar and pitch; four of the five major gains included purchased electric power, lime, fluorspar, and oxygen. If melting and refining was performed by only one process, similar to the case of iron smelting, these changes in mineral consumption would be viewed likewise as results of mineral substitution or other technologic change. However, there are four important processes in use for melting and refining--basic oxygen process (BOP), cupola, electric furnace (EF), and open hearth. Their existence raises the possibility that the substitution of one process technology for another has been the primary source of these changes in aggregate mineral requirements.

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[6] Calcined weight basis.

Iron-Scrap Ratio Constant

Melting and refining furnaces accounted for 94 percent of the consumption of pig iron and 94 percent of iron and steel scrap. Overall, these furnaces subsisted on net inputs of 73 percent new metal (pig iron) and 27 percent secondary metal (purchased iron and steel scrap). These operations also generated ferrous waste, termed "home" scrap. This material is recycled in-plant; it has no significance for the overall mineral supply picture, but it has to be considered because it displaces purchased scrap in supplying the characteristic scrap requirements of the melting and refining processes. The total quantity of metallics consumed in all melting and refining furnaces was supplied in almost equal shares by pig iron (49 percent) and all kinds of scrap (51 percent, table B-9).

The constancy of pig and scrap proportions in the charges also extended generally to the steel melting processes. Pig iron constituted about 70 percent of the charge in basic oxygen converters, 58 percent in open hearths, and 2 percent in electric furnaces from 1964 to 1970 (table B-10). In terms of net input, pig iron consistently contributed 77 percent of the ferrous metallics consumed per unit of steel mill product shipments (table B-11).[7]

Substitution of Processes

Beneath these indications of stability in pig iron and scrap consumption patterns there has been a tide of process substitution. In the steel mills the open hearth process was still dominant in 1964, consuming 73 percent of the total metallics (table B-12). By 1970, more than half of the 1964 open hearth consumption had been displaced, principally by the BOP process. Currents of substitution likewise were strong in the foundry industries. Iron foundries continued to use cupolas for about 80 percent of the meltings but air furnaces were displaced by electrics. Steel foundries continued to phase out open hearths and air furnaces and replaced them with electrics.

Fuels

Melting and refining processes for iron and steel differ primarily in their use of fuels. The statistics show the effects of process substitution on fuel usage (table 7). Fossil fuel consumption in steel melting furnaces declined from 1964 to 1970, apparently in correspondence to the decline in open hearth production (usage was equivalent to 3.4 million Btu per ton open hearth steel throughout the 1964-70 period). Electric power requirements for melting and refining constituted about one-third of the growth in purchased power in steel plants; the strong growth of electric furnace steelmaking is reflected in the aggregate usage of electric power for this purpose--from 68 kwhr per ton of raw steel in 1964 to 96 kwhr in 1970. Coke is consumed by foundries principally in cupolas; its usage remained stable at 390 pounds per ton of iron casting shipments. To summarize, the changes in fuel consumption

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[7] Foundry practice has been altered to use less pig iron but the effect has slight significance in the aggregate. Utilization of pig iron per unit of castings shipments from iron foundries declined from 23 percent to 19 percent (table B-11).

TABLE 7. - Fuel usage in iron and steel melting and refining, 1964-70

Year	In steel melting furnaces, quantity per short ton total raw steel						In foundries
	Fuel oil, gallons	Natural gas, cubic feet	Tar and pitch, gallons	Coke-oven gas, cubic feet	Fossil fuel, calorific value, million Btu	Purchased electric power, kw hr	Coke consumed, pounds per short ton iron castings shipments
1964	7.9	850	2.2	600	2.67	68	387
1965	6.8	800	2.4	550	2.46	71	378
1966	5.4	720	2.2	410	2.07	74	385
1967	4.5	680	2.0	260	1.79	80	398
1968	4.2	780	1.7	250	1.79	85	392
1969	3.6	650	1.5	210	1.52	87	389
1970	3.2	440	1.4	170	1.22	96	424

Source: Appendix tables B-20 through B-27.

TABLE 8. - Flux usage in steel melting furnaces, 1964-70

(Pounds per short ton raw steel)

Year	Limestone				Lime				Fluorspar				Lime equivalent[1]			
	OH	BOP	Electric	All	OH	BOP	Electric	All	OH	BOP	Electric	All	OH	BOP	Electric	All
1964	114	12	14	90	19	146	58	38	3	12	8	5	87	153	66	92
1965	106	7	16	79	20	139	56	44	3	12	8	5	84	143	66	91
1966	116	4	16	76	19	135	52	52	4	12	8	6	89	137	62	98
1967	83	18	16	54	18	145	54	64	4	12	7	7	68	156	64	96
1968	80	16	13	48	19	144	55	70	3	13	8	7	67	154	63	99
1969	86	15	12	45	19	152	57	81	4	13	7	8	71	161	64	108
1970	85	14	14	40	18	153	61	90	4	12	9	8	69	161	69	114

[1] Lime usage plus 60 percent of limestone usage.

Source: Appendix tables B-28 through B-30.

TABLE 9. - Oxidizer usage in steel melting furnaces, 1964-70

Year	Oxygen, by process, cubic feet per short ton raw steel				Ores and agglomerates, pounds per short ton total raw steel			
	OH	BOP	Electric	All	Ores	Pellets	Other	Total
1964	586	1,944	203	713	129	14	9	152
1965	621	1,864	207	794	102	11	10	123
1966	736	1,853	212	960	83	10	8	101
1967	826	1,900	222	1,104	65	9	6	80
1968	838	1,779	545	1,150	59	10	6	75
1969	964	1,895	524	1,298	43	9	5	57
1970	1,075	1,900	704	1,416	44	9	5	58

Source: Appendix tables B-16 and B-31.

have been substantially those associated with process substitution. The large-scale retirement of open-hearths has diminished the needs for fossil fuels; the growth of EF steelmaking has increased the need for electric power.

Fluxes

Melting and refining processes consume fluxes in highly characteristic combinations. Limestone, lime, and fluorspar are the principal fluxes used in steelmelting furnaces, the only operation for which we have any statistics. Limestone usage declined with the fortunes of the open hearth (table 8). Lime usage followed the growth of BOP and electric furnace processes. Fluorspar consumption followed the same course as lime.

Oxygen

Usage in steel furnaces doubled between 1964 and 1970, mainly from increased BOP steelmaking (table 9).

Ore and Agglomerates

Ore and agglomerates are used in steelmaking primarily as slag-forming materials. In steel processes, especially open hearths, usage has been declining (table 9).

Summary

Aggregate mineral raw material and energy requirements for melting and refining iron and steel products underwent major change between 1964 and 1970 primarily in response to substitution of steelmaking processes. Improvements in the technology of the various processes exerted only minor effects on aggregate usage of mineral raw materials and energy.

CONTEMPORARY PRACTICES COMPARED--AVERAGE VERSUS BEST

In a progressing technology, such as pig iron smelting, the average usage (tables 4-6) necessarily lags the leaders. Where substitution of mature processes is involved, such as in steel melting and refining, the average usage (tables 7-9) becomes meaningless for it is merely the sum of the weighted process consumptions in their proportions to total production.

In the light of the trends revealed in the preceding section, estimates of mineral raw material and energy requirements have been assembled to represent 1970 average and best contemporary practice usage (table 10-11). The differences measure the possibility and magnitude of improvement in mineral supply needs merely by replacing old inefficient facilities with those corresponding to today's best. The best practice estimates also provide a yardstick for comparing the prospective effects of direct reduction.

TABLE 10. - Mineral usage in contemporary pig iron smelting, average and best, 1970

	1970		Difference, best - average	
	Average	Best	Quantity	Percent
Ferrous inputs:				
Ores and agglomerates:				
Total..........lb..	3,147	-	-	-
Less, calcined flux..........do..	107	-	-	-
Net..........do..	3,040	2,900	-140	-5
Iron and steel scrap..........do..	116	None	-116	-
Mineral fuels:				
Coke..........do..	1,260	1,100	-160	-13
Natural gas..........cu ft..	486	(1)	-486	-
Fuel oil..........gal..	1.6	(1)	-1.6	-
Fluxes:				
Limestone..........lb..	496	185	-61	-12
Dolomite..........do..		250		
Oxygen..........cu ft..	148	None	-148	-

[1] May be substituted for a portion of coke.

TABLE 11. - Mineral usage in best contemporary steel melting and refining, 1970

	Process	
	Basic oxygen converter	Electric furnace
Ferrous inputs:		
Pig iron..........wt pct..	70	2
Scrap..........do..	30	98
Fuel:		
Electric power..........kwhr..	-	450
Fluxes:		
Lime..........lb..	150	57
Fluorspar..........do..	12	9
Oxygen..........cu ft..	1,900	-

Pig Iron Smelting

The criterion of contemporary best practice is minimum fuel consumption, modern pellet burden, 1,900° F blast temperature, and 20 grains of moisture per cubic foot of blast. In terms of 1970 technology the mineral usage per net ton of pig iron totals 2,900 pounds of pellets (65 percent iron, 5.5 percent silica, 0.5 percent alumina, all dry basis); 1,100 pounds of coke

(9 percent ash) or the equivalent in tuyere-injected supplements; 185 pounds of limestone, and 250 pounds of dolomite. This practice is reasonably typical of the six large blast furnaces (larger than 32 feet hearth diameter) in the United States and Canada. Local conditions and economics may dictate the substitution of some coke by fluid fuels, or other combinations of moisture and blast heat.

The fluid fuel used in 1970 was equivalent to about 30 pounds of coke, giving an equivalent coke rate of 1,290 pounds per ton of pig iron. Thus the best practice would be, overall, 190 pounds better, about 15 percent. Average 1970 coke rate could be improved by about 66 pounds per ton of pig iron by substituting agglomerates equivalent to modern pellet burden. The remaining potential for improvement in coke rate, 124 pounds (about 10 percent), represents the limit of gain from investments in replacing old furnaces and technologies with new.

It is worth pointing out that coke rate improvement carries with it a promise of increased production. Blast furnaces are primarily coke burners of limited capacity. An improvement of 66 pounds in coke rate, about 5 percent, would provide an increment of productive capacity equivalent to the growth of demand over the past 6 years. A coke rate improvement of 10 percent would connote an 11 percent gain in production per day from the same throughput consumption of coke. Whether output can be better augmented by adopting all-agglomerate burdens, or by investing in direct reduction kilns, is an issue that will vex nearly all steel plants in the years ahead.

Melting and Refining

What constitutes best practice for iron and steel producing is, for this level of discussion, very near to usual practice in BOP furnaces and high-powered electric arc furnaces for steelmaking. Foundry processes are not considered further in this report because the prevailing opinion is that foundry markets for metallized pellets are too small in scale and too dispersed in location to influence investments in direct reduction plants for some years ahead.

The ratio of pig iron to purchased scrap used for steelmaking (73:27) connotes a 3 to 1 sharing of raw steel production between the BOP and EF methods (assuming furnace yields of 87 and 94 percent, respectively, and 67 percent yield of shipments from raw steel). It suggests that further replacement of open hearths will be by combinations of BOP and EF plants which in the aggregate will maintain the present 3:1 ratio.

DIRECT REDUCTION

The term "direct reduction" refers to any reduction process other than the blast furnace for chemically reducing iron ores and agglomerates to metal. Domestic interest in direct reduction is confined to solid state processes. They yield a product which reflects the form and composition of the feedstocks (ore or pellets) and no refining or gangue separation occurs. In fact, reduction concentrates the gangue content of the product in proportion to the increased concentration of iron; a high degree of reduction concentrates gangue by about one-half.

There are three basic types of reactors used in direct reduction processes:

(1) Rotary kiln, using solid and liquid or gaseous reductant,

(2) vertical shaft, using gaseous reductant,

and (3) fluidized bed, using gaseous reductant.

Energy requirements per ton of reduced iron product range from 13 to 15 million Btu for rotary kilns, 12.5 to 19 million Btu for shaft furnaces, to 15.5 to 16 million Btu for fluidized bed reactors. For the purpose of this report a representative figure is adequate: 14 million Btu per short ton of iron in a product 95 percent reduced. A description of direct reduction principles and the prominent processes is presented in Appendix A.

COMPARATIVE MINERAL CONSUMPTION FROM DIRECT REDUCTION IN STEEL PLANTS

This section compares the raw materials requirements for iron smelting and for steel melting and refining by present practices with two cases that might be expected to result from implementation of direct reduction in steel plants. The arrangement provides a basis for determining the potential impact of direct reduction on mineral supply requirements. The two cases are as follows:

I. Substitution of direct reduction for blast furnace reduction, the metallized pellet being used to make pig iron; and

II. Direct-reduced iron substituted for scrap in electric arc steelmaking furnaces.

The comparisons are then related to the projected demand for iron.

The only basic raw material requirement for direct reduction of iron minerals is fossil fuel, about 14 million Btu per net ton of iron in a product 95 percent reduced. Natural gas has been the only fuel used thus far in direct reduction plants of U.S. producers; for these comparisons it is taken as the reductant and fuel source (1,000 Btu per cubic foot).

CASE I. Substitution Entirely in Blast Furnace Burden

This, the simplest case, involves the substitution of metallized pellets for hematite pellets in the blast furnace burden. It is not hypothetical. The use of metallized pellets has been thoroughly investigated in experimental blast furnaces in both the United States (81, 97, 115) and Japan (52), and these results have been confirmed in full-size furnace operations (52, 98). Experiments have ranged up to 80 percent prereduction.

Effects on Blast Furnace Operation

Metallized ores and agglomerates increase the output of the blast furnace in proportion to the use of reduced material in the burden. Experiments with SL/RN highly reduced pellets (about 93 percent) showed consistent gains in productivity and declines in coke rate and slag volume. For example, a burden 79 percent prereduced composed of hematite pellets (15 percent of the burden) and SL/RN highly reduced pellets (the remaining 85 percent of the burden) resulted in a 47-percent lower coke rate and a 75-percent gain in pig iron productivity compared to a base burden of Carol pellets (5.5 percent SiO_2; 0.4 percent Al_2O_3) (115).

For the purpose of the Case I comparison, the iron ore input is assumed to be "best practice," that is, bonded hematite pellets analyzing 65 percent iron and 6 percent gangue (silica plus alumina), all on the dry basis. This composition is typical of pellet production from modern plants in the United States and Canada. In 1970, 58 percent of total pellet shipments from U.S. and Canadian plants met or surpassed this criterion.

The complete substitution of pellets, 95 percent reduced, is expected to cut the coke rate by at least 50 percent--550 pounds of coke per ton of pig iron produced, compared to best contemporary practice (table 10). The diminished usage of coke also would cut the input of coke ash in proportion, save 85 pounds raw flux, and, in turn, result in about 100 pounds less of slag byproduct, all per ton of pig iron. A much larger gain in furnace productivity would result. Assuming a constant daily coke consumption, the 50-percent cut in coke rate would suggest about a 100-percent gain in productivity. The experiments referred to above experienced a gain of at least 75 percent in productivity from 79-percent prereduced burden. For this report a conservative estimate was taken--75 percent gain in productivity from the complete substitution of 95 percent reduced pellets.

The total energy budget per ton of pig iron produced in increased by the fuel expended in direct reduction, but a portion is recovered in the savings of blast furnace coke. The iron contained in a ton of pig iron is 0.93 ton on the average; assuming no losses of iron, the fuel usage attributable to direct reduction would be $14 \times 0.93 = 13.02$ million Btu per ton of pig iron, assuming 95 percent reduction.

Comparative Mineral Consumption

Iron Ores

The quantity of iron units for Case I would remain unchanged because the yield of pig iron from ore is about the same. However, the quantity of ferrous materials needed would decrease substantially by passing from 1970 average to best practice, 20.5 million tons less in terms of 1970 consumption. The quality of iron ore supply will be assured merely by continuing the trend toward all-agglomerate burdens. Locations of ore sources likely would not change much from the present supply network. The location of direct reduction plants would depend on fuel availability and price.

Raw Flux and Blast Furnace Slag

Metallized burdens would diminish the usage of flux and the production of slag. Compared to best contemporary practice, flux usage would decrease by 85 pounds and slag production would be curtailed by 100 pounds, both per net ton of pig iron (table 12). Each would be a change of 20 percent.

TABLE 12. - Case I. Comparative usage of mineral raw materials and energy

(Quantity per short ton pig iron)

Mineral raw material	Direct reduction, then blast furnace use	Best practice blast furnace reduction	Difference
Natural gas................cu ft..	13,020	NAp	+13,020
Coke..........................lb..	550	1,100	-550
Raw flux......................do..	350	435	-85
Slag (production)..............do..	(400)	(500)	(-100)
Blast furnace productivity gain.........................pct..	More than 75	-	More than 75

NAp - Not applicable.

The second comparison is between 1970 average practice and best practice (table 10). Average flux usage in 1970 was 61 pounds more than best practice, an amount equivalent to about 72 pounds of slag production, both per ton of pig iron.

The third comparison is between 1970 average practice and direct reduction. Average flux usage for pig iron smelting in 1970 totaled 496 pounds per ton of pig iron (table 10), 61 pounds greater than the usage in best practice and 146 pounds greater than the estimated usage for complete substitution of metallized burdens 95 percent reduced. By comparison to the 1970 average, the need for flux would be diminished 12 percent by going to best practice and an additional 17 percent by going further, to the complete substitution of metallized burden 95 percent reduced. Slag production would be curtailed in the same proportions.

In terms of 1970 pig iron consumption, 90 million tons (table B-8), the changes in flux consumption and slag production from complete substitution of metallized pellets 95 percent reduced are as follows:

(a) Compared to best practice,
-3.8 million tons flux consumed, and
-4.4 million tons blast furnace slag produced;

and (b) compared to 1970 average practice,
-6.6 million tons flux consumed, and
-7.7 million tons blast furnace slag produced.

These simple relations of blast furnace technology have complicated implications for mineral supply. The raw fluxes consumed are selected limestones and dolomites; much of the flux is transported hundreds of miles from Michigan quarries to lower Great Lakes steel plants. The blast furnace slag produced is a preferred source for concrete aggregate and roadstone in the steelmaking centers; the market consumes the supply. In general, the fluxstone minerals would be complete technical substitutes for blast furnace slag in these classes of use. In the ideal case of perfect substitutibility the fluxstone no longer needed in blast furnaces could be directed into slag uses with only a slight drop in supply: 3 percent from best practice to complete direct reduction;[8] 4.5 percent from 1970 average practice to complete direct reduction.

In the case of complete substitution of metallized pellets, the economic substitutibility of fluxstone is likely to be less than perfect, creating an excess supply of fluxstone at producing points and an excess demand for slag at steelmaking centers. The problem is that the markets for aggregate and roadstone uses of blast furnace slag generally would not support the costs of transporting fluxstone long distances from quarries to steelmaking centers for these classes of use. Again as a general matter, for these classes of use there are competitive sources of stone much nearer to the consumption points. The likely outcome would be a shift to production of stone nearer to steelmaking centers. Fluxstone production might decline by nearly the full amounts listed in (a) and (b) above; the curtailments in slag production likely would be supplied by nearby sources of stone.

Mineral Fuels

The effects of direct reduction upon fuel needs are both large and complex. Foremost is the new need for fuel in direct reduction. Coke needs drop by one-half, so does the supply of coke-oven byproduct fuels, including breeze, coke-oven gas, tar, and pitch.

The energy-intensive nature of iron smelting and refining is important to realize. Primary iron and steel producers consumed about 3,400 trillion[9] Btu in 1970, 5 percent of the Nation's energy budget. Of this amount, 2,778 trillion Btu, 82 percent of the total, was consumed in iron smelting, including coke plants, and in melting and refining iron and steel melts (table 3). The energy input for pig iron smelting alone (table 5) came to 1,656 trillion Btu, 49 percent of the total industry consumption.

The entire substitution of direct reduced pellets for hematite pellets (Case I) would impose an extreme demand for natural gas or equivalent fuel. If the 1970 consumption of pig iron (90.1 million tons, table B-8) had been met by metallized pellets (84 million tons Fe, based on 93 percent Fe in pig iron) the fuel consumption in direct reduction would have totaled 1,173 billion[10] cubic feet natural gas--about 20 times the natural gas consumed in

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[8] (-100 lb slag + 85 lb flux) ÷ 500 lb slag = 0.03.

[9] Billion = 10^9. Trillion = 10^{12}.

[10] See footnote 9.

blast furnace reduction (55 billion cubic feet). This quantity for direct reduction is equivalent to about 5 percent of the total U.S. consumption of natural gas in 1970 (22 trillion cubic feet); also, it represents about 1 year's growth in the Nation's natural gas supply.

Coke needs are cut back by about 50 percent; the need for metallurgical coal would fall in proportion. In recent experience, 1 ton of coal carbonized in slot ovens produces 0.698 tons of coke; 0.045 tons of coke breeze; 5,500 cubic feet of coke oven gas (net of coke oven underfiring needs), and 8.6 gallons of tar and pitch (only 40 percent available for fuel after refining uses and sales are allowed for). Since more than half of the coke breeze is consumed in sintering plants, a cut of one-half in supply would likely force some substitution of coal in that process. Coke oven gas is used outside the coke plant mainly in heating and annealing furnaces (about 60 percent) and for other purposes including boiler plants (30 percent). Tar and pitch available for fuel is eliminated completely by the 50-percent cutback in cokemaking. (By adopting best practice ironmaking compared to the 1970 average the quantity of tar and pitch available for fuel is diminished 1.1 gallon per ton of coal carbonized.) Since this fuel, however, is used mainly in open hearths (68 percent in 1970) which are being phased out, the requirements likely will be met sufficiently. A detailed review of byproduct-fuel use patterns revealed that a cutback of one-half in cokemaking would force the introduction of substitute fuel for byproduct fuel uses equivalent to 1.6 thousand cubic feet of natural gas per ton of pig iron, totaling 150 billion cubic feet in 1970.

Consumption of fuels in terms of 1970 pig iron consumption is altered by complete substitution of metallized pellets as follows:

(a) Compared to best practice:

+1,323 billion cubic feet natural gas consumed
-24.8 million tons coke consumed
-35.5 million tons coal carbonized
-1.6 million tons coke breeze produced
-195 billion cubic feet coke-oven gas produced
-302 million gallons tar and pitch produced

and (b) compared to 1970 average practice:

+1,268 billion cubic feet natural gas consumed
-166 million gallons fuel oil consumed
-31.8 million tons coke consumed
-45.6 million tons coal carbonized
-2.1 million tons breeze produced
-251 billion cubic feet coke oven gas produced
-387 million gallons tar and pitch produced.

The net effects of direct reduction on energy consumption for pig iron production can be discerned from these comparisons. Compared to best practice (a), the additional energy consumed totals 4.4 million Btu per ton of pig iron, an increase of more than one-fourth in energy requirements. About 40 percent of the additional fuel is needed merely to compensate for the shortage in byproduct fuels. With regard to comparison (b), the 1970 average energy requirements rise very little for a complete changeover to direct reduction. The additional energy needed averages only 0.5 million Btu per ton of pig iron, about 3 percent.

The connotations of these energy comparisons are the following:

1. The aggregate energy supply to the iron and steel industry in 1970 would be sufficient to support a complete transformation to direct reduction. Comparison (b) implies an increase of only 3 percent in total energy consumption.

2. Extreme substitutions of fuels would be required. How it would come about is not foreseeable. The industry traditionally has been run by coal. In 1970 coal supplied 67 percent of the energy input (if the coal equivalent of purchased electric power was included, the figure would rise to 77 percent). Direct reduction implies a wholesale shift away from coke.

3. The future, measured by the trend to best practice, would be toward an improvement in energy consumption for blast furnace reduction, but that increment of energy would be consumed by the adoption of direct reduction.

4. The place of byproduct fuels in the energy economy of iron and steel plants would become very important. Wherever direct reduction is implemented it will become a major component of the process line. In the same proportion, the supply of byproduct fuels per unit of output will decline. When these byproduct fuels, heretofore available at zero economic cost,[11] have to be replaced by purchased fuels, the whole question of byproduct fuel utilization will become very prominent. Comparison (a) disclosed that 40 percent of the additional energy required for direct reduction would be needed to substitute for byproduct fuels. This estimate is believed to be conservative but realistic. It was based on taking two-thirds of the 1970 experience, a factor supported by collateral evidence of the trends toward diminished fuel needs in steelmaking.

Productivity

Burdens containing metallized materials have the effect of increasing blast furnace productivity strongly, ranging from 0.6 to 0.8 times the percent of prereduced iron charged. This consequence of substituting metallized materials is especially pertinent because the 1964-70 period witnessed an unprecedented investment in productive capacity with hardly any corresponding growth in production. Direct reduction holds out the possibility of greatly increasing pig iron production with minimum investment in blast furnace facilities. The relative investment costs favor direct reduction for incrementation of capacity.

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[11] The economic value of coproducts is indeterminate. Cost department values are arbitrary. The point is clarified by determining whether the coke plant would be operated if the coproduct has no markets; if so, the coproducts have zero economic value at the point of production.

Graphic Interpretation

The effects of Case I substitution can be expressed in graphic form by plots of mineral usage scaled in proportion to substitution. Figure 1 displays these plots for (A) ferrous inputs (including scrap and miscellaneous); (B) coke and its coal equivalent; (C) raw flux consumed and blast furnace slag produced; (D) natural gas and equivalent fuels (including all other steel plant uses), and (E) furnace productivity. Each plot is arranged in two parts. At the left, the relations depict the transition in mineral usage from average 1970 practice to the contemporary best practice. At the right, the relations depict the results of substitution, from the usage in contemporary best practice without any direct reduction to complete substitution of metallized pellets 95 percent reduced.

The left-hand portion of each plot represents the two levels of mineral usage with regard to 1970 production. At the left margin the "average" usage is plotted. This is simply the aggregate input divided into the output of pig iron; it does not represent any specific practice. On the other hand, the 1970 "best practice" data do represent a definitely identifiable state of blast furnace smelting technology (table 10). A horizontal line connects the left margin and the best practice point; this is a base line of best practice. The broken curve connecting "average" and "best" is a tieline; it connotes a linear improvement in usage as best practice is substituted for 1970 average practice. The triangle bounded by the broken curve and the baseline suggests the magnitude of improvement in mineral usage. The width of this left-hand portion was selected to be half the width of the right-hand (direct reduction) portion solely for balance in presentation; this means that the slopes of the broken curves to the left are not functionally related to the slopes of the direct reduction curves on the right.

The curves in figure 1 facilitate interpolation between extreme conditions and permit one to gauge the effects of partial changes in technology, whether moving from "average" to "best" contemporary practice or from zero percent direct reduction toward 100 percent. If a time rate of substitution is assumed, the curves portray the change in mineral usage proportional to that state of the future. A third class of application also is time-related--to mark the curves to denote the growth (or decline) of supply in the future because of new developments (or exhaustion of deposits) and to relate these changes to the percentage of direct reduction needed for balancing the mineral supply per unit of pig iron produced. Total national requirements would be simply the extensions of these usage factors by the estimated quantity of pig iron production. Projections of demand for iron will be presented in a later section. A fourth application is to relate the projected growth of demand (as a percent of base-period demand) to the productivity growth in figure 1 to estimate the percent direct reduction needed, given the existing stock of blast furnaces.

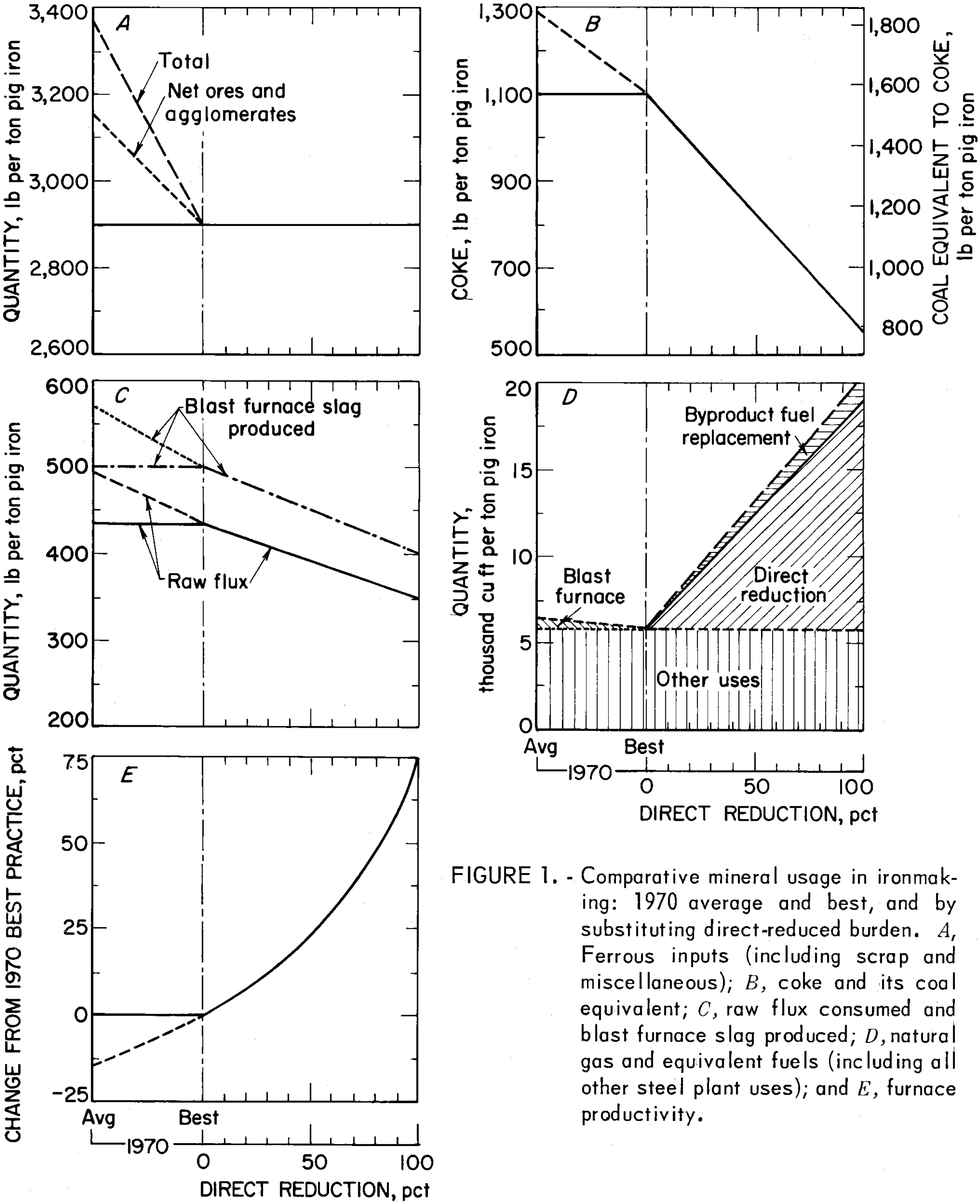

FIGURE 1. - Comparative mineral usage in ironmaking: 1970 average and best, and by substituting direct-reduced burden. *A*, Ferrous inputs (including scrap and miscellaneous); *B*, coke and its coal equivalent; *C*, raw flux consumed and blast furnace slag produced; *D*, natural gas and equivalent fuels (including all other steel plant uses); and *E*, furnace productivity.

CASE II. Partial Substitution in Electric Arc Furnace Charges

This case is at once practical and unconventional. All of the direct reduction plants in operation or under construction in the United States and Canada are intended to supply substantial proportions of the metallic inputs for electric arc furnace plants from iron ores in the form of direct reduced pellets or briquets.

This notion departs from conventional steelmaking technology and use of mineral inputs. All of these plants are predicated on continuous feeding of metallized pellets (or other free-flowing forms). All contemplate using at least one-third new iron in charges compared to the traditional 2 percent pig iron-98 percent scrap charge (table B-10).

The use of sponge iron in electric arc steelmaking furnaces has been demonstrated by numerous plants and laboratories, but success has been outstanding when highly reduced pellets or briquets are fed continuously into the melt (75, 87, 105, 112). By this means, full power can be applied to the furnace for nearly all of the melting period. Melting rate is accelerated, heat loss is diminished, and less electric power is consumed per ton raw steel. An increase in the proportion of continuously-fed metallized pellets is rewarded by further improvement in power consumption but at a diminished rate of return. The countereffect is caused by the increased bulk of slag; gangue constituents report to the slag, so does unreduced iron in the pellets. In the neighborhood of 40 percent reduced iron, a saddle point is reached. With further increase, power consumption rises, reaching the original level at about 75 percent metallized pellets.

To obtain this performance a low-gangue mineral is selected for metallization; the slag which develops in the arc furnace during continuous feeding is maintained slightly acid (1.5 basicity ratio), and it is run from the furnace frequently. All of the direct reduction plants in the United States and Canada for arc furnace feeds are based on iron minerals analyzing less than 3 percent silica.

Multifactor Analysis of Effects on Operations

Case II considers a hypothetical set of conditions at two levels of metallized pellet usage (40 percent and 75 percent)--two ore types (a 6 percent gangue referred to hereafter as "smelting-grade" hematite pellet and a 3 percent gangue hematite pellet referred to as "refining-grade"; table 13), and two slag basicity ratios (1.5 base-acid ratio to exemplify continuous-charged heats, and 3.0 ratio typical of single-slag heats).

TABLE 13. - Chemical composition of typical prereduced iron ores, percent

Constituent	Smelting grade	Refining grade
SiO_2	7.0	3.0
Other gangue[1]	1.0	2.5
C	1.5	1.5
O_2	1.2	1.0
Fe, total	89.3	92.0
Percent metallization	95.0	95.0

[1] All gangue, less SiO_2, assumed to be neutral.

Raw material and energy requirements were developed from contemporary best practice as a base. The additional requirements of lime and electrical energy were calculated from the quantity of gangue introduced by metallized pellets and the lime required for fluxing. The energy consumed for slag melting and solution was taken as 40 kwhr per 100 pounds of slag (105). Schedules of raw material and energy requirements are presented in tables 14 and 15.

The additional cost of melting and refining metallized pellets in the arc furnaces is principally determined by the gangue introduced to the furnace system and how basic a slag is maintained. For example, as in Table 14, 40 percent refining-grade metallized pellets refined with a 3.0 basicity slag (condition 1) would require 144 pounds of lime compared to 57 pounds in best all-scrap practice because the slag produced would be 2-1/2 times as great. The calculated power consumption would be increased by 55 kwhr, from 450 to 505 kwhr per ton of raw steel produced. Furthermore, this use of metallized pellets would crowd the limited volume of the furnace chamber with slag if conventional slag control were practiced. However, by fluxing the gangue and removing it in a 1.5 basicity ratio slag (condition 3), the additional lime required compared to base conditions would be 44 pounds, only half of the added lime required in condition 1. Similarily the added power consumption would be only 38 kwhr.[12]

Though metallized pellets incur costs in the added lime and power consumption their use entails, they permit a remarkable increase in furnace productivity when continuously fed. The best-practice heat time of 160 minutes stands for the highest efficiency of conventional furnace practice. Yet both condition 1 and condition 3 require hardly any more than two-thirds that time to produce a heat, 112 and 110 minutes respectively. In effect, the continuous charging of refining-grade metallized pellets has the possibility of increasing the output of steel from an electric furnace by nearly one-half.

The foregoing analysis is based on using refining-grade metallized pellets; the next question is to estimate the effects of using metallized smelting-grade pellets. Conditions 2 and 4 in Table 14 represent this class of ore mineral. Lime and power requirements are very high. Forty percent of smelting-grade metallized pellets would require 267 pounds of lime to form, 3.0 basicity slag (condition 2), that is, nearly twice the lime required for refining-grade metallized pellets (condition 1). The quantity of slag to be handled would be about 5 times that of base conditions.[13] Power consumption would increase accordingly, to 565 kwhr in condition 2, 60 kwhr more than in condition 1.

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[12] No saddle point in power consumption occurs in these comparisons because the base condition represents a highly efficient practice.

[13] If condition 2 was established in a single-slag practice the volume of slag would limit the steel holding capacity of the furnace to only two-thirds of the base capacity.

TABLE 14. - Raw material requirements for best practice and alternate electric arc furnace practices

Conditions	Best practice	Direct reduction plus electric furnace practice							
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Percent prereduced material	0	40	40	40	40	75	75	75	75
Slag basicity[1]	3.0	3.0	3.0	1.5	1.5	3.0	3.0	1.5	1.5
Ore grade[2]	NAp	Refining	Smelting	Refining	Smelting	Refining	Smelting	Refining	Smelting
Raw materials	Quantity per ton raw steel								
Direct reduction:									
Oxide ore ... lb	NAp	1,294	1,341	1,294	1,341	2,428	2,500	2,428	2,500
Fuel ... million Btu	NAp	6.468	6.705	6.468	6.705	12.138	12.502	12.138	12.502
Electric furnace:									
Prereduced ore ... lb	-	924	952	924	952	1,734	1,786	1,734	1,786
Scrap ... do	2,127	1,276	1,276	1,276	1,276	532	532	532	532
Lime ... do	57	144	267	101	162	219	452	139	254
Electric energy ... kwhr	450	505	565	488	522	553	665	521	586
Relative tap to tap time ... min	160	112	117	110	113	121	132	118	125

NAp - Not applicable.

[1] Weight ratio $(CaO + MgO)/(SiO_2 + Al_2O_3)$.

[2] Ore composition from table 13.

TABLE 15. - Energy requirements for contemporary practice and alternate electric arc furnace practices

Conditions	Best practice	Direct reduction plus electric furnace practice							
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Percent prereduced material	0	40	40	40	40	75	75	75	75
Slag basicity[1]	3.0	3.0	3.0	1.5	1.5	3.0	3.0	1.5	1.5
Ore grade[2]	NAp	Refining	Smelting	Refining	Smelting	Refining	Smelting	Refining	Smelting
Operation	Quantity, million Btu per ton raw steel								
Pellet induration	NAp	0.435	0.514	0.435	0.514	0.815	0.838	0.815	0.838
Direct reduction	NAp	6.468	6.705	6.468	6.705	12.138	12.502	12.138	12.502
Lime preparation	0.182	0.477	0.890	0.330	0.538	0.730	1.494	0.458	0.834
Electric furnace	1.537	1.731	1.943	1.670	1.793	1.902	2.291	1.786	2.001
Electric power conversion loss	1.025	1.154	1.295	1.113	1.195	1.275	1.527	1.191	1.341
Total	2.744	10.265	11.347	10.016	10.745	16.860	18.652	16.388	17.516

NAp - Not applicable.

[1] Weight ratio $(CaO + MgO)/(SiO_2 + Al_2O_3)$.

[2] Ore composition from table 13.

The most interesting comparison is among conditions 4, 3, and 7, that is, smelting-grade metallized pellets providing 40 percent of the charge (condition 4), and refining-grade pellets at 40 percent (condition 3), and at 75 percent (condition 7). Smelting-grade pellets (condition 4) compared to refining-grade pellets (condition 3) require 61 pounds of additional lime (162 to 101 pounds) and 34 kwhr extra energy.[14] These increments are of about the same magnitude as the increments from base practice to condition 3. In effect, by going from base conditions to condition 3 (40 percent refining-grade pellets, 1.5 basicity) the lime and energy expenditures of 44 pounds and 38 kwhr permit the 50 minute improvement in heat time. Next, by substituting smelting-grade pellets (condition 4) for condition 3 another similar increment of lime and energy cost is incurred, but there is no further payout in furnace performance. Instead the heat time becomes a little longer.

The comparison between 40 percent smelting-grade and 75 percent refining-grade pellets (conditions 4 and 7) further illustrates the comparative advantage of low-gangue ore. The lime, energy, and heat time relations taken together suggest that the cost of melting 75 percent refining-grade pellets (condition 7) is within 5 percent of condition 4, yet condition 7 permits using nearly twice the amount of metallized pellets, 75 percent of the charge.

The energy accountings in table 15 provide further insights. The base condition of melting and refining consumes about 2.7 million Btu per ton raw steel. On a similar basis the energy budget totals 3.1 million Btu for condition 3; 3.5 million for condition 4, and 3.4 million for condition 7.

Comparative Mineral Consumption

Iron Ores

It is obvious from the foregoing discussion that the smelting-grade pellet has no place in this electric-arc steelmaking system. Events to date bear out this impression. All of the U.S. and Canadian direct reduction-electric arc furnace plants are based on pellets even lower in gangue content than the 3 percent gangue refining-grade pellet (none of the ores listed in the description of the direct reduction processes in Appendix A exceed 2.3 percent gangue). The extent to which this system of steelmaking is adopted will have the effect of determining the substitution of low-gangue refining-grade pellets for smelting-grade pellets, the contemporary standard of pellet technology in the United States. The smelting-grade pellet is a highly developed composition intended for blast furnace smelting, probably close to the ultimate for that purpose. For electric furnace use, however, it is plainly unsuitable.

The chart in figure 2 depicts the linear substitution of refining-grade metallized pellets for smelting-grade metallized pellet types to the extent that electric-furnace melting of new iron is substituted for blast furnace

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[14] At early 1972 price levels the combined effect of these lime and energy costs is worth nearly $1 per ton of raw steel; about $2 per ton of metallized pellets.

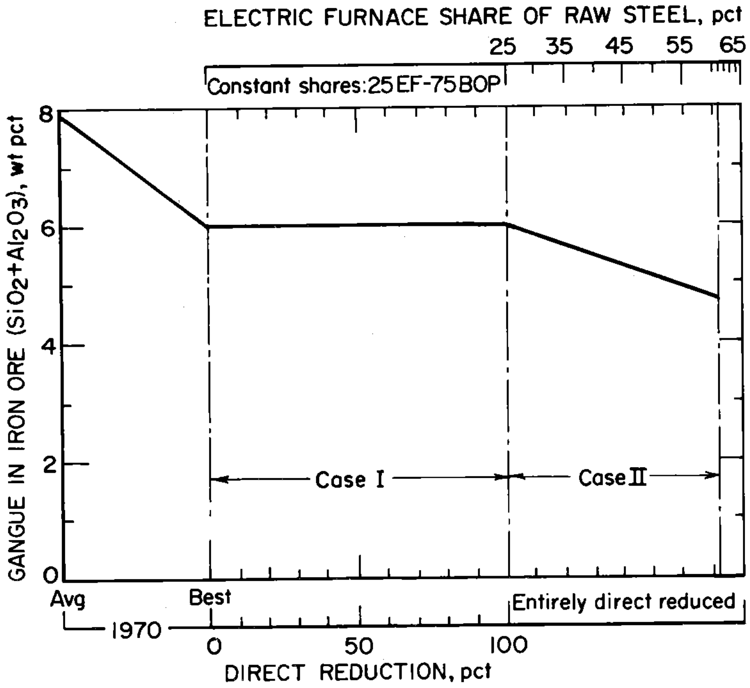

FIGURE 2. - Comparative gangue in iron ore and agglomerates for iron smelting and steel melting and refining: 1970 smelting-grade, average and best; prereduced smelting-grade burden in blast furnaces (Case I), and direct-reduced refining-grade metallics in electric furnace steelmaking (Case II).

smelting (or for direct reduction and blast furnace melting and refining). If the historical 73:27 split is maintained between primary) iron ores) and secondary (iron and steel scrap (inputs (table B-8), and electrics go to melting 40 percent reduced pellet--60 percent scrap charges, then, under 1970 conditions of yields, the extreme condition would be a 39 percent BOP--61 percent EF split in steelmaking; the resulting distribution of new iron would be 55 percent to BOP furnaces and 45 percent to electrics.

The arrangement of figure 2 follows after figure 1 but the mineral usage ordinate is scaled in percentage gangue. The 1970 average gangue content was estimated to be 7.9 percent (see table B-14 for U.S. and Canada analyses). The move to best practice would bring the gangue content to 6 percent or so. Implementation of direct reduction entirely for blast furnace burdens would not incur any change in gangue level. This is the Case I situation (see preceding section).

Case II is shown at the right-hand side of figure 2. The comparison is made between 100 percent reduction of iron ore for blast furnace burdens (Case I) and progressive substitution of electric furnace use (Case II). All metallized material used in the electric arc furnace is presumed to be refining-grade (3-percent gangue). The course of substitution requires an increasing proportion of refining-grade pellets.

In terms of the 1970 steel industry, the consequences of a complete swing to 40 percent of charge as metallized pellets in electric furnaces would be as follows:

1. <u>A great overcapacity of BOP furnaces:</u> BOP-made raw steel totaled 63 million tons in 1970, but only 51 million tons would be needed to supply 39 percent of the 1970 total. U.S. capacity in 1971 was 78 million tons (55) and more was being built.

2. <u>Corresponding undercapacity in electric furnaces</u>: Raw steel needed to supply 61 percent of the U.S. total would be 80 million tons, but U.S. production in 1970 totaled only 20 million tons, close to the capacity.

3. Excess capacity for blast furnace-grade pellets: BOP steel would require about 45 million tons pig iron, equivalent to 66 million tons hematite iron oxide pellets (based on 1970 pellet composition, table B-14). However, the U.S. and Canadian capacity totaled 83 million tons (United States--61 million, Canada--22 million) in 1970 (25), with more capacity being built.

4. An almost total lack of domestic capacity to supply electric-furnace-grade metallized pellets: The need would be for 34 million tons of iron-in-pellets to provide the feed for direct-reduction and electric-arc furnace steelmaking. The existing U.S. capacity totals about one-tenth of this need.

The implications of using 75 percent of metallized iron and 25 percent of scrap in electric-arc furnace charges will not be discussed. Although this combination of inputs is metallurgically feasible and might prove economical for an individual plant, in the aggregate it is not a feasible condition for the present structure of the industry. This 75:25 charge is inconsistent with the present iron input ratio of 73 primary to 27 secondary. To discuss it would require description and discussion of an entirely different industrial setting, a subject beyond the scope of this report.

Flux

In this discussion the consequences for flux usage and consumption are limited to the feasible case, that is, condition 3 in table 14. Compared to the best practice, flux usage increases to 101 pounds per ton or raw steel, that is, by 77 percent over the best practice usage, 57 pounds.

The total use of flux is a composite of quite different use patterns in the various processes. Figure 3 illustrates the case. The 1970 usage pattern is based on the 1970 composite of process shares in steelmaking and the conventional pig iron percentages (table B-10); it was composed of 181 pounds of calcined flux equivalent in blast furnaces and 114 pounds in steel furnaces, for a total of 295 pounds per ton of raw steel. Best practice is predicated on 75 BOP-25 EF shares in steelmaking, conventional pig iron percentages, and best practice ironmaking; flux usage comes to 159 pounds in the blast furnace and 135 pounds in steel furnaces, 294 pounds total per ton of raw steel. Case I leads to 128 pounds of calcined flux equivalent usage in blast furnaces at 100 percent use of metallized smelting-grade pellets, and the same 135 pounds in steel furnaces, for a total of 263 pounds. The drop of 31 pounds flux usage per ton of raw steel is entirely in the blast furnace.

Substitution of electric furnace melting and refining for the blast furnace-BOP process chain is depicted in the Case II section of figure 3. Flux consumption is diminished by going to electric arc furnace use of metallized pellets. The combination of 40 percent metallized pellets and 60 percent scrap and the resulting 39 percent BOP--61 percent EF shares of raw steel production uses 195 pounds of flux per ton of raw steel, that is, 66 pounds calcined equivalent of raw flux and 129 pounds of burnt lime. The net result of Case II is a drop of only 6 pounds of flux usage in steel furnaces, about 5 percent, but a major drop in blast furnace raw flux consumption, 62 pounds

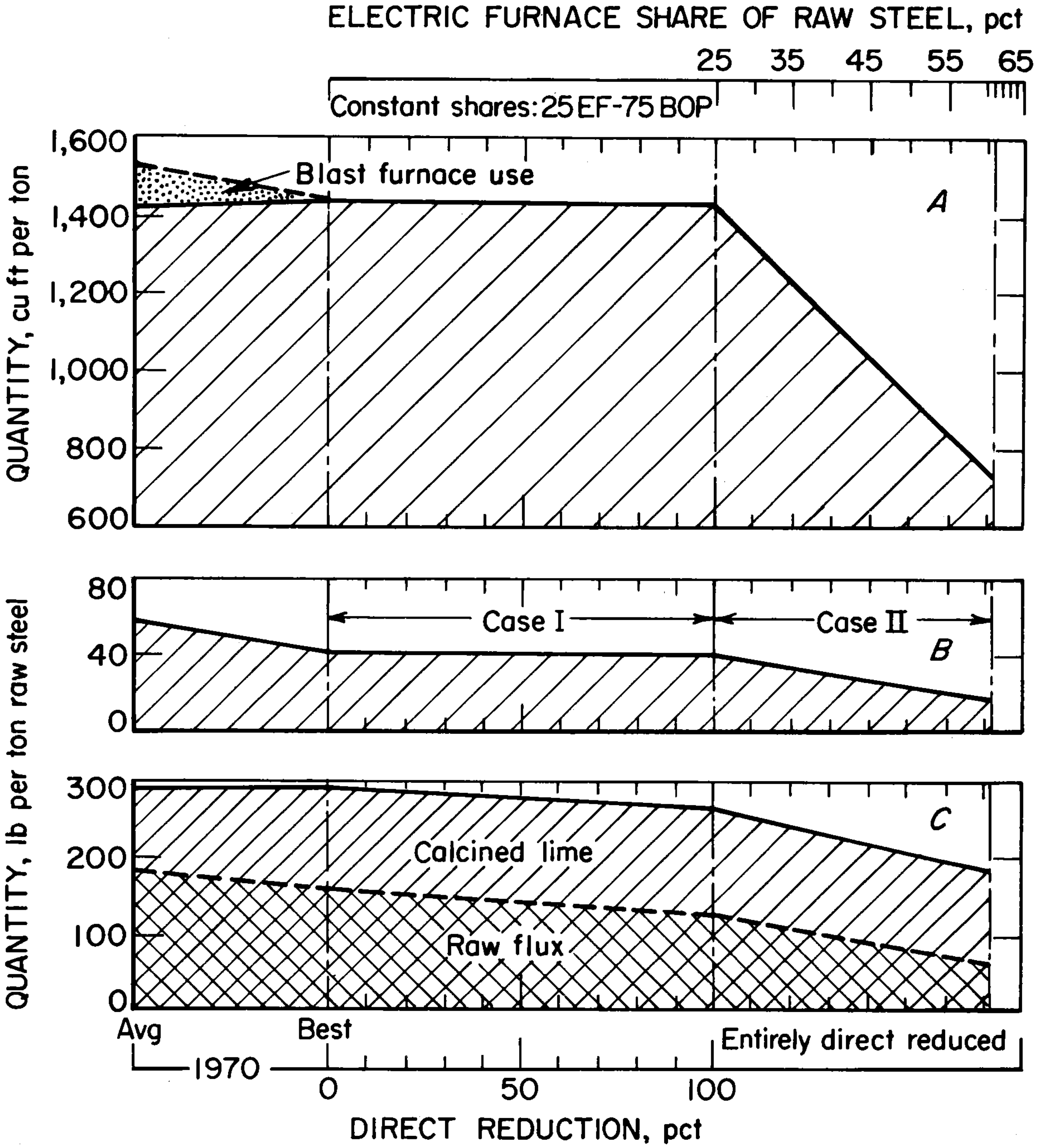

FIGURE 3. - Comparative oxidant and flux usage in iron smelting and steel melting and refining: 1970 average and best; prereduced burden in blast furnaces (Case I), and direct-reduced iron in electric furnace steelmaking (Case II). *A*, Metallurgical oxygen; *B*, iron ore and agglomerates in steel furnaces; and *C*, calcined flux, including calcined equivalent of raw flux (limestone and dolomite).

calcined flux equivalent (128 pounds to 66 pounds), all per ton of raw steel. In terms of 1970 raw steel production--

(a) Calcined flux consumption would drop 0.4 million tons;

and (b) Raw flux consumption would drop 7.1 million tons.

The description of flux usage in figure 3 may be used similarly to the analysis described in Case I, figure 1. The Case I description, however, was limited to blast furnace usage and figure 1 was scaled in pounds per ton of pig iron produced. Figure 3 includes steelmaking as well and is scaled per ton of raw steel produced. Figure 3 shows that the effect of Case I was to diminish the need for raw flux, the burnt lime needs for steelmaking remaining the same. It depicts further the effect of Case II substitution, the swing to using metallized pellets in electric steelmaking. This substitution for the blast furnace--BOP combination would have very little effect on burnt lime needs, but it would mean a virtually complete swing away from blast furnace flux wherever implemented. The disruption of fluxstone needs for blast furnaces in Case I was equivalent to 31 pounds per ton of raw steel; in Case II the effect would be twice as great (61 pounds). Effects on blast furnace slag production would be in proportion.

Oxygen

The availability of metallurgical oxygen for iron and steelmaking provided the basis of the upheavals in process substitution which occurred during the 1960's. In 1970 the usage of oxygen averaged 1,416 cubic feet per ton of raw steel in steelmaking furnaces (table 9) and about 148 cubic feet per ton of raw steel in blast furnaces (table 6). In best practice steelmaking (75 BOP--25 EF shares) oxygen usage would total 1,425 cubic feet per ton in steelmaking, and Case I substitution of direct reduced pellets in blast furnaces would not change that figure. Blast furnace smelting under best practice conditions was set up assuming no oxygen usage. Figure 3 depicts these relationships.

Oxygen usage in steelmaking is likely to fall off greatly under conditions of Case II substitution. The displacement of BOP steelmaking is the cause. While it required 1,900 cubic feet oxygen per ton of raw steel, best practice EF steelmaking would consume none. At the limit of Case II conditions, 39 BOP--61 EF shares, oxygen usage would fall to 741 cubic feet per ton of raw steel, less than half of 1970 usage. Figure 3 shows these movements. In terms of 1970 raw steel production the magnitudes of change are as follows:

(a) Best practice to complete Case I:

No change.

(b) Best practice to complete Case II:

-113 billion cubic feet oxygen.

(c) Average 1970 to complete Case II:

-102 billion cubic feet oxygen.

Ores in Steel Furnaces

The use of iron ore in steel furnaces has declined with the technology of the open hearth, but a small usage is foreseen for BOP and EF charges where metallized pellets are not involved. Iron oxide is the solvent of steelmaking slags; ordinarily it is more effective and cheaper to feed iron oxides as ore than to create it by oxidizing the ferrous charge. Where metallized pellets are charged, as in Case II electric steelmaking, the need for iron oxide in slag is satisfied by the residual unreduced iron in these pellets. The amounts of ore involved are small: 58 pounds per ton or raw steel in 1970; 40 pounds under Case I conditions, and 18 pounds at the limit of Case II substitution. These relations are plotted in figure 3. In 1970 terms the magnitudes of change are as follows:

(a) Best practice to complete Case I:

No change.

(b) Best practice to complete Case II:

-1.5 million tons iron ores.

(c) Average 1970 to complete Case II:

-2.6 million tons iron ores.

Mineral Fuels

Case II represents a shift in the use of metallized product from blast furnace ironmaking to electric furnace steelmaking. The effects upon mineral fuel usage are threefold: (1) Diminished need for coking coal and byproduct fuels in the blast furnaces--BOP steelmaking chain, (2) a new need for coal or other fuels to support additional electric power generation, and (3) a need for replacement of the byproduct fuel no longer produced, especially in heating furnaces and steam raising.

The effects of shifting these process shares in steelmaking can be measured directly. The two boundary cases are Case I (75 BOP--25 EF shares) and Case II (39 BOP--61 EF). The following assumptions are involved:

1. All primary iron is direct-reduced 95 percent;

2. At the Case I limit, the direct-reduced primary iron is consumed entirely in blast furnaces to supply pig iron to BOP furnaces (70 percent pig iron in charges) and to electrics (2 percent pig iron in charges);

3. At the Case II limit, the direct-reduced primary iron consumed in electric furnaces is refining-grade pellets in 40 percent iron--60 percent scrap charges refined under 1.5 basicity ratio slags (condition 3); and

4. At the Case II limit condition, the pig iron produced is used entirely in BOP furnaces.

The shift from Case I to Case II conditions has the primary effect of cutting coke requirements by 48 percent. The BOP share of 75 percent in Case I steelmaking is the basis for 99 percent of pig iron production and coke consumption. Between Case I and Case II, the BOP share in steelmaking falls by nearly one-half, from 75 percent to 39 percent, and pig iron use is eliminated from EF charges.

The additional need for electric power requires a major boost in electric power generating capacity and a fuel supply to support it. The EF share in raw steel production at the Case II limit condition is 2.44 times Case I (61 percent against 25 percent). Power usage per ton of EF steel increases by 8.4 percent (from 450 to 488 kwhr per ton raw steel). Total electric power consumption thus increases 165 percent from Case I to Case II. In terms of contemporary power generation and distribution parameters,[15] Case II requires 281 pounds of additional coal or equivalent fuel per ton of raw steel.

Total needs for electric power compared to 1970 experience would be even greater. In these sets of comparisons, Case I is limited to the effects of direct reduction on smelting processes, thus it excludes the effects of changing the EF steelmaking share from 15 percent in 1970 to 25 percent in best practice and the improvement in EF power consumption. In Case II these changes in EF steelmaking become pertinent components of these comparisons; together they require an additional 16 pounds of coal per ton of raw steel.

The byproduct fuel deficit is especially important. Production of coke byproducts is cut 48 percent, proportional to cokemaking. Availability of byproduct breeze and coke-oven gas for fuel use is diminished in the same proportion. The estimated fuel deficit in passing from the Case I to the Case II use of direct reduction is equivalent to 350 cubic feet of natural gas per ton of raw steel.

In terms of 1970 raw steel production levels, the shift in use of metallized pellets, 95 percent reduced, from Case I conditions (entirely in blast furnace) to Case II conditions (40 percent metallized ore and 60 percent scrap in EF charges and a 39 BOP--61 EF sharing of raw steel production) alters the pattern of mineral fuel consumption and byproduct fuel production as follows:

-17.0 million tons coking coal consumed,
-11.9 million tons coke consumed,
-0.8 million tons breeze produced,
-94 billion cubic feet coke oven gas produced,
+11.5 million tons coal for electric power generation, and
+46 billion cubic feet natural gas or equivalent fuel for heating.

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[15] Coal, 13,100 Btu per pound; heat rate, 10,500 Btu per kwhr, and 85 percent electrical efficiency.

To complete the picture, the comparison is needed between the 1970 average steelmaking practice and the "best" steelmaking practice of Case I. The principal difference is between the mineral fuel requirements for 48 million tons of raw steel produced in 1970 by open hearths and the fuel needs for equivalent raw steel production from BOP and EF steelmaking in an industry composed of 75 percent BOP and 25 percent EF production. A much smaller factor is the improvement in electric power consumption in EF practice. In terms of 1970 raw steel production, the estimated changes in mineral fuel consumption are as follows:

-417 million gallons fuel oil,
-58 billion cubic feet natural gas, and
+1.0 million tons coal for electric power generation.

The multiple effects of direct reduction on mineral fuel requirements have been brought together in figure 4. The ordinate is scaled in terms of fuel consumption per ton of raw steel. In this graph, only the energy required for iron smelting and steelmaking is included. Excess energy from byproduct fuels has been netted out. Only the net coal needs are included. By the same reasoning electric power requirements are presented in terms of the coal equivalent required per ton of raw steel in passing from the conditions of 1970 average to 1970 best practice (table 11), complete direct reduction (Case I, table 16), and the complete shift to steel furnace use (Case II).

This form of presentation summarizes the mineral supply implications of technologic change in iron and steelmaking by implementing best practice and direct reduction. The total energy budget does not undergo much change but the components undergo a great deal of substitution.

Heat Time and Productivity

The time effect of using reduced pellets in the electric arc furnace is very important. The estimated time required for the complete heat cycle, tap to tap, is cut from 160 minutes in best practice, to 110 minutes in Case II. The 50-minute difference amounts to almost one-third of the best practice heat time and implies a 45-percent gain in output compared to conventional furnace practice. It opens the possibility of replacing old open hearths by expanding the production from existing arc furnaces.

Summary of Conclusions

The changes in mineral consumption resulting from Case I and Case II implementations of direct reduction are summarized in table 16. In each instance the comparison is scaled in terms of 1970 consumption. The magnitudes of the effects are evident and do not require comment.

The possibilities for increasing output by using metallized pellets are shown above for the blast furnace (Case I) and the electric arc furnace (Case II). Whether these possibilities will be needed, however, is a matter of market growth.

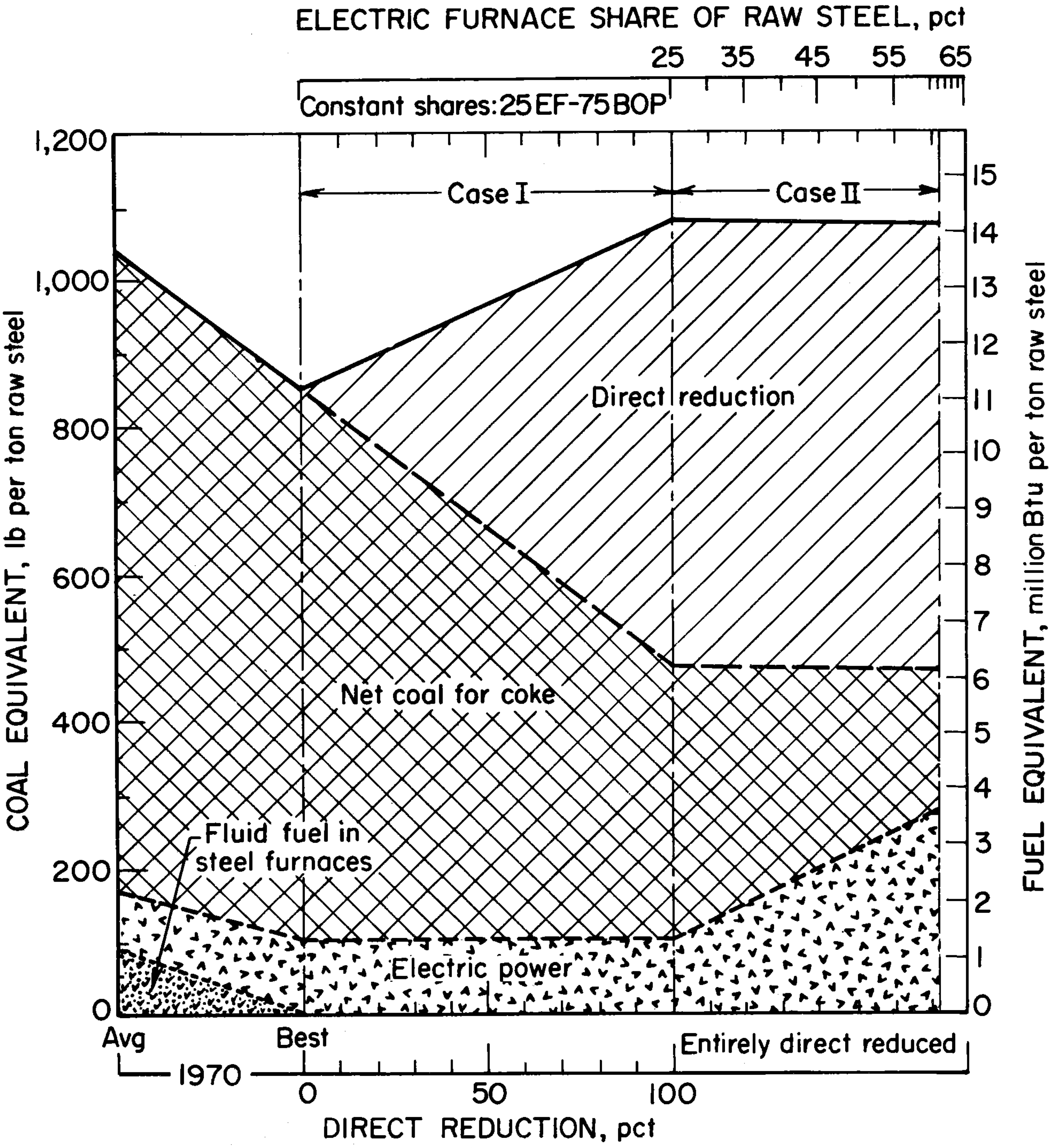

FIGURE 4. - Comparative mineral fuel usage for direct reduction; blast furnace ironmaking, and steel melting and refining: 1970 average and best; prereduced burden in blast furnaces (Case I), and direct-reduced iron in electric furnace steelmaking (Case II). [Electric power measured by coal equivalent; coal for coke is net of byproduct fuel consumed outside iron and raw steel manufacture.]

TABLE 16. - Summary of changes in mineral consumption resulting from direct reduction in iron and steel production[1]

Mineral inputs	Iron smelting: Case I compared to 1970 practices		Iron smelting and steelmaking: Case II compared to 1970 average practice	
	Best practice	Average practice	Change in quantity	Percent change[2]
Ferrous inputs:				
Ore and agglomerates:[3]				
Smelting-grade....million short tons..	None	-20.5	-79.3	-53
Refining-grade............do..........	NAp	NAp	+57.0	([4])
Iron and steel scrap........do..........	None	None	None	0
Fuels and energy:				
Coke........................do..........	-24.8	-31.8	-43.7	-77
Coal equivalent[5]..........do..........	-35.5	-45.6	-62.6	-77
Purchased electric power..billion kwhr..	None	+2.2	+26.5	+310
Coal equivalent[6]..million short tons..	None	+1.0	+12.5	+310
Coal equivalent, total......do..........	-35.5	-44.6	-50.1	-58
Natural gas[7].............billion cu ft..	+1,323	+1,210	+1,256	+1,115
Fuel oil..................million gal..	None	-583	-583	-100
Byroduct fuels:				
Coke breeze.......million short tons..	-1.6	-2.1	-2.8	-77
Tar and pitch............million gal..	-302	-387	[8]-523	[8]-100
Coke-oven gas..........billion cu ft..	-195	-251	-344	-77
Fluxes, oxidants, and slag:				
Fluxes:				
Limestone and dolomite.........million short tons..	-3.8	-8.3	-15.4	-62
Lime.....................do..........	NAp	+2.4	+2.0	+34
Fluorspar................do..........	NAp	+0.2	-0.2	-40
Iron ore in steel furnace...do..........	NAp	-1.2	-2.6	-69
Oxygen[9]..................billion cu ft..	NAp	+10.9	-102	-51
Blast furnace slag produced...........million short tons..	-4.4	-7.7	-15.8	-60

NAp - Not applicable.

[1] Basis: 1970 consumption (table 3) and best practice (tables 10 and 11).

[2] Quantity related to 1970 consumption for steelmaking.

[3] Includes all input sources to blast furnaces in 1970.

[4] Consumption of refining-grade pellets in 1970 not known. Supply estimated at 5 million short tons.

[5] Based on 69.8 percent yield of coke.

[6] Based on 10,500 Btu/kwhr heat rate and 85 percent transmission efficiency.

[7] Or equivalent mineral fuel.

[8] Refining uses could consume all of available supply under Case I conditions; quantity listed is the change in production of tar and pitch.

[9] Based on transitional usage in EF: 700 cubic feet per ton in Case I comparisons; no oxygen in best EF practice compared to Case II.

Future requirements for minerals by iron and steel producers will depend primarily on the markets for iron and steel products. The Bureau of Mines has performed a detailed study of these markets and published its findings and projections to the year 2000 in the chapter on "Iron" in the 1970 edition of "Mineral Facts and Problems" (4). Table 17 summarizes that work. Figure 5 illustrates these relationships. Continued growth of demand for iron and steel products is foreseen, though the growth rate may average out to be as low as 1.0 percent over the 1968-2000 interval. Economic capacity of U.S. blast furnaces in 1970 was estimated to be 106 million tons of pig iron.[16] By this measure, the year 2000 projection for pig iron is only 60 percent greater than the 1970 capacity estimate. By comparison, that capacity could be increased at least 75 percent by direct reduction to 95 percent reduced pellets and 100 percent use in blast furnaces. Thus, the projected growth of pig iron demand to the year 2000 could be met without additional blast furnace capacity in the ideal case.

TABLE 17. - U.S. production and demand for iron, 1968, and forecasts to the year 2000

(Million short tons)

	Year		Growth rate, percent
	1968	2000	
TOTAL DEMAND			
High	120	221	1.9
Low		162	1.0
Median	-	(192)	1.5
PRIMARY DEMAND			
High	84	175	2.3
Low		130	1.3
Median	-	(153)	1.9
PRIMARY PRODUCTION			
High	56.3	117	2.3
Low		87	1.3
Median	-	(102)	1.9

Source: Bureau of Mines Bulletin 650 (4).

Demand projections for primary iron are contingent on the continuation of recent technology in the split between primary iron-in-ore and secondary iron and steel scrap. Another facet of the equation is imported iron and steel products--they displace both primary and secondary iron.

The projection for domestic primary iron is based on the continuation of 67 percent domestic production of iron-in-ore and 33 percent imported: This split has been maintained since the late 1950's. Whether this projected future will be realized will depend on cost and availability. Figure 6, also

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[16] Estimated from maximum output rates during peak periods of demand in 1968, 1969, and 1971.

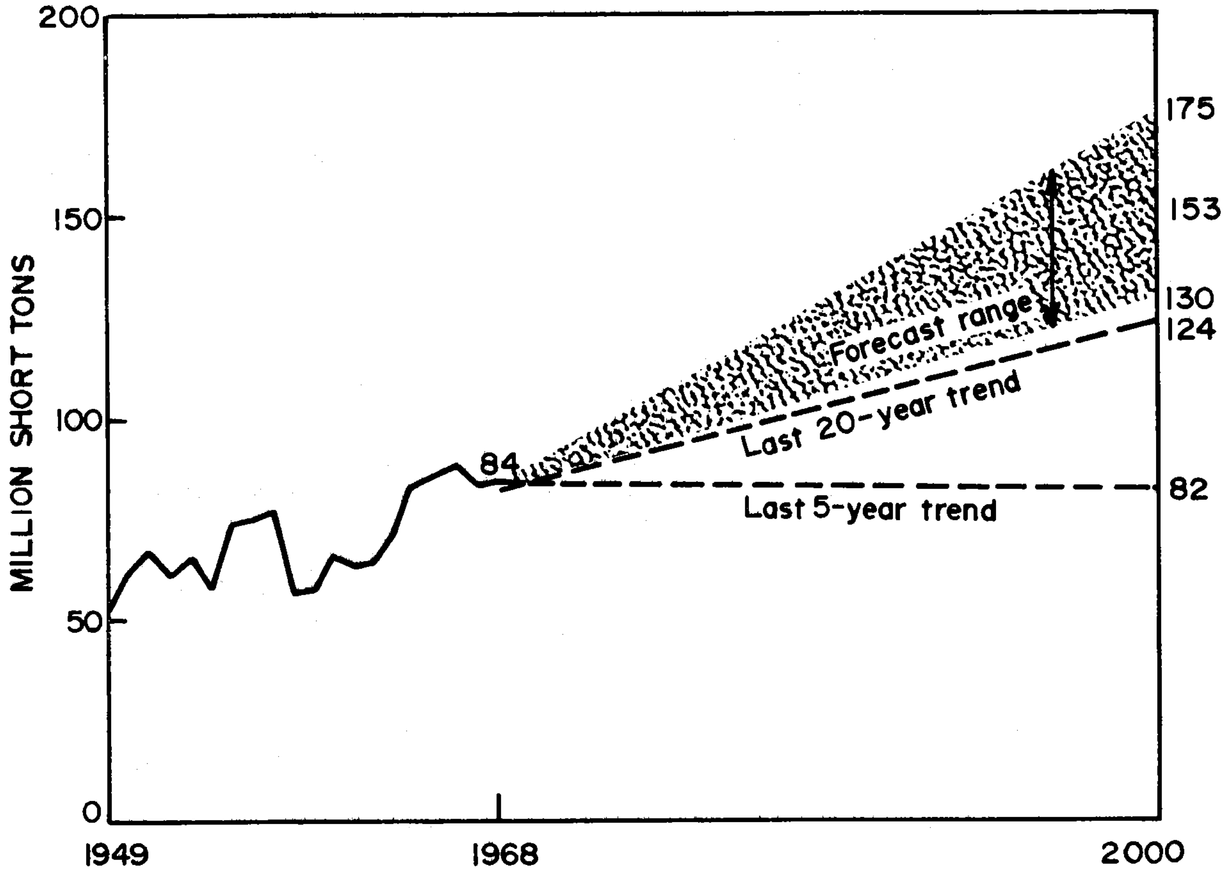

FIGURE 5. - Comparison of trend projections and forecasts for primary iron demand.

taken from "Minerals Facts and Problems," shows the supply schedule for domestic iron ore. At the average 1968 price of $15.40 per short ton of iron-in-ore f.o.b. mine, the reserves total about 2 billion tons of recoverable iron (4); this supply is denoted by the broken segment of the curve.

The steeply rising supply curve in figure 6 reflects the increased average cost from performing beneficiation and agglomeration upon an increasing proportion of the iron minerals mined. The cumulative consumption of domestic iron units to the year 2000 has been estimated to range between 2.19 and 2.69 billion tons (4). This range is represented in figure 6 by the rising solid curve between the rising broken curve segment and the horizontal full curve. Thus, these rising segments represent in an approximate way the rate of cost increase in U.S. ore mining to the year 2000, given current technology. This rising curve also provides a measure of how the competitive pressures on domestic producers are likely to increase; by comparison, foreign ores are abundant (at the current price level they already supply one-third the U.S. market).

Figure 6 brings out a second relation of consequence. The rising solid curve connotes substitution of nonmagnetic taconites as the known resources

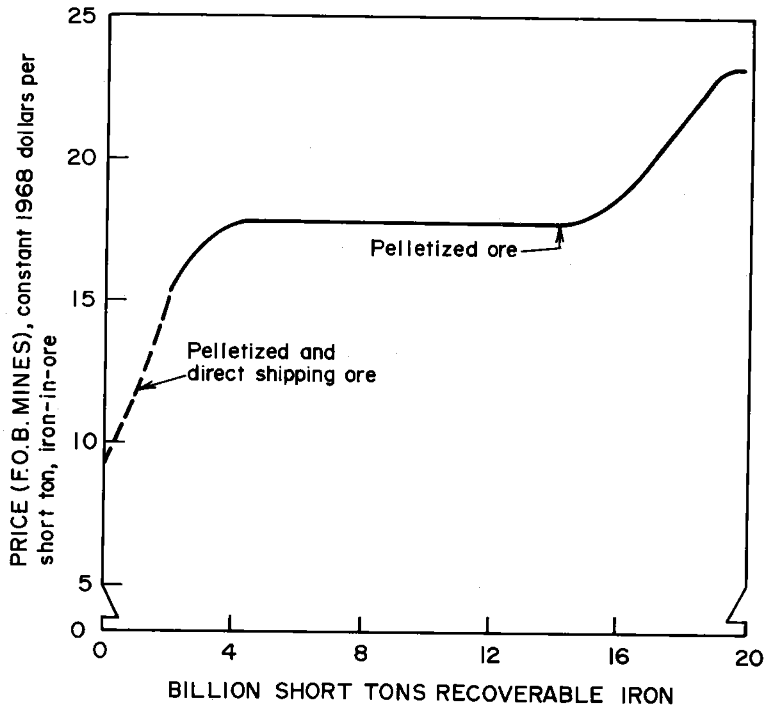

FIGURE 6. - Projected domestic availability for iron.

of magnetic taconites become exhausted. Intensive use of concentrates processed from these nonmagnetic minerals likely will be needed long before the year 2000 to meet the cumulative demand for domestic iron ore.

EFFECTS OF DIRECT REDUCTION ON MINERAL REQUIREMENTS

Ferrous Raw Materials

Direct reduction has no immediate effect on the quantity of iron ore and agglomerates. The determinative conditions of supply for new iron units are (1) the size of the market for domestic iron and steel products, and (2) the counterflow of discarded goods in iron and steel scrap.

The ratio of new iron to secondary iron in the U.S. supply has been remarkably stable. The constancy of the 73:27 pig-scrap ratio in ferrous metallic supply is indicative of a remarkable equilibrium in the supply of these materials, especially in the face of unprecedented waves of material and technology substitution in the iron and steel industry, and unprecedented pressures of imports upon the market for steel. There is no credible alternatives to this 73:27 split as a model of future supply simply because it has withstood such intensive buffeting in the 1964-70 period.

Iron Ore and Agglomerates

Direct reduction has three potential consequences for iron ore and agglomerate requirements: quantity, form, and composition. The quantity issue has no effect as long as the 73:27 split endures.

The physical form of iron minerals supplied to direct reduction plants for the U.S. market is important both for the reduction process and the final use of the reduced product in iron and steel production. All of the direct reduction plants commissioned to date by U.S. producers depend on closely sized and shaped particles. The Midrex and Armco plants are designed for feeds of indurated pellets for reduction in a shaft kiln. Conscientious screening to remove pellet chips has been found essential if high pressure drop and bridging are to be avoided.[17] The fluidized bed processes are

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[17] This experience parallels the results of unpublished research by the Bureau of Mines on blast furnace smelting of pellets.

utterly dependent on precise particle sizing. Rotary kilns and static bed shaft kilns (HyL) are not so constrained in the size and shape of feed, but the demands for control of these characteristics in the reduced product likely will require precise sizing of feed in any event. Both of the markets for reduced iron product--the blast furnaces and the melting and refining furnaces--likely will require pellets or briquets distinguished by a high degree of uniformity in size, degree of reduction, and mechanical properties. They are easy to handle and feed, and they react uniformly. Finally, agglomerates now account for three-fourths of the iron mineral supply to U.S. furnaces (table 3) and this proportion will grow just to serve present needs. Thus, the pellet preparation facilities needed prior to direct reduction already have been largely provided for.

Chemical composition overshadows all else as the most important issue resulting from direct reduction. The attractiveness of reduced iron pellets (or briquets) for charging directly into foundry or steel plant furnaces is unquestioned; the method eliminates the tremendous capital outlay for a blast furnace. However, the chemical composition of domestic iron oxide pellets available to the contemporary U.S. market is entirely unsuitable for this purpose because with few exceptions the gangue content is much too high for melting and refining furnace use.

The contemporary mining and beneficiation technology in the United States and Canada is designed to produce oxide pellets containing residual gangue (SiO_2 + Al_2O_3) totaling about 6 percent. This level of gangue is entirely satisfactory for blast furnace feed; below 5 percent gangue the gains for blast furnace use diminish. Furthermore, increased beneficiation involves the greater loss of iron yield. Present technology recovers about 70 percent of the iron-in-ore in the beneficiated product. Altogether there is not much point to further beneficiation below the 5 percent gangue level for blast furnace needs, whether as oxide pellets or as reduced pellets. For this class of use both the technology and the capacity are ample. In 1970 the shipments of pellets from U.S. plants totaled about 60 million net tons; Canadian shipments (mostly to the United States) totaled 28 million tons.

Melting and refining processes allow for much less gangue to be introduced. Exactly what level is tolerable depends on both technologic and cost factors. All of the direct reduction plants in the United States are intended to provide reduced iron products for melting and refining processes. Each of these developments is based on iron mineral feeds which do not exceed 3.0 percent gangue (SiO_2 + Al_2O_3); for the most part steel producers are looking more towards 2 percent as the limit. Only a tiny fraction of U.S. capacity for iron minerals beneficiation can provide this quality of feed. (Pea Ridge is the best known.) More than 95 percent of the U.S. capacity cannot qualify for this use, based on present practice. Although the gangue concentration can be diluted by charging iron and steel scrap, it does not change the basic problem.

This mismatch of present U.S. beneficiating capacity to the present demand for direct reduction feedstock has resulted in a complete reliance on foreign ores to supply the direct reduction plants. All of these plants are located on tidewater. Only the Armco plant is located in an established steel production center; the other plants are new ventures in steelmaking. Further implementation of direct reduction is likely to be in this direction.

The gap between present day magnetic beneficiating technology in the U.S. Great Lakes district and the gangue requirements for use in melting and refining can be closed. Bureau of Mines research has developed multiple-stage flotation and magnetic separation circuits for beneficiating magnetic feeds into "superconcentrates." Gangue levels below 3 percent are readily attainable (57). Costs are incurred in lower yield of iron from crude ore,[18] and in the investment, operating, and reagent costs of the superconcentrating circuit. The deterrents to implementation of this technology apparently are economic and financial--economic because of uncertainty over price and cost structures, and financial because of uncertainty over allocating limited investment funds into this development.

As to the nonmagnetic iron minerals in the Great Lakes district, the possibilities of further economical beneficiation to attain a refining-grade concentrate are unknown. Contemporary beneficiation technology produces a diversity of gangue concentrations: One plant achieves modern smelting-grade quality (silica plus alumina total 6 percent maximum) and a new plant will produce similar quality products, but other plants produce pellets analyzing from 7 percent to 9 percent gangue (SiO_2 + Al_2O_3). Moreover, there is no economical technology to upgrade these minerals further (roasting to convert hematite to magnetite before beneficiating generally is too expensive). As things now stand, a demand for refining-grade agglomerates will push these nonmagnetic minerals toward the margin of acceptability. Only a new technology could intervene in that movement; iron ores are so readily available worldwide that an ore of poor composition will become increasingly unusable, regardless of price.

A third possibility exists in Minnesota. There, exploratory deep drilling indicates the magnetic taconite formations downdip at depths too deep for economical surface mining. New technology of underground mining will be needed.

Not to be overlooked are the abundant deposits of Southern ores. Though high-grade imports have displaced these ores almost completely from conventional ironmaking, they may in time become useful feeds for direct steelmaking processes.

For the future, a vitally important decision will be called for: Whether to rely much more heavily on imported iron ores or to support timely development of the new technologies required for economical beneficiation of nonmagnetic taconites, for underground mining of magnetic taconites, and for nonconventionally separating and refining Southern hematites.

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[18] At 70 percent recovery of iron, 1.4 tons of iron-in-ore must be mined per unit of output; at 50 percent recovery, 2.0 tons of iron-in-ore must be mined, almost half again as much mining.

The entire domestic supply of iron-in-ore recoverable in 1968 without price increases was estimated at 2 billion tons (the broken portion of the curve in figure 6). However, the median projection to the year 2000 (table 17) of demand for domestic primary iron cumulates to 2.44 billion tons. The shortage (at 1968 prices) will become evident near 1985. If the technology needed is to be available in, say, 1982 and a leadtime of 10 years is required, the time for decision is already upon us.

Iron and Steel Scrap

The existing shares of pig iron and scrap in the supply of ferrous metallics (73:27) will, if maintained, protect iron and steel scrap in the aggregate from any effects of direct reduction. Thus the primary question is whether the 27 percent share of the ferrous input held by scrap is likely to be maintained.

The likelihood is strong for maintaining scrap's share because the forces are strong for an abundant supply of scrap. In recent years imported steel products have captured most of the growth in the domestic market. As a result the production of waste, both prompt industrial and obsolete, has increased at a much faster rate than the growth of domestic demand for scrap. Prices of scrap generally have declined relative to pig iron (except during scattered flurries of demand). A great growth in the export of scrap has supported the domestic market (table B-13). The basis of that growth, expansion in Japan and Europe, has passed its peak. Although increased use of BOP furnaces abroad will constrict those markets further, an upsurge in electric-arc furnace steelmaking abroad will create an additional market for exports.

The abundance of waste metal confronts a diminished dependence upon waste metal supplies where direct-reduced iron is available. In the first place, the conventional blast furnace--BOP chain of processing is essentially independent of purchased scrap.[19] Second, the direct reduction--electric furnace chain is likely to use at least 30 percent reduced iron if it uses any at all. Third, direct-reduced iron typically contains very low concentrations of other metallics; thus it is useful for blending with low-priced contaminated scrap to provide a minimum cost metallic input.

The direct reduction--electric furnace chain poses problems of price behavior whose outcomes are not at all clear. This process chain puts in conflict the scrap producers (traditional suppliers of 98 percent of the ferrous input to electric furnaces) and the reduced iron producers (who would supply about 43 percent of the ferrous input, given 40 percent of the charge). On the defensive would be the scrap suppliers, used to dealing in the volatile markets for scrap. On the offensive, and viewing the possibilities of very large gains in ore usage, would be the ore producers, firms skilled in marshalling huge blocks of capital for gigantic ore developments, and used to working on long-term supply contracts. In this contest the ore producers would have a high floor under their price because of the large capital investment entailed.

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[19] If merchant scrap is desired home scrap can be exchanged readily for it.

Some writers assert that direct reduction will be valuable as a means of enforcing price discipline on scrap. If scrap is abundant and low-priced, as it has been since 1958 except for a brief surge in 1969, the more likely course will be that direct reduction will provide a support for scrap prices. The steel producer who is using 40 percent metallized pellets in his electric furnace simply cannot ignore lower-priced scrap. In the present context, reduced iron for electric furnaces will originate from foreign ores and will compete with scrap intended for export, the scrap use that tends to "make the market" in coastal areas. Abundant scrap may demoralize ore prices.

A second question regarding iron and steel scrap is the policy of government regarding the recycling of ferrous metals. Prompt industrial scrap by and large is recycled effectively. The distressed area is consumer discards, that is, municipal wastes, old appliances, and autos. Thus far, there has been no policy for coping with this admitted recycling problem.

Fluxes

Direct reduction will accelerate the trends already in motion to substitute burnt lime for raw limestone (including dolomite). In so doing there will be a continuation of the present substitution of limestone deposits. Fluorspar usage will change in tandem with burnt lime usage.

Limestone and Dolomite

The use of raw flux in steel furnaces is going the way of the open hearth, into oblivion. In blast furnaces the use of prereduced iron in the charge will diminish the need for flux proportional to the concentration of reduced iron in the burden. The saving comes about principally from the saving of coke. (There is less coke-ash slag to flux, hence less fluxstone is needed.) No saving is attributable to the reduced form of the iron minerals because the gangue-to-iron ratio ordinarily would remain unchanged during reduction.

If the blast furnace smelting process is replaced by charging reduced iron into electric steel furnaces, the move will shift fluxstone demand from raw stone to calcined lime. Dolomite usage is eliminated in this substitution.

Lime

The movement to increased lime usage is also a movement toward higher quality flux; increased manufacturing activity in fluxes, and substitution of mineral resources.

Calcined lime is used in melting and refining furnaces. The physical chemistry of these oxidizing processes requires high basicity slags; at best the desulfurization of steel by oxidizing slag is less than 10 percent as efficient as in the blast furnace. Limestone produced for burnt lime thus must be much lower in sulfur and in silica content compared to raw fluxstone suitable for blast furnaces. The increased basicity requirements, again compared to blast furnace slags, increase the usage of lime even further. Sources of stone for lime calcination are much more differentiated than those for fluxstone. Even in the major deposits selective mining is practiced to produce burnt lime of the quality demanded.

The effect of incorporating reduced iron in melting and refining furnace charges is to require more lime simply because more gangue is introduced. For example, a typical BOP furnace is charged with 70 percent hot metal containing 0.9 percent silicon, equivalent to 1.4 percent SiO_2 in the charge, and the lime requirement is roughly 140 pounds per ton of raw steel. An electric furnace feed incorporating 40 percent of reduced iron made from concentrates analyzing only 3 percent SiO_2 would have a much higher concentration of SiO_2 in the charge (1.8 percent). Continuous feeding and fluxing a less-than-basic slag (1.5 ratio compared to the neutral 1.8 ratio) is a lime-saving method, but it may be costly in iron losses. If the incorporation of reduced iron in electric arc furnace charges is substituted for BOP furnace steel production, the increased lime usage beyond the usual electric furnace usage will be more than offset by the savings in lime compared to BOP usage.

Fluorspar

Direct reduction will have a minor effect on fluorspar usage. Its only effect would be in electric furnaces, but in that process the use of continuous charging is expected. The type of slag and the flushing action to be experienced will likely be free of need for fluorspar. The technology most applicable for the slag flush will be that of the "obsolete" open hearths which characteristically flush most of the gangue early in the heat.

Fuels and Energy

Major changes in fuels and energy supply would be direct consequences of direct reduction. More fuel would be needed. Different types of fuel might be used. The dependence on coal supplies would be shifted from coking coals.

The first point to note is that direct reduction increases the fuel and energy requirement to transform iron minerals into raw steel compared to the traditional blast furnace smelting route. Estimates suggest that direct reduction of low-gangue iron minerals and arc furnace steelmaking (while maintaining the aggregate pig scrap ratio of 73:27) would consume at least one-quarter more energy than the 1970 technology mix of blast furnaces, open hearths, BOP's and electrics.[20]

On the other hand, direct reduction is free to use a variety of fuels. All of the U.S. reduction plants are based on natural gas or fuel oil and steam inputs, to produce CO and H_2 by catalytic reforming. Rotary kiln processes can utilize solid fuels to advantage, especially low-rank fuels such as lignite.

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[20] Including in both cases the energy consumed in making coke, sinter, lime, and oxygen.

Any consideration of direct reduction implies an upsurge of arc furnace melting and a corresponding increase in electric power generation. This category of energy conversion can be supplied by any of the fuels available to the electric utility generating industry, but the efficiency of energy transformation from mineral fuel to the arc furnace charge is low.

The common thread throughout the question of fuel substitution is the large-scale decline of metallurgical coke if direct reduction is implemented. The highly developed technology of coal preparation, blending, and coking now required to make coke of high strength, low CO_2 reactivity, and tolerable sulfur and ash contents would become much less important. But coke also supplies byproduct fuels in large quantities. Thus, if coking is abandoned the fuel equivalents of the byproduct fuels will have to be supplied from other sources.

The other point to be stressed is the vastly enlarged possibility of fuel and energy substitutibility for direct reduction. Iron ore reduction is simply done, in chemical terms; direct reduction processes offer opportunities to economize on fuel inputs by switching fuels when prices change, exactly as electric utility generating stations have learned to do.

COLLATERAL FACTORS

Collateral factors now in motion may influence the implementation of direct reduction. The factors most evident are (1) stack gas injection in the blast furnace, an alternative to prereduced burdens; (2) continuous casting of steel, a scrap-saving development tending to change the traditional mix of steelmaking processes, and (3) direct steelmaking, a radical departure that would obsolete existing extractive and refining technologies.

Stack Gas Injection

This term refers to the method of increasing the reduction capacity of a conventional blast furnace operation by injecting hot reducing gases into the stack portion of the furnace. A crude analogy is that of superimposing a shaft reduction kiln upon the stack portion of a conventional blast furnace. Similar to the use of prereduced burden, the coke rate is diminished and furnace productivity is increased. Experiments to date have diminished coke rate by more than one-third, equivalent to a 65 percent prereduced burden. Thus far the experience with stack gas injection has been confined to experimental blast furnaces. The first experiments were performed in the Bureau of Mines furnace in 1967 (35). The findings have been confirmed in a smaller Japanese furnace (52).

Stack gas injection is attractive because it would improve the performance of conventional blast furnaces and burdens. The method performs the equivalent of direct reduction when and as needed; takes advantage of whatever fuel choices exist in steelmaking plants, including byproduct fuels; avoids the problems of handling and storing metallized pellets, and obviates the need to invest in reduction plants.

Continuous Casting

All of the activity in the United States and Canada to implement direct reduction has been linked thus far to electric arc furnace steelmaking. In each instance the steel plant has provided continuous feeding equipment for introducing metallized pellets, electric arc furnaces for melting and refining, and continuous casting for the raw steel produced. The blast furnace--BOP chain of processing has not been supplied with metallized pellets to date.

Continuous casting increases the yield of shipments from raw steel compared to traditional ingot casting. Likewise, it also diminishes the production of home scrap, thus increasing the need for purchased scrap or metallized pellets to balance the charges in steelmaking furnaces. Table 18 displays calculations of the aggregate shares and amounts of pig iron and scrap consumed per ton of shipments for yields ranging from 66 to 80 percent. The yields of 70, 75, and 80 percent are hypothetical, reflecting the increased implementation of continuous casting by the steel industry (shipment yields of about 82 percent have been reported for continuous casting plants). Table 18 is based on maintaining the existing 73 pig iron--27 purchased scrap split among ferrous inputs. Increasing yield of shipments connotes less home scrap, so the aggregate pig-scrap ratio in steelmaking charges increases, from 54:46 at 66 percent yield, to 65:35 at 80 percent yield.

Continuous casting has been adopted widely since 1967; by 1971 the U.S. capacity had reached 17 million tons (27). The increase in yield will increase the aggregate pig-scrap ratio in steelmaking charges, and result in redistribution of the proportions of BOP and EF methods, given the respective pig iron-scrap percentages of 70:30 and 2:98 that have been maintained since 1964. At 66 percent yield the estimated shares would be 76 percent BOP and 24 percent EF. At 80 percent yield, the proportion would have risen to 93 percent BOP and 7 percent EF. These proportions assume no change in the traditional patterns of mineral consumption.

The effects of continuous casting on direct reduction likely will be complex. A straightforward inference from table 18 would call for larger proportions of BOP-made steel to go with further implementations of continuous casting. This may determine the course in large integrated steel plants, that is, the use of smelting-grade reduced pellets in blast furnaces to feed more BOP furnaces. In non-integrated steel plants the main iron source has been purchased scrap anyway, so the adoption of continuous casting merely diminishes the number of heats required for producing a given quantity of steel product without changing the shares of ferrous inputs.

Direct Steelmaking

Direct steelmaking connotes the conversion of raw materials into steel in one processing operation. There is a consensus that it will be a major factor in steelmaking by the turn of the century (56). Before then, exceedingly complex technical problems remain to be solved. Millions have been spent in research; many more will be required.

TABLE 18. - Yield of shipments from raw steel and process substitution

Yield, shipments from raw steel...percent..	66	68	70	75	80
Shipments....................short tons..	1.00	-	-	-	-
Raw steel production...............do.....	1.52	1.47	1.43	1.33	1.25
Ferrous inputs constant:					
Pig iron........................do.....	.91	-	-	-	-
Purchased scrap..................do.....	.27	-	-	-	-
Total.......................do.....	1.18	-	-	-	-
Iron equivalent[1]...............do.....	1.11	-	-	-	-
Steelmaking:					
Pig scrap ratio.........................	54:46	55:45	56:44	61:39	65:35
Scrap, total................short tons..	.78	.74	.70	.58	.49
Less: purchased................do.....	.27	.27	.27	.27	.27
Difference: home..............do.....	.51	.47	.43	.31	.22
Iron equivalent[2]...............do.....	.50	.46	.42	.30	.22
Iron balance:					
Inputs..........................do.....	1.11	1.11	1.11	1.11	1.11
Home scrap......................do.....	.50	.46	.42	.30	.22
Total in.....................do.....	1.61	1.57	1.53	1.41	1.33
Output, raw steel[3]...............do.....	1.50	1.46	1.42	1.32	1.24
Output, other....................do.....	.11	.11	.11	.09	.09
Slag and dust[4]...................do.....	.08	.08	.08	.07	.07
Unaccounted[5]....................do.....	.03	.03	.03	.02	.02
Process distribution:					
BOP...........................percent..	76	78	79	87	93
Electric.......................do.....	24	22	21	13	7
BOP/electric ratio......................	3.2	3.5	3.8	6.7	13.0

[1] 93 percent of pig iron; 97 percent of scrap; 94 percent of total pig iron and scrap.
[2] 98 percent of home scrap consumption.
[3] 99 percent of raw steel production.
[4] 5.5 percent of raw steel production.
[5] 2 percent of raw steel production.

Investment decisions concerning direct reduction are affected by the uncertain impendency of direct steelmaking. Access to technologic information and to patent rights is important for avoiding unwitting investment in contemporary technology after the corner has been turned on the road to direct steelmaking. Most of the major steelmaking nations have supported major research programs reaching back 20 years, but no comparable research program exists in the United States.

METALLURGICAL, INDUSTRIAL, AND ENVIRONMENTAL CONSEQUENCES

Metallurgical Consequences

1. The gangue content of iron ore products will become a major factor in their competitive position. Direct reduction postpones gangue separation to a later step. Conventional blast furnacing effectively separates the gangue as a slag. Steel refining processes are not well suited for performing this separation. The strongest emphasis on gangue control will come from operators who charged metallized pellets into basic-lined steel furnaces. Every ton of gangue requires at least 1-1/2 tons of calcined flux plus the time and energy expense to melt and refine it.

The average Great Lakes pellets in 1970 would, if prereduced, assay nearly 10 percent silica. Gangue in this concentration is intolerable for steel furnaces. It is notable that all of the prereduced pellet tests reported have been based on reduced material assaying 4 percent silica or less, equivalent to less than 3 percent silica in hematite. Major efforts will be needed to develop technologies for producing "superconcentrates" if the present position of domestic iron ore in the mineral supply chain is to be maintained.

2. Pressures for utilization of scrap will increase. The role of metallized pellets in arc furnaces is based on substitution for scrap. Direct reduction will make inroads into scrap markets where steelmakers are accustomed to paying higher prices to get good scrap. The issue for scrap will be intensified because waste continues to be generated, and a market mechanism for effective recycling needs to be maintained. Yet the export market for scrap likely will become constricted as foreign steelmakers swing more completely to BOP steelmaking and become less concerned for U.S. scrap. Continuing imbalance between the rates of waste generation and scrap consumption will create a permanent surplus of ferrous waste.

3. There will be little need to expand blast furnace ironmaking facilities. Direct-reduced products have the twin effects of (1) competing with both pig iron and scrap as a refining furnace charge component, and (2) substituting for oxide agglomerates (pellets or sinter) in the blast furnace. Prereduced pellets could increase the annual output of existing blast furnaces sufficiently to provide an ample supply of pig iron for the projected demand in the year 2000 (153 million tons of primary iron).

Whether that quantity of primary iron would be produced by direct reduction or whether the move will be to smelt oxide pellets in the blast furnace using stack gas injection to make the blast furnace in effect a shaft kiln as well, is an issue that needs analysis. In either event there is no aggregate need for additional blast furnace construction.

4. Increased substitutibility of fuels will occur. Direct reduction releases the iron and steel industry from its complete dependence on coking coal for iron reduction. Through direct reduction, the multiple functions of coke can be differentiated and each can be provided for in the most

efficient way. Thus, other fuels can substitute in providing reducing gas, carbon for solution in iron, and sensible heat from combustion. Prereduced pellet burdens in blast furnaces still would require coke to provide the structural matrix of the stock column, but the coke usage might be as little as half of the best practice blast furnace coke rate. Even then, coke usage may be diminished by substitution of coked briquets.

The choice of energy source substitutes will be difficult because the technology of iron and steel in the United States has not had to cope with fuel substitution in its principal fuel-consuming processes. An integrated knowledge of (1) theories of combustion and heat transfer related to actual process environments, and (2) engineering theory for efficient applications will be needed.

Industrial Consequences

1. Technologic change is inherently disruptive to the existing industrial system of relationships. Direct reduction, adopted for expansion, would make the established methods of production proportionally less important. If direct reduction becomes a substitute, the shock becomes even worse. In either event, direct reduction would alter the relative positions now held by the input factors, which include capital, labor, mineral raw materials, and energy sources.

The framework for decisions is technologic and economic, but models are not available to measure and test the implications of direct reduction on the functioning of the iron and steel industry.

2. Redistribution of iron and steel production will occur. The first effect of direct reduction will be to augment the supply of iron to coastal steel plants, mainly mini-mills. The second thrust will be into coastal major plants.

Effects on marketing patterns already have been observed. All of the direct reduction plants in the United States are located on or near the coasts. The U.S. Steel plant located in Venezuela is intended for exporting reduced iron to the United States and to other markets.

Mini-mills admit to aggressively flexible pricing, to keep the production volume up in slow times as well as good. This policy will intensify the pressures on the present major producers who are located inland, operate large mills, and price their product in the traditional price system.

The mini-mill movement is well underway. In 1970 the mini-mills had an aggregate melting capacity of 5 million tons and shipped 3.8 million tons, thus providing about 4 percent of total shipments. The U.S. market for that class of products is about 20 million tons, one-fifth of the total steel market.

The coastal major plants have the greatest access to foreign markets, which are growing at more than twice the rate of the U.S. market, a differential that has been observable for at least 40 years.

The same coastal plants also have the best access to foreign sources of ore and direct-reduced iron. Thus, greater expansion along the coasts will be expected compared to inland locations. The newer coastal facilities also will have the effect of thrusting their competitive radii farther inland toward the older plants along the Great Lakes crescent.

3. Import pressures on the U.S. iron and steel industry will increase. Direct reduction promises to energize the fourth and subsequent waves of imported iron and steel goods.

The first wave was the movement, beginning in 1953, to imports of high-grade iron ores. That wave crested at about one-third of domestic consumption in 1959 and that share has been maintained since. The second wave was the importation of steel products. Imported products have skimmed off virtually all the growth in domestic steel consumption since 1957. The third wave, composed of imported manufactures, has turned into a tide more recently. Foreign autos are the visible sign of a movement that is skimming the growth from domestic markets for consumer and producer durables. If these three import waves had been resisted successfully, the domestic iron ore industry of 1970 would have been more than twice as large, and the iron and steel industry about 40 percent larger.

The fourth wave, direct reduction, already is evident. All of the direct reduction plants supplying the U.S. market are based on abundant foreign sources of superior quality ores and agglomerates. The Great Lakes pellets as a class are not competitive in gangue content with these foreign ores. To become competitive in the direct reduction market, either a price discount will be required, or else the technology and production functions will have to be changed significantly.

A fifth wave, that of importing reduced iron already has begun . The Venezuelan plant has started operations. Australian ores have been tested extensively for this purpose, so have Brazilian ores. The net result of this fifth wave would be a further shrinkage in the value added by U.S. iron and steel industries.

A sixth wave, the production of high quality semifinished slabs, blooms, etc. in the country of ore origin, all made with the minimum of scrap and commanding a better price for that reason, is foreseeable. At that point the consuming nations such as the United States may have to support the development of a recycling technology to avoid an unreasonable trade deficit.

4. Fuel utilization will become important. The technologic unfettering of iron and steel from coal, resulting from direct reduction, will pose numerous questions of fuel and energy choice. In the past all other fuels together amounted to only one-third of the energy consumed. Direct reduction will initiate questions of fuel supply that inevitably will be far-ranging. Fuel substitution issues will be large scale because iron and steel is a major consumer in the Nation's energy budget. Moves away from coking coal are bound to affect the coal industry, especially the limited regions where coking coal is produced; iron and steel consumes one-fifth of the Nation's coal production.

Moves to fluid fuels will bring iron and steel firms into the turbulent international markets for these fuels. The differentiation of energy functions brought about by direct reduction will raise questions of using nuclear-generated process heat. Consciousness of these forces and foresighted perception of their industrial effects will be called for because of the investment decisions to be made for implementing direct reduction.

Environmental Consequences

Direct reduction processes may offer a windfall opportunity for the steel industry to abate a vexing class of environmental problems in the coke and sinter plants and blast furnaces. Coke is essential for the blast furnace. The blast furnace produces screenings and flue dust, and the sinter plant consumes coke breeze and ore fines to produce new agglomerates. One alternative is to abandon the polluting process in favor of a nonpolluting one, in this case, direct reduction. Another alternative is to simply import the product, leaving the pollution to the producing country.

Direct reduction will create an environmental problem in iron ore treatment. Trends toward "superconcentrates" are likely to increase the production of tailings and the solid waste impact on the environment in the areas of the ore beneficiating plants. As things now stand, the Great Lakes iron ore industry mines about 4 tons of crude ore to ship one ton of iron-in-ore. To produce a ton of superconcentrates as much as an extra 2 tons of crude ore might be needed and tailings might become nearly double the quantity experienced today. The average experience would be better no doubt, but the point is clear. With ore so cheap worldwide, the easier solution might be to continue importing low-gangue ore and concentrates.

Energy substitution resulting from direct reduction is bound to have important effects on environmental issues associated with fuels. Direct reduction fuel gas may be supplied by mine-mouth coal gasification plants with as yet unknown pollution problems. A trend to more EF steelmaking will increase the magnitude of environmental issues related to electric power generation, especially coal mining.

Each of these environmental consequences might be abated by simply importing the product. That would be no more than a short-term solution. Eventually, the producing nation, wherever it is, may come to recover its costs for pollution abatement. Furthermore, the prospect of greater dependence on iron ore mining and iron ore production outside the country may have security implications.

SUMMARY

The potential effects of direct reduction upon mineral supply requirements for iron and steel production in the United States were estimated by reference to recent experience. The pattern of mineral consumption in the 1964-70 period reflected unprecedented movements of advance in ironmaking technology and of large-scale substitution in steelmaking processes: 14 of the 20 principal commodities underwent major change in average usage. The ratio of primary to secondary iron inputs remained unchanged. Best contemporary practice was identified.

The potential effects of direct reduction compared to 1970 best practice were identified by a two-stage analysis as follows: (I) For blast furnace burdens, the complete substitution of hematite pellets by smelting-grade (6 percent gangue) reduced pellets, and (II) for EF steelmaking, the partial substitution of scrap by refining-grade (3 percent gangue) reduced pellets. The effect of (II) also is to substitute partially for the traditional two-step ironmaking-steelmaking process chain based on the molten pig iron.

Potential mineral supply effects of direct reduction include the following: (1) In blast furnace smelting, a need for one-half less coke and one-fifth less flux (also, one-fifth less slag production); (2) in EF steelmaking, the effects of substituting for nearly one-half of the blast furnace ironmaking production: (a) displacement of nearly one-half of the smelting-grade iron ore pellets for direct reduction by refining-grade iron ore pellets; (b) proportional diminutions in blast furnace consumption of coke and flux, and in BOP consumption of oxygen, and (c) an immense need for substitute fuels to provide up to one-half of the fuel budget; (3) the 1970 energy budget of iron and steel would be adequate in magnitude to support a complete changeover to direct reduction, and (4) the use of direct-reduced material could greatly improve furnace productivity: (a) perhaps 75 percent in blast furnace ironmaking, and (b) 45 percent in EF steelmaking.

A massive alteration in facilities would be required to realize the Case II condition. Compared to the 1970 industry there would be about 12 million tons overcapacity of BOP furnaces; a need for about 60 million tons of additional EF capacity; a 17-million ton glut in the supply of smelting-grade hematite pellets, and a near-total lack of U.S. capacity to supply 51 million tons annually of refining-grade pellets.

Collateral factors now in motion may influence the implementation of direct reduction. Those most evident are (1) stack gas injection in the blast furnace, an alternative to prereduced burdens; (2) continuous casting of steel, a scrap-saving development tending to change the traditional mix of steelmaking processes, and (3) direct steelmaking, a radical departure that might obsolete the existing extractive and refining technologies.

Metallurgical consequences of direct reduction include the following: (1) Gangue content of iron ore products will become a major factor in their competitive position; (2) pressures for utilization of scrap will increase; (3) there will be little need to expand blast furnace ironmaking facilities, and (4) increased substitutibility of fuels will occur.

Industrial consequences include the following: (1) Technologic change will disrupt the existing system of relationships; (2) geographic redistribution of iron and steel production will occur; (3) import pressures on the U.S. iron and steel industry will increase, and (4) fuel utilization will become more important.

Environmental consequences will depend in large measure on the courses of iron ore treatment and energy substitution.

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APPENDIX A.--DIRECT REDUCTION PROCESSES

The term "direct reduction" refers to the mode of reducing iron minerals to metal. It is applied to any process other than the blast furnace for chemically reducing iron ores and agglomerates to metal. Because iron reduces so readily and the market for iron is so large, literally hundreds of processes have been proposed involving a great variety of reducing agents, types of equipment, and product forms. A recent review tabulated the characteristics of 81 processes for direct reduction in the solid state and 22 processes for smelting and melting iron (50). Smelt-melt processes have not been attractive for U.S. conditions, and will not be considered further in this report.

In the United States the contemporary and near future interest in direct reduction is confined to the solid state processes (table A-1). The first commercial plant in this country began operation in 1969 in Oregon. A second plant utilizing the same process began operations in 1970 in South Carolina. In Venezuela, a leading U.S. producer of steel is bringing a large direct reduction plant on stream in 1972. Another is under construction in Texas. Each of these investments in reduction capacity is designed to supply ferrous inputs for new or augmented steelmaking capacity, principally electric arc furnaces.

TABLE A-1. - Direct reduction plants of U.S. producers

Year began operation	Location	Process	Annual capacity metallized product, short tons per year
1969	Oregon	Midrex	400,000
1970	South Carolina	Midrex	400,000
1972[1]	Venezuela	Nu-Iron	1,000,000
1972[1]	Texas	Armco	400,000

[1] Estimated.

Principles of Reduction

Reduction is the chemical reaction by which the metallic oxide is decomposed to the elemental state of the metal; the oxygen ions are separated in a new compound. To be successful the reduction of iron ores must be highly selective. A high degree of iron reduction is desired along with minimum reduction of the residual constituents.

Solid state reduction yields a product which reflects the form and composition of the feedstock. No refining or gangue separation occurs. Hematite (Fe_2O_3) is the highest oxide of iron and the most common iron ore mineral. It consists of 30 percent oxygen by weight; solid state reduction leaves a porous structure, known generically as sponge iron. Reduction has the effect, too, of concentrating the gangue content of the product in proportion to the increased concentration of iron; a high degree of reduction concentrates gangue by about one-half.[1] The proportion of gangue to iron remains unchanged.

Iron ore reduction is not difficult to accomplish. The challenge for centuries has been to perform reduction selectively, reliably, cheaply, and in a reasonable time period. The reducing agents commonly in use are carbon, hydrogen, and carbon monoxide.

The completeness of reduction is limited by the thermodynamic equilibria between the oxides and the reducing substances. Hematite (Fe_2O_3) is reduced to metallic iron through intermediate magnetite (Fe_3O_4) and wustite ($Fe_{0.95}O$) phases depending on temperature. The three following reaction paths can occur isothermally.

Under 1,200° F: $Fe_2O_3 \longrightarrow Fe_3O_4 \longrightarrow Fe$

1,200-1,650° F: $Fe_2O_3 \longrightarrow Fe_3O_4 \longrightarrow Fe_{0.95}O \longrightarrow Fe$

Over 1,650° F: $Fe_2O_3 \longrightarrow Fe_{0.95}O \longrightarrow Fe$

These reactions have characteristic differences in enthalpy requirements (table A-2). Hematite reduction to magnetite is exothermic by either hydrogen (reaction 1) or carbon monoxide (reaction 2). From magnetite to wustite, both reactions are endothermic (reactions 3 and 4); thus, these reactions depend on a thermal reserve to keep them going. The wustite to metal reaction is endothermic by hydrogen (reaction 5), exothermic by carbon monoxide (reaction 6).

The total reaction heat requirement for reducing hematite to metallic iron at 1,880° F by hydrogen (reaction 7) is mildly endothermic; by carbon monoxide (reaction 8), mildly exothermic, and by carbon (reaction 9), highly endothermic.

In practice the heat consumption is far greater than the heat of reaction because of thermodynamic and kinetic limits. Particles such as pellets can be heated faster than they can be reduced. The heating cycles and reducing gas compositions are adjusted to optimize performance. Gaseous reduction is the only reaction mechanism of importance in direct reduction processes.[2]

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[1] Fe_2O_3 is 69.95 percent iron; reduction to 100 percent Fe concentrates iron 43 percent in the product (1.00 ÷ 0.6995 = 1.43). Nonreactive gangue also is concentrated in proportion to initial concentration as follows: 1 percent gangue, 44 percent (1 ÷ [0.99 x 0.6995] = 1.44); 5 percent gangue, 50 percent; and 8 percent gangue, 55 percent.

[2] It is ironic that direct reduction processes proceed by "indirect reduction" reactions. The "direct reduction" reaction by carbon to reduce iron, manganese, and silicon is confined to higher temperature, liquid-phase processes. Solid state processes depend on gaseous reduction, the so-called "indirect reduction" reactions.

TABLE A-2. - Enthalpy changes in iron ore reduction

(+ = Endothermic reaction)
(- = Exothermic reaction)

Reaction	Enthalpy change		
	Calories per gram-mole Fe reduced		Million Btu per short ton Fe reduced at 1,880° F
	77° F	1,880° F	
Hematite reduced to magnetite:			
1. 1/2 $Fe_2O_3 + 1/6 H_2 = 1/3 Fe_3O_4 + 1/6 H_2O$ ..	-470	-650	-0.042
2. 1/2 $Fe_2O_3 + 1/6 CO = 1/3 Fe_3O_4 + 1/6 CO_2$ ..	-2,110	-1,930	-.125
Magnetite reduced to wustite:[1]			
3. 1/3 $Fe_3O_4 + 0.28 H_2 = 1.05 Fe_{0.95}O + 0.28 H_2O$........................	+5,850	+3,700	+.239
4. 1/3 $Fe_3O_4 + 0.28 CO = 1.05 Fe_{0.95}O + 0.28 CO_2$......................	+3,120	+1,580	+.102
Wustite reduced to iron:			
5. $1.05 Fe_{0.95}O + 1.05 H_2 = Fe + 1.05 H_2O$..	+6,020	+3,680	+.238
6. $1.05 Fe_{0.95}O + 1.05 CO = Fe + 1.05 CO_2$..	-4,370	-4,380	-.283
Hematite reduced to iron:			
7. 1/2 Fe_2O_3 + 3/2 H_2 = Fe + 3/2 H_2O.....	+11,400	+6,720	+.434
8. 1/2 Fe_2O_3 + 3/2 CO = Fe + 3/2 CO_2.....	-3,360	-4,730	-.305
9. 1/2 Fe_2O_3 + 3/4 C = Fe + 3/4 CO_2.....	NAp	+25,300	+1.633
Reducing gas synthesis:			
10. $CH_4 + H_2O = CO + 3 H_2$................	+49,270	+54,330	+1.315
11. CH_4 + 1/2 O_2 = CO + 2 H_2..............	-8,530	-5,290	-.171
12. $H_2 + CO_2 = CO + H_2O$..................	+9,840	+7,630	NAp
Basic reactions:			
13. C + 1/2 O_2 = CO.......................	-26,420	-27,210	NAp
14. CO + 1/2 O_2 = CO_2	-67,640	-67,250	NAp
15. C + CO_2 = 2 CO.......................	+41,220	+40,040	NAp
16. H_2 + 1/2 O_2 = H_2O	-57,800	-59,620	NAp

NAp - Not applicable.

[1] The composition of wustite is nonstoichiometric, varying with temperature and whether it is in equilibrium with Fe_2O_3 or Fe_3O_4. $Fe_{0.95}O$ is representative.

Source: (77, 114).

The limiting factor in iron reduction is the ratio of partial pressures--for hydrogen, H_2O/H_2; for carbon monoxide, C/CO at lower temperatures, and CO_2/CO at higher temperatures. The equilibria shift to more complete reduction at higher temperatures. Neither H_2 nor CO reductant is effective in reducing manganese or silicon from their oxides in solid state reduction. The equilibria for C/CO and CO_2/CO intersect at about 1,300° F; below that temperature excess CO deposits as soot. Carbon monoxide reduces hematite to magnetite beginning about 1,100° F, and reduction to wustite can start about 1,300° F. Above 1,340° F hydrogen becomes a more intense reductant than carbon monoxide because its equilibrium moves farther toward complete reaction (<u>79</u>). These thermodynamic considerations determine the boundaries of efficiency in reduction reactions.

The physical constitution of iron ore minerals, that is, particle size, porosity, gangue form, and catalytic considerations, all have their impacts upon the suitability of a particular process for a specific ore feed (<u>100</u>, <u>107</u>, <u>111</u>).

The usual sources of reducing gas are synthesis gas mixtures for the gaseous reduction processes and, for rotary kiln processes, some form of coal. Synthesis gas mixtures are produced from natural gas by steam reforming (table A-2, reaction 10) or by partial oxidation with oxygen (reaction 11); in both cases the shift reaction (reaction 12) is used to adjust the gas composition. The reactions are endothermic and much heat must be supplied. Reaction rates and completeness are controlled by kinetic factors. (Thermodynamic equilibria are useless as predictors in these reactions.) Many proprietary catalytic processes are known, for synthesis gas is the primary feedstock of the synthetic organic chemical industry. The raw gas is dried to improve the H_2O/H_2 ratio, and often is passed through a lime scrubber to remove excess CO_2. Fuel oil also can be substituted for natural gas though desulfurization of the synthesis gas may be required.

Measuring Reduction

Regardless of the reductant used, it is neither practical nor desirable to carry the chemical reaction to 100 percent completion. There is always a portion of iron which has not been freed of oxygen. A measure of reaction completion is helpful when comparing direct reduction products. Two such measures, the degree (or percent) of metallization and percent reduction are defined as follows:

$$\text{Percent metallization} = \frac{\text{metallic iron}}{\text{total iron}} \times 100$$

$$\text{Percent reduction} = \frac{(\text{wt } O_2 \text{ in ore}) - (\text{wt } O_2 \text{ in reduced product})}{\text{wt } O_2 \text{ in ore}} \times 100$$

Raw Materials and Energy

Gaseous reductant processes depend on reducing the ore by a stream of reducing gas passed through the reactor vessel. The physical characteristics of the iron-bearing material--size, surface area, and porosity--all serve to limit the rate of iron ore reduction. Less than ideal conditions in any of these characteristics will require additional fuel to perform the needed degree of reduction. The waste gases from the reduction operation contain residual reducing constituents and heat; utilization of this chemical and thermal energy is an important feature of all direct reduction processes.

Solid reductant processes use coal as the reductant source, though carbon monoxide performs the reduction. The coal particles in intimate contact with the ore provide a high concentration gradient for reduction. Coal combustion provides a portion of the process heat; it also provides carbon monoxide for reduction. (At higher temperatures carbon dioxide also gasifies carbon, reaction 15.) Nearly any coal can be used if its ash softening temperature is not too low; lignites have been successful (81).

The technical possibilities of energy source substitution seem likely to increase. Differential costs between energy types are likely to rise; thus efficient substitution will become increasingly important. The direct reduction processes use more fuel per unit output than blast furnaces, mainly in heat losses and in less efficient recovery of sensible heat in the process. However, direct reduction offers greater possibilities for energy substitution.

Direct reduction processes can be used upon iron ore or agglomerates. Since no gangue removal or separation occurs in direct reduction, the quality of the parent ore concentrate is reflected directly in the reduced material. Ideally the ore would have no more than 2 percent gangue in the feed and be low in sulfur and phosphorus (0.020 percent). Higher gangue levels may be tolerated (4 to 5 percent) if phosphorus removal is not required in steelmaking (23).

Mineral raw materials other than fuels and ores are not required in most solid state reduction processes. Since no gangue separation is performed, there is no need to flux it. Gaseous reduction processes do not consume flux. Processes using solid reductants, for example, SL/RN, do require the use of limestone or dolomite to react with the sulfur liberated when the reductant is consumed.

Types of Processes[3]

Interest in direct reduction processes in the United States is centered upon three basic types of reactors:

1. Rotary kiln, using solid and liquid or gaseous reductant.

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[3] Reference made to specific proprietary process developments is solely to facilitate understanding and does not imply endorsement by the Bureau of Mines.

2. Vertical shaft, using gaseous reductant.
    (a) Continuous
    (b) Batch
3. Fluidized bed, using gaseous reductant.

Prominent direct reduction processes are listed in table A-3.

TABLE A-3. - Prominent direct reduction processes for the U.S. iron and steel industry, 1971

Name[1]	Type	Fuel	Product
SL/RN (95, 104)......	Rotary kiln.........	Solid, plus gas or liquid.	Lump or pellets.
Allis-Chalmers (65)..	.....do.............	Gas or liquid. Augment with solid.	Pellets.
Midrex (108).........	Vertical shaft, continuous.	Gas or liquid.......	Pellets.
Armco (73)...........	.....do.............	Gas or liquid.......	Pellets.
HyL (72, 90).........	Vertical shaft, batch.	Gas.................	Lump or pellets.
FIOR (70, 111).......	Fluidized bed.......	Gas.................	Briqueted fines.
Nu-Iron (111)........	.....do.............	Gas.................	Briqueted fines.

[1] Underlined numbers in parentheses refer to items listed in bibliography.

Rotary Kiln

Rotary kilns are widely used in minerals processing for drying, roasting, and calcining; in particular, they are used to indurate (heat-harden) iron ore pellets for blast furnace feed. Ore reduction is a natural extension of pellet induration.

The rotary kiln has the following two major advantages in reducing iron ore:

1. The operation presents a minimum of operating problems compared with other reactors; and

2. All ranks of coal may be used, in addition to gaseous or solid fuels.

Rotary kilns make advantageous use of solid fuels. The reaction of coal is twofold, as follows:

1. It provides sensible heat in burning, and forms CO and CO_2, the ratio depending on the fuel-air ratio at the burning particle surface; this reaction occurs at the surface of the tumbling bed.

2. It provides additional reductant within the bed at higher temperatures, where the incandescent pieces of carbon can react with CO_2 to form CO (reaction 15), which reacts readily with the iron oxide minerals.

Because of the intense concentration gradients which prevail in the kiln bed (carbon in contact with iron oxide) and the continual movement of the bed and gases, the reduction to wustite is hastened; iron reduction is nearly complete by the time the charge has reached the final temperature stage in the kiln.

Coals which are highly reactive with CO_2 are advantageous in rotary kilns. Bureau of Mines research has demonstrated great superiority for lignite, a highly reactive fuel, over anthracite in pilot-scale rotary kiln reduction tests, the lignite producing a much higher degree of reduction under similar operating conditions (81). On the other hand, metallurgical coals are blended to produce low-reactivity coke for blast furnaces (58); the idea is to minimize the heat and carbon consumed by carbon gasification high up in the furnace stock column and the needless loss of CO in the top gas. In this regard the rotary kiln and blast furnace uses are not competitive.

SL/RN (Figure A-1)

This process represents a merger of commercial interests in the SL and the RN processes. The SL process had been developed by Steel Company of Canada (S) and Canadian Lurgi (L) to reduce high-grade iron ore concentrates, the RN process by Republic Steel Corporation (R) and National Lead Company (N) to upgrade low-grade ores by reduction (95, 104).

The rotary kiln is charged with iron ore, reductant, and flux. Lump ore or pellets may be used. Low-volatile solid fuel (anthracite, coke, or char) is charged with the ore and flux. Gas or oil fuel is fired through shell burners or from the discharge end. High-volatile fuels (bituminous coal, for one) are injected near the discharge end. Their volatile constituents pass off and augment the reducing atmosphere; the char is recovered and reused. The kiln contents discharge into a cooling drum. Screening and magnetic classifying separates the reduced product from char and spent flux.

The temperature level for reduction is varied to suit the materials being used; it ranges normally between 1,830° and 1,970° F. Flux is charged to absorb sulfur liberated from the solid reductant. Good results have been experienced with lignite as a reductant. Fuel consumption is equivalent to about 14 million Btu per net ton of sponge iron product, about three-fourths supplied as solid fuel, the remainder as gas or oil. SL/RN plants have been constructed in Canada, Korea, Yugoslavia, and New Zealand to reduce four quite different ore types (88, 92, 100).

Allis-Chalmers (Figure A-2)

This manufacturer of rotary kilns has developed a rotary kiln reduction process specifically to cope with fuel substitution problems. Though natural gas is a highly desirable reductant-fuel, its availability is subject to interruption. If direct reduction is to expand, a capability for

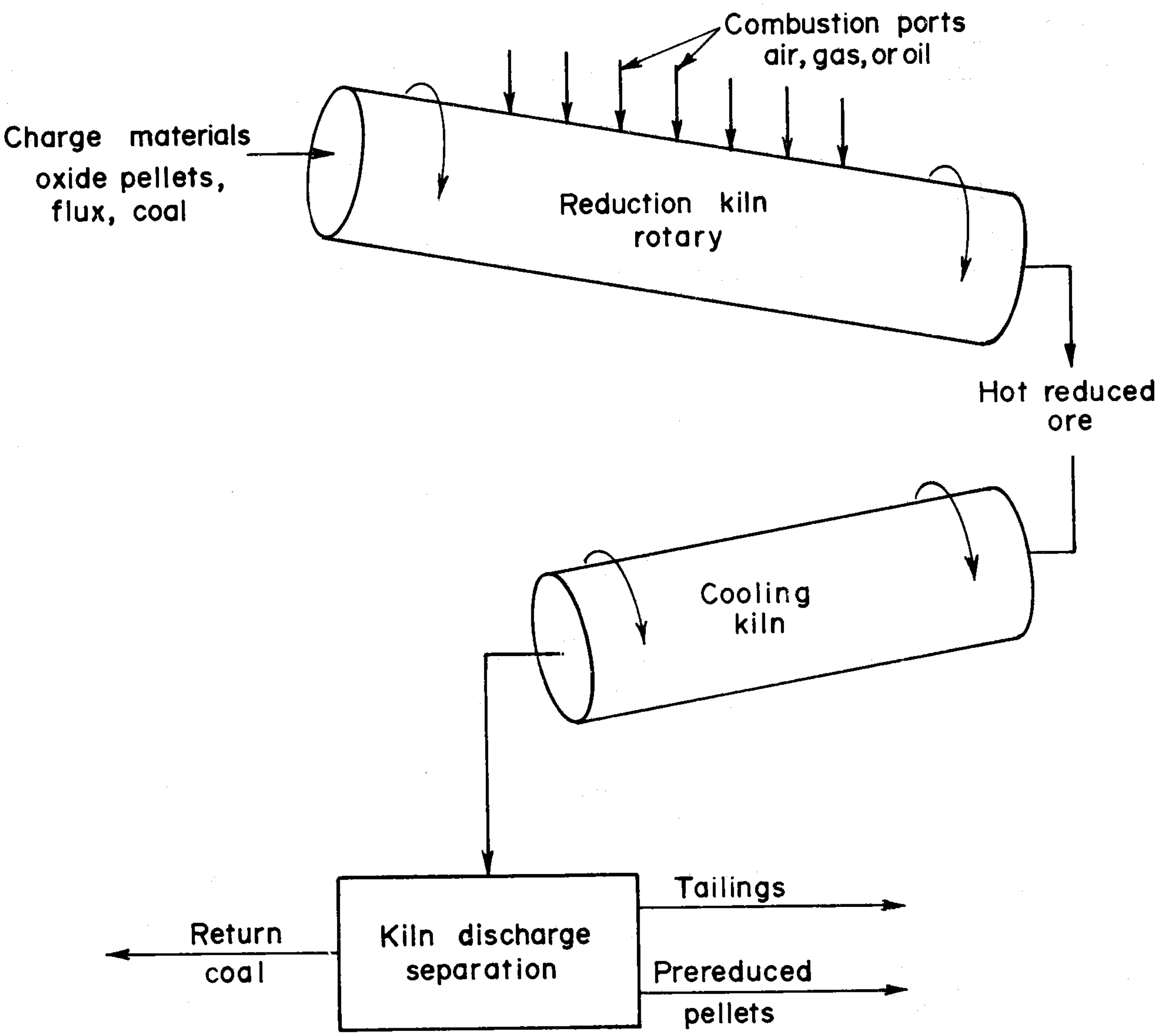

FIGURE A-1. - Schematic of SL/RN process.

reductant-fuel substitution is foreseen, quite analogous to the trend toward multifuel capabilities in modern electric utility power generating stations.

The kiln operation is unique. The kiln wall is pierced by many small burner ports in a grid pattern. Along the length of the kiln the ports in one line are manifolded. Fuel gas, such as natural gas, is injected when the kiln's rotation carries that line of ports beneath the bed. The flow of fuel gas from the ports creates a strongly reducing atmosphere within the bed. In the course of kiln rotation the line of ports emerges from beneath the bed, whereupon the flow of fuel is shut off. In further rotation above the bed the line of ports is used to inject air; this stream mixes with and ignites unreacted reducing gases rising from the bed, thus developing the sensible heat required.

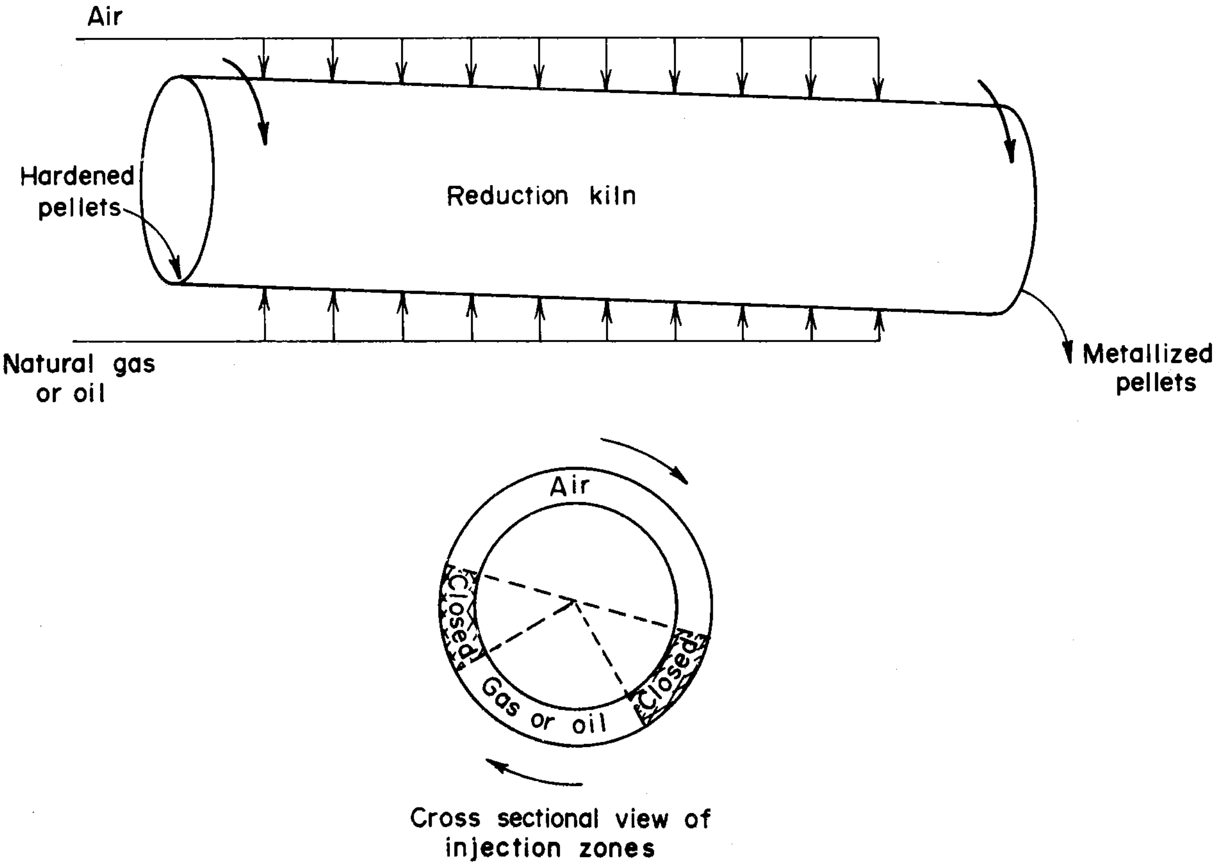

FIGURE A-2. - Schematic of Allis-Chalmers rotary reduction kiln.

In 1971 the process was redeveloped to permit the use of fuel oil as a complete substitute for natural gas and to accomplish the changeover without interrupting kiln operations. Along with fluid fuels, the process also can use solid fuel and flux as needed. Any sulfur-bearing material, whether coal or fuel oil, may require that flux be charged also.

Fuel consumption is reported to be 16 million Btu per net ton of metallized iron at the pilot plant scale. In a commercial plant the manufacturer anticipates about 14.5 million Btu per net ton using natural gas, somewhat less using oil. If pelletizing incorporated 10 percent coal, the added process heat required is calculated to be less than 12 million Btu per net ton of metallized iron.

The Allis-Chalmers reduction kiln been used to desulfurize pellets; it is also said to be able to handle fluxed pellets.

Shaft Kiln

A shaft kiln is a vertical refractory-lined cylinder in which a column of solids is maintained, and through which a stream of reaction gas is forced. As applied to iron ore reduction, the shaft is filled from the top with the charge of iron ore minerals. After reduction the metallized product is discharged from the bottom. The stream of hot reducing gas (generated and heated elsewhere) enters at one end, flows through the stock column, reacting and exchanging heat, and is discharged from the opposite end. There are two major classifications of feeding and discharge: continuous and batch. The modes of generating and heating reducing gas are numerous, the choice depending on fuel availability and needs in the specific plant.

Shaft kiln processes are limited in kiln cross section by the necessity of obtaining efficient distribution of the reducing gas into the center of the stock column. Furnace height is limited by the strength of the ore particles (or pellets) and a declining rate of increase in reduction efficiency as the column becomes extended.

Continuous shaft kilns maintain a full stock column and discharge the product continuously, or at such frequent intervals that most of the stock column is maintained. Charging is essentially continuous. Heating and reduction takes place over a vertical distance in the bed. The continuous process moves the feedstock through this reaction gradient at the rate needed for completion of reduction; the speed is regulated by the rate of product discharge.

Batch kilns are loaded, reacted, and emptied. The reaction gradient moves through the bed and the material at the far end of the bed may not become completely reduced in the time cycle allowed. The deeper the bed the greater the completion of heat transfer and reduction accomplished.

Interest in the United States has been focused on continuous shaft kilns. They have an advantage over batch kilns in uniformity of product. Continuous kilns also are labor saving.

Continuous Shaft Kilns

The continuous-type of process is represented by the Midrex and Armco processes in the United States, and the Purofer process in West Germany. All three utilize hot reformed natural gas to supply heat and reductant to the stock column. The major difference is in fuel reforming and recovery. Secondary differences in operating features also exist. Only the Midrex and Armco processes will be described.[4]

Midrex (Figure A-3)

The Midrex process is a development of Midland-Ross Corporation. Three plants are in operation: Portland, Oreg. (1969); Georgetown, S.C. (1970); and Hamburg, West Germany (1970). Two plants are under construction in Canada. The Portland and Georgetown plants are designed for 95 percent metallization (96, 108, 111). The Midrex process utilizes steam-reformed natural gas. Reductant proportions are about 60 percent H_2 and 40 percent CO. Top gas is recycled to the reformer. Details of gas synthesis are proprietary.

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[4] Readers interested in this class of process will find an analysis of process operation and control in the literature pertaining to the Purofer process (111, 113).

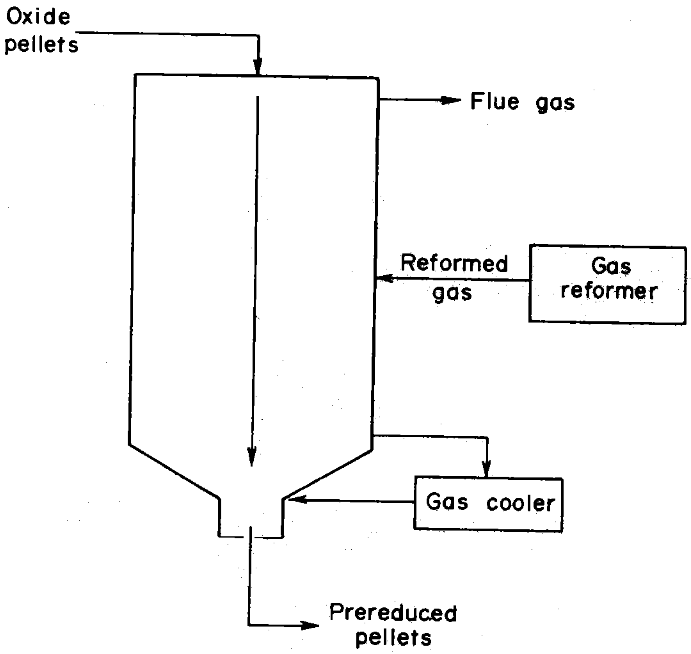

FIGURE A-3. - Midrex continuous vertical shaft kiln process.

At Portland, the plant combines pelletization and reduction. High-grade Peruvian ore (68-69 Fe, 1.5 SiO_2, 0.8 Al_2O_3, 0.02 P, and 0.01 S) is pelletized and indurated, then fed by skip hoist into the top of the reduction furnace. Pellets may be fed hot, direct from induration, or cold, from stockpiles. There are two reduction furnaces, each with its own gas reformer. Energy consumption per net ton of pellet product is about 11.6 million Btu in natural gas and 900 kwhr of electric energy.

The Georgetown plant has one reduction module, double the size of the Portland units. There is no pelletizing facility; the plant consumes Swedish ore pellets (68 Fe, 1.3 SiO_2, 0.8 Al_2O_3, 0.03 P, and 0.01 S). Metallized pellets are discharged continuously at varying rates, up to 50 tons per hour.

Both the Portland and the Georgetown plants are owned and operated by Midrex. Midrex supplies metallized pellets to the adjacent steel plants, Oregon Steel Mills, Inc. and Georgetown Steel Corporation, respectively. Both are types of "mini-mills," specializing in light bar and structural products for primarily regional trade. Both steel plants consume the metallized pellets in electric arc furnaces. The pellets are fed continuously during melting. At Georgetown, metallized pellets can be used to provide about half the charge in the 65-ton arc furnaces, with a resulting power consumption of about 500 kwhr per ton raw steel. Because the metallized pellets are low in tramp element content, they can be used to dilute the residual elements in low-priced steel scrap, such as No. 2 bundles, thus minimizing metallics cost without exceeding tramp element limits.

Reduction operations at Portland experienced difficulties initially from pellet fusion and clustering, resulting in the channeling of reducing gases and nonuniform reduction. To prevent fusion, close temperature control is required. Midrex operations have been successful 50° F below the fusion temperature and they are working toward 25° F below fusion. Chunk breakers have been added--they can be extended from the kiln wall into the bed flow to break up pellet clusters. Variation from day to day in average carbon content of 1.5 percent carbon pellets is ±0.025 percent carbon; for total Fe the variation is ±1 percent at an average 93 percent iron content.

Armco (Figure A-4)

The Armco process is similar to the Midrex process in the reduction operation; they differ in the reducing gas production and recycling. A 1-million-ton-per-year plant is under construction at Armco's Houston, Tex., steelworks. This works has one blast furnace (27 foot hearth diameter), four open hearths (165 tons), and five electric arc furnaces (2--117 tons and 3--175 tons). Direct reduction will augment the iron supply of an already fair-sized steelworks by using inexpensive natural gas instead of expensive coke (39, 73).

Armco will start by using Pea Ridge magnetite concentrate pellets (69 Fe, 1.8 SiO_2, 0.3 Al_2O_3, 0.07 P, and 0.02 S) from Missouri. This is only a temporary source; South American ores are likely to provide the principal supply (ores analyzing 0.7 SiO_2 and 1.4 Al_2O_3 are available). The plant at Houston is accessible to natural gas but any source of H_2 and CO would be satisfactory.

Pilot plant results have shown that operating below 1,600° F results in very little shrinkage in the pellets, but the reaction rate is very slow. At higher temperatures, the reaction speed increases but shrinkage can become severe, depending on the structure of the parent ore. Some ores swell during reduction and break up. The degree of reduction is controlled by varying the

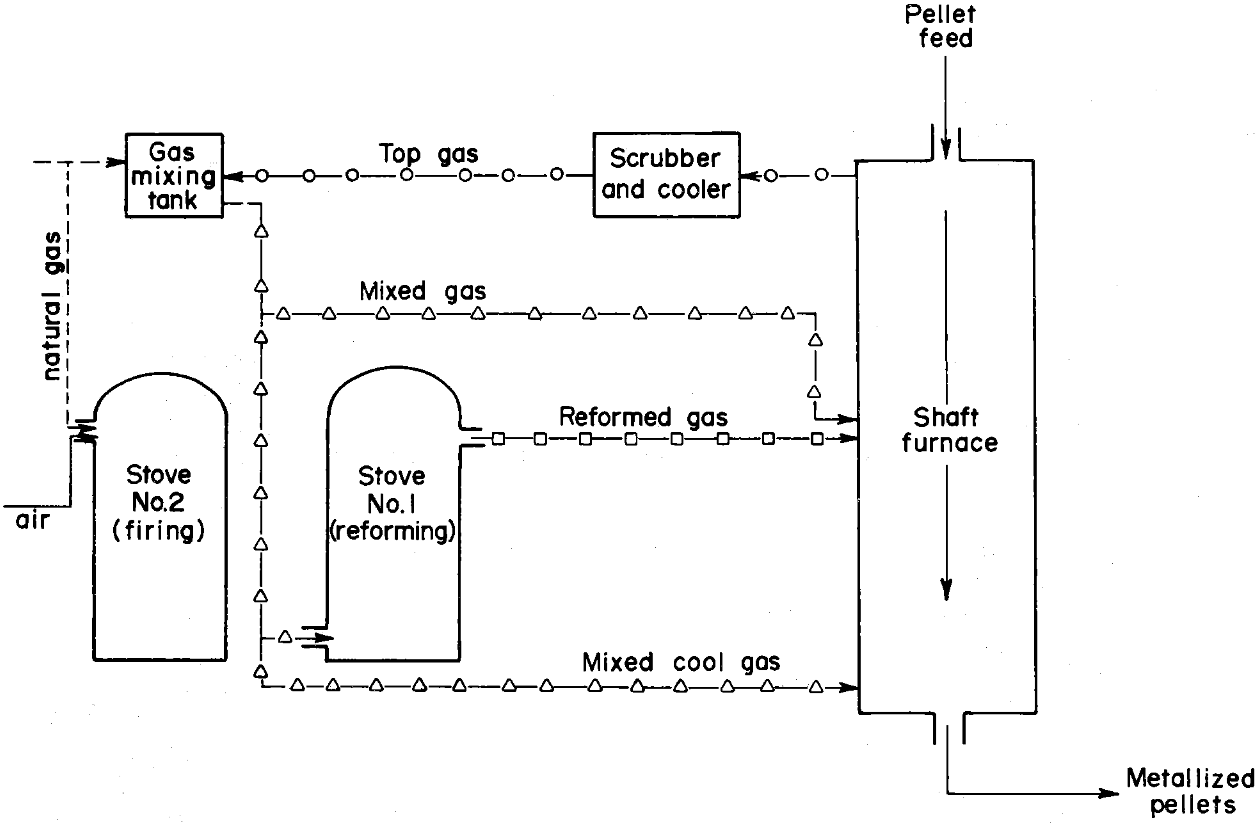

FIGURE A-4. - Armco direct reduction process.

rate of discharge. Highly reduced pellets can be carbonized to any desired carbon content by increasing the residence time in the kiln. The simplest testing for control of reduction is the determination of oxygen content in pellet product. Sticking is always a problem for control. At their best, continuous shaft kilns can produce metallized product at about the same rate per unit area of cross sections as a blast furnace produces molten iron.

The synthesis gas supply for Armco's kiln will be provided by a conventional catalytic steam reforming unit although Armco's process development had featured a unique synthesis gas process based upon reforming mixtures of natural gas and cooled and dried top gas from the continuous shaft kiln in a pebble stove. Two regenerative stoves filled with beds of alumina spheres were required. While the one bed was being heated to temperatures up to 2,800° F, the other was being used to supply heat to the reforming mixture as it flowed through. This method of reforming was highly efficient in minimizing fuel gas requirements; the natural gas consumption per ton of iron in metallized product was projected as 11 million Btu in a full-scale plant. Unfortunately, the supply of suitable alumina pebbles was insufficient to meet the Armco construction schedule, so the firm turned to catalytic steam reforming for the Houston plant. Anticipated fuel consumption is 12.5 million Btu per net ton of iron in metallized product.

Batch Shaft Kiln

The simplest method of gas-solid contacting is the static bed in which solids are held in a fixed position with no relative motion among particles. Gas is forced to flow through the bed between the particles. Since the solids are immobile, there is no appreciable loss due to abrasion. Channeling of gas from nonuniform bed density may represent serious operating problems. Also, difficulty in solids removal and excessive temperature gradients may be troublesome.

HyL (Figure A-5)

The prime example of this type is the HyL process. The initials signify the Mexican steel producing firm which developed it--Hojalata y Lamina, S.A., Monterrey. This process has been operating commercially since 1957. Four plants totaling about 2,000 tons per day are operating in Mexico (72, 78, 84, 90).

The batch charge is subjected to a four-step cycle. For the sake of economy in reducing gas utilization, four kilns are operated and the gas is passed from one to the next. Each kiln operates in a different cycle step. There are three reducing steps; the fourth is for unloading and loading. At the conclusion of the step time period the reducing gas flow is moved one step to the kiln ahead. During the cycle the bed of ore in a kiln is subjected to the following four steps in turn:

1. Initial Reduction: The fresh ore is heated and partially reduced by hot gases from the kiln in the primary reduction stage.

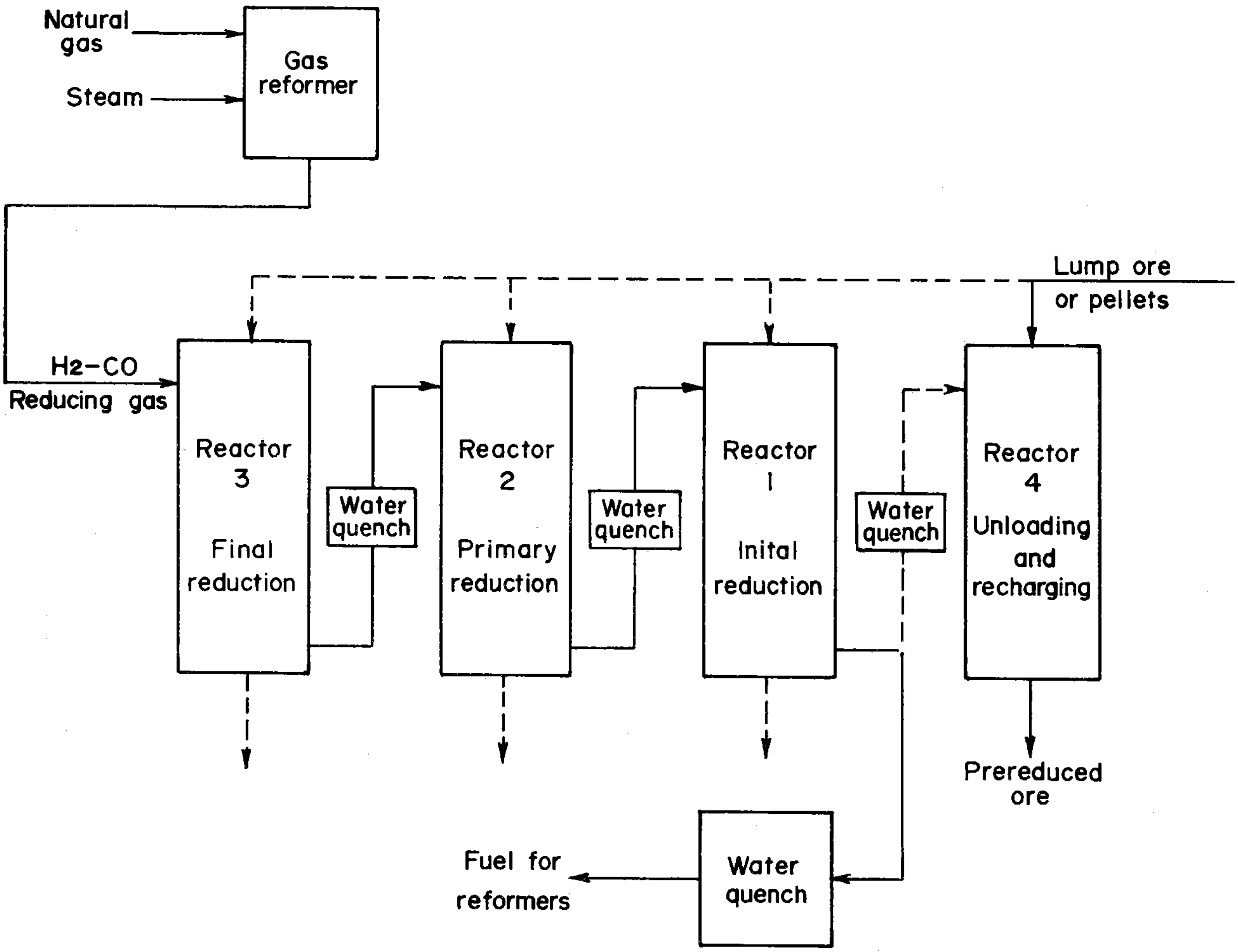

FIGURE A-5. - HyL process.

2. Primary Reduction: Further reduction takes place using hot reducing gas from the kiln in the cooling stage.

3. Cooling: Fresh, cool reformed gas is passed through the bed of reduced iron to complete the reduction and to add carbon to the metallized product.

4. Unloading and Reloading: Cooled reduced iron product is removed through the bottom, then fresh ore is loaded from the top.

For the present plant design each step requires 3 hours, a total cycle time of 12 hours. Reduction temperature may be varied from 1,600° to 1,900° F depending on ore reducibility, but is subject to fusion limits as in the continuous vertical kilns.

Reducing gas is prepared in a single reforming furnace by the catalytic reaction of natural gas and steam. The fresh gas (74 percent H_2 and 13 percent CO) is cooled, then is passed into the top of the kiln which is in the third step. The gas stream passes down the bed, cooling the metallized product and completing the reduction process. The exiting gas is quenched to remove water vapor formed by iron reduction during the step 3 passage. This stream of reducing gas next is heated to a high temperature in an external furnace. The heated stream is directed into the kiln which is in step 2, primary reduction; the bulk of iron reduction occurs in this step. Upon exiting, the stream again is quenched and reheated. The stream then is directed into the kiln in step 1, initial secondary reduction, where the ore is heated and some reduction takes place. The exiting gas is burned to raise steam and supply heat.

The HyL process has been used to reduce sized ore, also pellets; the desired size range is minus 1-1/2 inches, plus 1/4 inch. Metallization of 82 percent has been reported for lump ore and 87 percent in pellets; 90 percent metallization in pellets is expected. Production increased 36 percent using pellets which were 10 percent richer in iron. Natural gas consumption per ton of reduced iron recently averaged 23 million Btu for lump ore and 19 million Btu for pellets.

This process is especially attractive for implementation in developing countries where capital is scarce and labor is ample. It is mechanically simple and easy to maintain. The percentage of metallization is bound to vary from the top to the bottom of the batch because in principle the last element of depth in the bed will become completely reduced only after infinite residence time. The variation that can be tolerated in the product is a practical judgment. If a higher average degree of reduction is required, the residence time in each step will have to be prolonged. In reference to the needs of steelmakers in the United States, there is some doubt that the HyL process as presently constituted can produce the uniformity of product and high degrees of metallization needed (close to 95 percent) to compete against the continuous kiln processes.

Fluidized Bed Reactor

The fluidized bed technique is a widely used method of gas-solids contacting. Fluidization is the conversion of a bed of granular solids into suspension by the kinetic energy of a stream of gas flowing upward through the bed. The bed expands and behaves as a two-phase suspension. The reactors for high temperature applications are refractory lined vertical cylinders.

The two primary reduction processes utilizing the fluid bed reactor are the FIOR and the Nu-Iron processes.

FIOR Process (Figure A-6)

The FIOR Process, developed by Esso Research, uses a fluidized bed to reduce finely ground ore. This technique allows intimate contact with reducing gases producing a uniformly reduced product. The reduced particles are then briqueted while hot (70, 110).

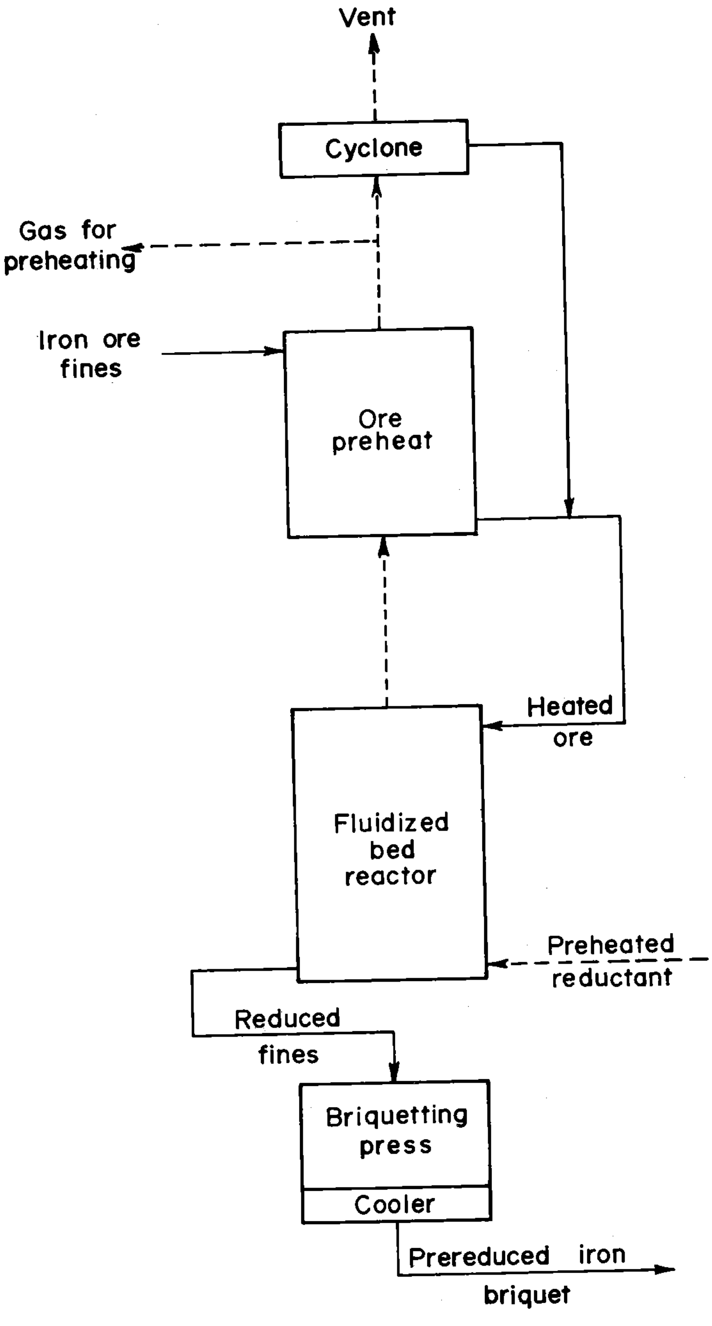

FIGURE A-6. - FIOR process.

Esso Research Laboratories at Baton Rouge, La., constructed a 5-ton-per-day pilot plant which started production in 1962. This facility demonstrated the technical feasibility of the process. A larger pilot plant (300 tons per day of product) was constructed at Dartmouth, Nova Scotia, and was operated in 1965 to obtain the necessary data for further scale-up. Arthur G. McKee Company, Inc. has become the sole licensee. Gross energy requirements are expected to be 15.5 million Btu per net ton of iron product using reformed natural gas or naphtha.

The ore is preheated to 1,500° to 1,600° F by passing a portion of the offgas through the containing vessel. The heated finely ground ore is then reduced to iron during passage thru the fluidized bed reactor. The reductant is produced by the partial combustion of natural gas with air to produce gas containing 41 percent H_2, 21 percent CO, and 38 percent N_2. The FIOR process is capable of operating with gases produced by natural gas, partial oxidation, or the direct use of hydrocarbons (<u>70</u>). The process is best used with hematite ores and achieves 90 to 95 percent metallization. The degree of metallization is controlled directly by the partial pressure of hydrogen in the reducing gas. Published information is scant.

Nu-Iron (Figure A-7)

United States Steel Corporation has been active in direct reduction process research since 1953. Their intention at that time was to develop a process for using the rich Venezuelan ore directly (63 percent iron, compared to 50.5 percent iron in the standard direct-shipping ore of those days). The soft, porous hematite could be concentrated at about 10-mesh size. Hydrogen supply for reduction was plentiful in Venezuelan oil and gas.

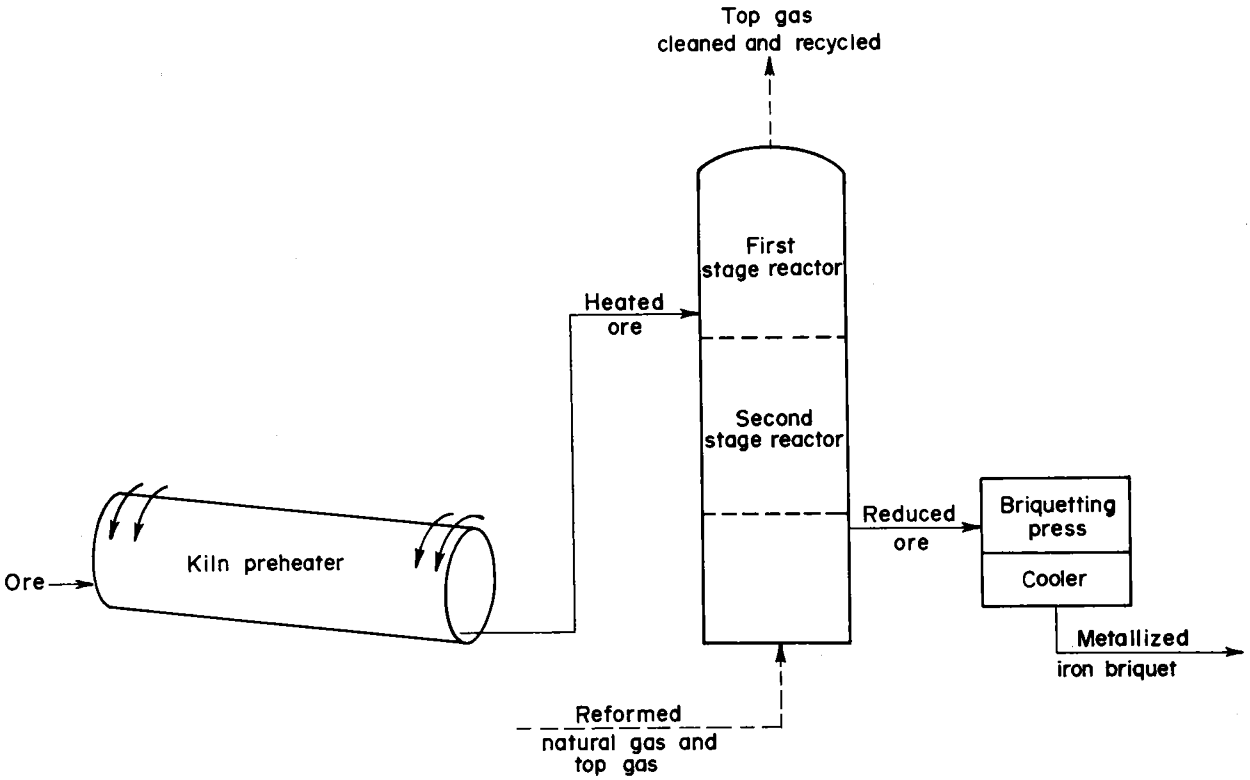

FIGURE A-7. - Nu-Iron process.

The particle size suggested fluidized bed reduction followed by briqueting. A reduction process was developed by 1960, but contemporary advances in blast furnace technology had made direct reduction unattractive. (At that time, too, the markets for steel were depressed.) The resurgence of demand for steel products since 1964 has coincided with a development program for direct reduction that has been carried through the pilot plant stage to the construction of a 1-million-ton-per-year plant at Puerto Ordaz, Venezuela. The reduction plant came into operation in 1971; output of briquets was expected in 1972 (79, 101, 111).

The sized ore is preheated to 1,700° F in a rotary kiln. It is then charged into the top of the first reactor where the ore is fluidized by an ascending stream of partially spent reducing gas from the secondary reactor; Fe_2O_3 is reduced to wustite at 1,300° F. The ore is moved by gravity from the upper to the lower reactor, the second stage unit. There an ascending stream of fresh reducing gas completes the reduction from wustite to metal at 1,200° to 1,300° F. The metallized product is discharged hot into briqueting machinery and the product is cooled in an inert atmosphere. The spent reducing gas from the primary reactor is used for fuel.

The Venezuelan plant was designed to produce one million metric tons per year of 75-percent-reduced product, equivalent to 86 percent total iron content in the product. Reducing gas is produced by steam reforming natural gas. Fuel consumption per metric ton of product is about 16 million Btu.

This process is an example of matching advantageously the characteristics of the feedstock and the optimum operating range of the process. The ore particle size is suitable for fluidizing (by comparison, the Great Lakes taconites have to be ground to nearly 400 mesh for concentration, far too fine for fluidization). The porous structure of the Venezuelan hematite offers no constraint to gaseous reduction. (By comparison, magnetites of low porosity are very slow to reduce.) Finally, using the high-hydrogen reducing gas, the wustite-iron reduction can take place efficiently at a comparatively low temperature and still have the exit gas be an efficient reductant for the hematite-wustite reduction in the primary reactor.

APPENDIX B.--DETAILED TABLES

TABLE B-1. - Consumption pattern of iron, 1968

End use	In steels			In irons	Total steels and irons	Per capita consumption, pounds[1]
	Carbon	Alloy	Stainless and heat-resistant			
CONSUMPTION, MILLION SHORT TONS IRON						
Transportation	21.1	2.3	0.2	6.5	30.1	299
Construction products	27.3	2.2	.1	2.4	32.0	318
Machinery and equipment (industry and agriculture)	14.3	1.8	.1	5.2	21.4	213
Containers	7.9	-	-	-	7.9	79
Pipes, tubes, and equipment (oil and gas)	3.2	1.2	.2	1.0	5.6	56
Home appliances and equipment	4.9	0.1	.1	1.0	6.1	61
Other	12.7	.2	.1	3.9	16.9	168
Total	91.4	7.8	.8	20.0	120.0	1,193
DISTRIBUTION OF CONSUMPTION, PERCENT						
Transportation	17.6	1.9	0.2	5.4	25.1	-
Construction products	22.8	1.8	.1	2.0	26.7	-
Machinery and equipment (industry and agriculture)	11.9	1.5	.1	4.3	17.8	-
Containers	6.6	-	-	-	6.6	-
Pipes, tubes, and equipment (oil and gas)	2.7	1.0	.2	0.8	4.7	-
Home appliances and equipment	4.1	0.1	.1	0.8	5.1	-
Other	10.6	.2	.1	3.3	14.1	-
Total	76.2	6.5	.7	16.7	100.0	-

[1] U.S. population July 1, 1968 = 201.152 million.

Source: BuMines Bulletin 650, p. 301 (4).

TABLE B-2. - Population, personal income, and steel mill product consumption and outlays, 1957-70

Year	Population, thousands	Per capital personal disposable income, current dollars	Apparent consumption steel mill products, thousand short tons	Finished steel price composite, Iron Age, cents per pound	Per capita steel mill product consumption and outlays		
					Consumption, pounds	Outlay	
						Amount, dollars	Percent of disposable income
1957.....	171,984	$1,801	75,702	5,800	880	$51	2.8
1958.....	174,882	1,831	58,798	6,060	672	41	2.2
1959.....	177,830	1,905	72,096	6,196	811	50	2.6
1960.....	180,684	1,937	71,531	6,196	792	49	2.5
1961.....	183,756	1,984	67,299	6,196	732	45	2.3
1962.....	186,656	2,066	72,639	6,196	778	48	2.3
1963.....	189,417	2,139	78,777	6,273	832	52	2.4
1964.....	192,120	2,284	87,943	6,368	916	58	2.6
1965.....	194,592	2,436	100,553	6,368	1,033	66	2.7
1966.....	196,920	2,605	99,024	6,399	1,006	64	2.5
1967.....	199,114	2,751	93,667	6,464	941	61	2.2
1968.....	201,152	2,946	107,646	6,600	1,070	71	2.4
1969.....	203,216	3,130	102,682	7,091	1,011	72	2.3
1970.....	205,395	3,358	97,109	7,650	946	72	2.2
Average:							
1957-61	-	1,893	-	-	777	47	2.5
1966-70	-	2,954	-	-	995	68	2.3

Sources: Column 1: (5), p. 219.
Column 2: (5), p. 213.
Column 3: (1).
Column 4: (3).
Column 5: column 3 ÷ column 1 x 2,000.
Column 6: column 5 x column 4 ÷ 100.
Column 7: column 6 ÷ column 2 x 100.

TABLE B-3. - Primary iron and steel product shipments, 1964-70

(Thousand short tons)

Year	Steel mill products		Iron and steel foundries						Total castings and mill products	
			Gray iron		Malleable		Steel			
	Quantity	Percent	Quantity	Percent	Quantity	Percent	Quantity	Percent	Quantity	Percent
1964......	84,945	83.2	14,316	14.0	1,001	1.0	1,835	1.8	102,097	100.0
1965......	92,666	83.1	15,713	14.1	1,136	1.0	1,961	1.8	111,476	100.0
1966......	89,995	82.6	15,716	14.4	1,133	1.0	2,155	2.0	108,999	100.0
1967......	83,897	83.0	14,329	14.2	1,041	1.0	1,857	1.8	101,124	100.0
1968......	91,856	83.0	15,971	14.4	1,102	1.0	1,731	1.6	110,660	100.0
1969......	93,877	83.2	15,923	14.1	1,172	1.0	1,897	1.7	112,869	100.0
1970......	90,798	84.6	13,946	13.0	852	.8	1,726	1.6	107,322	100.0

Source: Survey of Current Business (10).

TABLE B-4. - Raw steel production in the United States economy, 1960-70

(Thousand short tons)

Year	Production of raw steel				Raw steel in U.S. economy		
	World	United States			Imported equivalent[2]	Total U.S. + imported	
		Amount	Percent of world	Percent yield[1]		Amount	Percent of world
1960......	381,582	99,282	26.0	71.7	4,685	103,967	27.3
1961......	390,062	98,014	25.1	67.5	4,686	102,700	26.3
1962......	394,056	98,328	25.0	71.8	5,710	104,038	26.4
1963......	422,239	109,261	25.9	69.2	7,870	117,131	27.7
1964......	479,025	127,076	26.5	66.9	9,626	136,702	28.5
1965......	503,083	131,462	26.1	70.5	14,728	146,190	29.1
1966......	519,124	134,101	25.8	67.1	16,025	150,126	28.9
1967......	547,600	127,213	23.2	66.0	17,356	144,569	26.4
1968......	582,548	131,462	22.6	69.9	25,694	157,156	27.0
1969......	632,010	141,262	22.4	66.5	21,104	162,366	25.7
1970......	652,735	131,514	20.1	[3]67.7	19,740	151,254	23.2

[1] Percent yield is the ratio of annual net shipments to raw steel production without allowance for inventory changes. Shipments are listed in table B-5.

[2] Imported equivalent is an estimate of the amount of raw steel represented by imported steel products assuming the same yield of shipped product from raw steel as was experienced in that year by the steel industry in the United States.

[3] Yield in 1970 calculated from shipments adjusted to conform to basis in 1969 and earlier years. See footnote to table B-5 for adjustment.

Sources: AISI (1) and Bureau of Mines Minerals Yearbook.

TABLE B-5. - Steel product shipments to U.S. consumers, 1960-70

Year	Apparent supply	From U.S. mills		Plus imports	Net imports
		Total shipments	Less exports		
	SHIPMENTS, THOUSAND SHORT TONS				
1960..........	71,531	71,149	2,977	3,359	382
1961..........	67,299	66,126	1,990	3,163	1,173
1962..........	72,639	70,552	2,013	4,100	2,087
1963..........	78,777	75,555	2,224	5,446	3,222
1964..........	87,943	84,945	3,442	6,440	2,998
1965..........	100,553	92,666	2,496	10,383	7,887
1966..........	99,024	89,995	1,724	10,753	9,029
1967..........	93,667	83,897	1,685	11,455	9,770
1968..........	107,646	91,856	2,170	17,960	15,790
1969..........	102,682	93,877	5,229	14,034	8,805
1970..........	97,109	[1]90,798	7,053	13,364	6,311
	DISTRIBUTION OF SHIPMENTS, PERCENT				
1960..........	100.0	99.5	-4.2	4.7	0.5
1961..........	100.0	98.3	-3.0	4.7	1.7
1962..........	100.0	97.1	-2.8	5.6	2.9
1963..........	100.0	95.9	-2.8	6.9	4.1
1964..........	100.0	96.6	-3.9	7.3	3.4
1965..........	100.0	92.2	-2.5	10.3	7.8
1966..........	100.0	90.9	-1.7	10.9	9.1
1967..........	100.0	89.6	-1.8	12.2	10.4
1968..........	100.0	85.3	-2.0	16.7	14.7
1969..........	100.0	91.4	-5.1	13.7	8.6
1970..........	100.0	93.5	-7.3	13.8	6.5

[1] Shipments for 1970 are not strictly comparable with those of previous years. Beginning that year the shipments statistics compiled by AISI include estimates for a relatively small number of companies which report raw steel production but not shipments to AISI. These companies shipped an estimated 1.8 million tons of steel mill products in 1970.

Source: AISI (1).

TABLE B-6. - Pig iron and steel production in steel plants, 1964-70

(Thousand short tons)

Year	Pig iron		Raw steel, by method			
	Total	Used in steel plants	Total[1]	Open hearth	BOF process	Electric furnaces
1964............	85,601	82,404	127,076	98,956	15,442	12,678
1965............	88,185	84,470	131,462	94,779	22,879	13,804
1966............	91,500	86,955	134,101	85,303	33,928	14,870
1967............	86,984	83,357	127,213	70,690	41,434	15,089
1968............	88,780	85,610	131,462	65,836	48,812	16,814
1969............	95,017	91,279	141,262	60,894	60,236	20,132
1970............	91,435	87,021	131,514	48,022	63,330	20,162

[1] Bessemer included with open hearth.

Source: AISI (1).

TABLE B-7. - Distribution of raw steel production, 1964-70

(Percent)

Year	Open hearth	BOF process	Electric furnaces
1964....................	77.8	12.2	10.0
1965....................	72.1	17.4	10.5
1966....................	63.6	25.3	11.1
1967....................	55.6	32.6	11.8
1968....................	50.1	37.1	12.8
1969....................	43.1	42.6	14.3
1970....................	36.5	48.2	15.3

TABLE B-8. - Consumption of pig iron and purchased iron and steel scrap in the iron and steel industry, 1964-70

(Thousand short tons)

Year	Pig iron	Iron and steel scrap			Total pig iron and purchased scrap	
		Total consumption	Home scrap production	Apparent purchased scrap consumption	Quantity	Percent pig iron
1964..........	86,382	84,012	52,262	31,750	118,132	73.1
1965..........	88,945	89,655	55,213	34,442	123,387	72.1
1966..........	91,770	90,849	55,463	35,386	127,156	72.2
1967..........	87,371	84,728	53,312	32,416	119,787	72.9
1968..........	89,953	87,060	53,545	33,515	123,468	72.9
1969..........	94,635	94,308	56,287	38,021	132,656	71.3
1970..........	90,126	85,559	52,575	32,984	123,110	73.2

Source: Bureau of Mines Minerals Yearbook.

TABLE B-9. - Consumption of pig iron and iron and steel scrap in iron and steel furnaces, 1964-70

(Thousand short tons)

Year	Pig iron			Iron and steel scrap				Total pig iron and scrap	Percent pig iron
	Steel furnaces	Iron furnaces	Total	Steel furnaces	Iron furnaces	Blast furnaces	Total		
1964...........	78,925	3,874	82,799	64,348	14,848	4,816	84,012	166,811	49.6
1965...........	81,040	3,930	84,970	68,272	16,329	5,054	89,655	174,625	48.7
1966...........	83,947	3,834	87,781	68,778	16,845	5,226	90,849	178,630	49.1
1967...........	80,404	3,309	83,713	65,027	14,977	4,724	84,728	168,441	49.6
1968...........	79,948	3,182	83,130	67,281	15,512	4,267	87,060	170,190	48.8
1969...........	84,187	3,003	87,190	74,341	15,188	4,779	94,308	181,498	48.0
1970...........	81,118	2,180	83,298	66,451	13,806	5,302	85,559	168,857	49.3

Source: Bureau of Mines Minerals Yearbook.

TABLE B-10. - Pig iron proportion used in furnaces, 1964-70

(Percent)

Type of furnace	1964	1965	1966	1967	1968	1969	1970
Basic oxygen converter........	69.4	70.4	71.0	70.7	70.9	70.1	69.9
Open-hearth..................	59.8	58.4	58.5	58.4	56.0	54.9	58.6
Electric.....................	2.1	2.3	1.6	2.1	2.6	1.4	1.9
Cupola.......................	21.6	20.3	19.4	18.6	16.4	16.3	13.8

Source: Bureau of Mines Minerals Yearbook.

TABLE B-11. - Consumption of pig iron and scrap related to product shipments, 1964-70

Year	Metallics consumed, thousand short tons		Percent pig iron	Unit consumption of metallics, tons per short ton shipments		
	Pig iron	Scrap		Pig iron	Scrap	Total
BLAST FURNACES AND STEEL MILLS						
1964	79,090	22,497	77.8	0.931	0.265	1.196
1965	81,172	24,440	76.8	.876	.264	1.140
1966	84,060	24,956	77.1	.934	.277	1.211
1967	80,457	22,868	77.8	.959	.273	1.232
1968	80,248	23,387	77.4	.874	.255	1.129
1969	84,178	27,384	75.4	.897	.292	1.189
1970	81,047	22,929	78.0	.893	.253	1.145
IRON FOUNDRIES						
1964	4,161	13,684	23.3	.272	.893	1.165
1965	4,418	15,017	22.7	.262	.891	1.153
1966	4,380	15,710	21.8	.260	.932	1.192
1967	3,763	14,608	20.5	.245	.950	1.195
1968	3,550	13,876	20.4	.220	.858	1.077
1969	3,761	14,670	20.4	.220	.858	1.078
1970	3,078	12,927	19.2	.208	.874	1.082
STEEL FOUNDRIES						
1964	192	2,031	8.7	0.105	1.107	1.212
1965	188	2,212	7.8	.096	1.128	1.224
1966	185	2,256	7.6	.086	1.047	1.133
1967	164	2,001	7.5	.088	1.078	1.166
1968	131	1,832	6.7	.076	1.058	1.134
1969	113	2,126	5.1	.060	1.121	1.181
1970	98	2,078	4.5	.057	1.204	1.261

Sources: Bureau of Mines Minerals Yearbook and Survey of Current Business (10).

TABLE B-12 - Distribution of iron consumption among furnaces by type of consumer, 1964-70, percent

Year	OH	BOP	Bessemer	Electric	Cupola	Air	Blast	Direct casting	Other[1]
MANUFACTURERS OF STEEL INGOTS AND CASTINGS									
1964...........	72.5	12.0	0.7	8.5	1.0	0.04	3.2	2.0	0.04
1965...........	67.0	16.9	.4	9.2	1.2	.04	3.2	2.0	.04
1966...........	59.1	24.6	.2	9.6	1.1	.04	3.3	2.0	.03
1967...........	52.3	31.5	.1	10.1	.8	.04	3.1	2.0	.01
1968...........	45.6	35.4	(2)	10.7	1.3	(2)	2.7	3.9	.4
1969...........	40.4	39.6	-	11.8	1.2	.02	2.9	3.9	.2
1970...........	34.2	45.0	-	12.2	1.2	.03	3.4	3.8	.3
IRON FOUNDRIES AND MISCELLANEOUS USERS									
1964...........	-	-	0.4	1.4	84.5	7.1	-	3.6	[3]3.1
1965...........	-	-	.2	1.5	83.8	7.1	-	4.1	[3]3.2
1966...........	-	-	.4	1.8	83.3	7.0	-	4.2	[3]3.4
1967...........	-	-	.2	4.0	83.0	5.8	-	3.6	[3]3.4
1968...........	-	-	(2)	7.5	85.8	(2)	-	4.5	2.2
1969...........	-	-	-	9.9	83.5	1.0	-	4.6	0.9
1970...........	-	-	-	11.9	79.8	1.4		5.7	1.2
MANUFACTURERS OF STEEL CASTINGS									
1964...........	22.7	-	0.3	60.0	9.6	7.4	-	-	-
1965...........	21.1	-	.13	63.2	9.0	6.7	-	-	-
1966...........	19.6	-	.12	64.0	9.7	6.6	-	-	-
1967...........	18.8	-	.14	66.1	12.1	2.9	-	-	-
1968...........	18.1	-	(2)	63.8	15.5	(2)	-	0.1	2.5
1969...........	14.6	-	-	72.6	10.7	2.0	-	-	0.03
1970...........	12.9	-	-	75.4	10.1	1.6		-	-

[1] Includes vacuum melting and miscellaneous melting processes.
[2] Included in "Other".
[3] Includes ferroalloy furnaces (about 2.7 percent).

Source: Bureau of Mines Minerals Yearbook.

TABLE B-13. - U.S. foreign trade in iron ore and agglomerates and iron and steel scrap, 1964-70

(Thousand short tons and million dollars)

Year	Exports		Imports for consumption		Trade balance	
	Quantity	Value	Quantity	Value	Quantity	Value
			IRON ORES AND AGGLOMERATES			
1964..........	7,799	$79.7	47,497	$421.3	-39,698	-$341.7
1965..........	7,935	80.4	50,515	443.8	-42,580	-363.4
1966..........	8,712	92.2	51,810	462.4	-43,098	-370.2
1967..........	6,615	71.6	49,964	443.9	-43,349	-372.3
1968..........	6,590	70.8	49,214	453.8	-42,624	-382.9
1969..........	5,779	62.3	45,649	402.5	-39,870	-340.2
1970..........	6,151	67.9	50,261	479.4	-44,110	-411.5
			IRON AND STEEL SCRAP			
1964..........	7,898	243.3	282	8.3	7,616	235.1
1965..........	6,249	199.7	212	7.5	6,037	192.3
1966..........	5,857	177.0	406	8.2	5,451	168.7
1967..........	7,635	250.9	230	8.6	7,405	242.4
1968..........	6,571	200.7	294	11.3	6,277	189.4
1969..........	9,177	302.7	335	13.5	8,842	289.2
1970..........	10,364	447.4	301	11.2	10,063	436.2

Source: Bureau of Mines Minerals Yearbook.

TABLE B-14. - Analysis of shipments of ores, 1964 and 1970

Type	Year	Percent of shipments	Content, weight percent[1]				
			Iron	Phosphorus	Silica	Alumina	Moisture
U.S. combined areas:							
Ores not treated....	1964	22.3	51.8	0.157	7.2	2.0	10.4
	1970	7.7	51.6	.143	7.8	1.6	10.2
Treated ores........	1964	37.3	54.6	.074	8.1	1.1	5.7
	1970	28.2	54.3	.080	8.9	1.2	6.8
Agglomerates........	1964	40.4	62.2	.030	7.3	.7	1.9
	1970	64.1	62.6	.025	6.6	.6	2.2
Total............	1964	[2]92.2	57.1	.075	7.6	1.1	5.2
	1970	[2]97.9	59.4	.050	7.3	.9	4.1
Canada combined areas:							
Ores not treated....	1964	31.0	54.1	.059	7.6	.9	8.1
	1970	15.9	54.1	.058	8.8	1.3	8.7
Treated ores........	1964	40.9	62.0	.016	5.8	.6	2.8
	1970	28.2	63.2	.021	4.8	.7	3.3
Agglomerates........	1964	28.1	62.1	.006	5.6	.7	1.0
	1970	55.9	63.4	.009	5.1	.5	1.3
Total............	1964	[2]38.6	59.6	.026	6.3	.7	3.9
	1970	[2]53.6	61.8	.020	5.6	.7	3.1

[1] Iron and moisture on natural basis; others on dried basis.

[2] Total amount, million short tons.

Source: American Iron Ore Association (2).

TABLE B-15. - U.S. consumption of iron ores and agglomerates, 1964 and 1970

Source, nation and district	1964		1970	
	Million short tons	Percent of total	Million short tons	Percent of total
United States:				
Great Lakes...........	69.7	51.0	73.4	53.0
Other.................	18.5	14.0	17.1	12.0
Total..............	88.2	64.0	90.5	66.0
Canada:				
Great Lakes...........	5.9	4.0	4.7	3.0
Eastern and other.....	18.6	14.0	20.2	15.0
Total..............	24.5	18.0	24.9	18.0
Other foreign..........	24.2	18.0	22.7	16.0
Total..............	136.9	100.0	138.1	100.0

Source: American Iron Ore Association (2).

TABLE B-16. - Iron ore and agglomerates consumption in the steel industry, 1964-70

(Thousand short tons)

Year	Smelting pig iron				Steelmaking[1]			
	Ores		Agglomerates	Total[2]	Ores	Pellets	Sinter and others[3]	Total
	Iron	Manganese						
1964......	50,765	51	85,486	131,085	8,204	867	552	9,263
1965......	49,887	112	88,437	133,470	6,703	706	660	8,069
1966......	47,962	91	97,163	140,572	5,551	650	539	6,740
1967......	42,390	133	96,875	135,649	4,152	604	384	5,140
1968......	43,708	94	102,417	142,789	3,866	679	391	4,936
1969......	42,550	106	109,914	148,864	3,041	632	359	4,032
1970......	38,186	103	109,003	143,859	2,879	578	339	3,796

[1] Ores from Minerals Yearbook; agglomerates from AISI. Used mixed sources to include aggregate details.

[2] Ores and agglomerates consumed less flue dust and sludge recovered.

[3] Includes briquets, nodules, and other forms.

Sources: AISI (1) and Bureau of Mines Minerals Yearbook (ore consumed in steel).

TABLE B-17. - Bituminous coal consumption in iron and steel, 1964-70

(Thousand short tons)

Year	In coke production			Other purposes	Total	Percent of U.S. consumption
	Oven	Beehive	Total			
1964.....	86,732	2,025	88,757	7,394	96,151	22.3
1965.....	92,086	2,693	94,779	7,466	102,245	22.2
1966.....	93,523	2,369	95,892	7,117	103,009	21.2
1967.....	90,900	1,372	92,272	6,330	98,602	20.5
1968.....	89,497	1,268	90,765	5,657	96,422	19.3
1969.....	91,743	1,158	92,901	5,560	98,461	19.4
1970.....	94,581	1,428	96,009	5,410	101,419	19.6

Source: Bureau of Mines Minerals Yearbook.

TABLE B-18. - Pennsylvania anthracite consumption in iron and steel, 1964-70

(Thousand short tons)

Year	Coke making	Agglomeration plants	Total	Percent of apparent U.S. consumption
1964.................	492	1,014	1,506	10.5
1965.................	507	966	1,473	11.4
1966.................	515	897	1,412	12.4
1967.................	528	819	1,347	12.5
1968.................	532	748	1,280	12.6
1969.................	543	623	1,166	13.2
1970.................	472	464	936	11.3

Source: Bureau of Mines Minerals Yearbook.

TABLE B-19. - Coal consumption in steel plants, 1964-70

(Thousand short tons)

Year	In production of		Other purposes	Total
	Coke	Steam[1]		
1964..................	78,698	6,329	715	85,743
1965..................	83,930	6,688	684	91,302
1966..................	85,520	6,632	760	92,911
1967..................	82,698	6,098	781	89,577
1968..................	81,245	6,106	669	88,021
1969..................	84,065	5,362	531	89,958
1970..................	87,209	4,751	319	92,278

[1] Includes coal consumed in generating electric power.

Source: AISI (1).

TABLE B-20. - Coke and coke breeze consumption in iron and steel, 1964-70

(Thousand short tons)

Year	Coke				Coke breeze			
	Blast furnaces	Foundries	Other uses	Total	For steam	Agglomerating plants	Other uses	Total
1964........	56,920	2,963	677	60,560	632	1,764	434	2,830
1965........	59,870	3,183	610	63,663	642	1,744	427	2,813
1966........	60,937	3,244	405	64,586	644	1,873	505	3,022
1967........	56,911	3,060	363	60,334	594	1,695	517	2,806
1968........	56,406	3,166	591	60,163	508	1,634	589	2,731
1969........	60,869	3,326	482	64,677	439	1,650	775	2,864
1970........	61,043	3,136	361	64,540	366	1,948	704	3,018

Source: Bureau of Mines Minerals Yearbook.

TABLE B-21. - Coke consumption in steel plants, 1964-70

(Thousand short tons)

Year	In blast furnaces			In foundries	Other	Total
	Pig iron	Ferro-alloys	Total			
1964..........	56,065	999	57,063	31	464	57,558
1965..........	57,880	1,169	59,049	25	422	59,496
1966..........	58,620	1,017	59,637	21	269	59,926
1967..........	54,917	1,067	55,984	14	216	56,214
1968..........	55,378	860	56,238	15	179	56,431
1969..........	59,921	655	60,176	14	235	60,424
1970..........	57,597	554	58,151	23	188	58,362

Source: AISI (1).

Table B-22. - Natural gas consumption in steel plants, 1964-70

(Million cubic feet, based on 1,000 Btu per cubic foot)

Year	Blast furnace area		Steel melting furnaces	Other	Total
	Blast furnaces	Other uses			
1964..................	38,796	8,902	108,540	356,867	513,105
1965..................	46,636	5,709	105,571	389,160	547,076
1966..................	51,510	6,145	96,002	363,468	517,125
1967..................	44,255	5,766	85,932	398,508	534,461
1968..................	46,507	5,995	102,159	432,189	586,850
1969..................	44,355	7,247	92,446	490,472	634,520
1970..................	44,474	10,262	57,797	480,983	593,516

Source: AISI (1).

TABLE B-23. - Fuel oil consumption in steel plants, 1964-70

(Thousand gallons)

Year	Blast furnace area		Steel melting furnaces	Other	Total
	Blast furnaces	Other uses			
1964..................	46,189	13,752	1,008,296	610,256	1,678,493
1965..................	53,131	12,333	889,580	655,460	1,610,504
1966..................	53,247	[1]21,053	721,661	655,010	1,450,971
1967..................	67,225	14,011	567,663	605,089	1,253,988
1968..................	80,778	[1]15,757	549,585	637,700	1,283,820
1969..................	116,770	[1]17,091	504,673	599,462	1,237,996
1970..................	146,031	[1]19,801	416,822	652,799	1,235,453

[1] Includes coke oven underfiring.

Source: AISI (1).

TABLE B-24. - Coke oven gas consumption in steel plants, 1964-70

(Million cubic feet, based on 500 Btu per cubic foot)

Year	Blast furnace area		Steel melting furnaces	Other	Total
	Blast furnaces	Other uses			
1964................	8,458	14,648	76,335	616,793	716,234
1965................	11,233	18,022	71,864	686,976	788,095
1966................	7,529	[1]252,602	55,042	599,718	[1]914,891
1967................	13,433	[1]276,923	32,762	563,110	[1]886,228
1968................	12,118	[1]265,568	32,800	570,588	[1]881,074
1969................	11,021	[1]295,660	29,946	579,014	[1]915,641
1970................	9,177	[1]319,628	22,056	577,075	[1]927,936

[1] Includes coke oven underfiring: 225,119 in 1966; 237,541 in 1967; 231,922 in 1968; 254,991 in 1969; and 274,603 in 1970.

Source: AISI (1).

TABLE B-25. - Tar and pitch consumption in steel plants, 1964-70

(Thousand gallons)

Year	Blast furnace area		Steel melting furnaces	Other	Total
	Blast furnaces	Other uses			
1964..............	(1)	(1)	280,833	14,289	295,122
1965..............	(1)	(1)	317,963	15,837	333,800
1966..............	(1)	(1)	298,958	16,520	315,478
1967..............	20,936	(1)	248,222	33,741	302,899
1968..............	22,906	1,874	218,089	19,895	262,764
1969..............	43,351	(1)	205,548	15,311	264,210
1970..............	42,500	(1)	176,902	41,503	260,905

[1] Included with "Other".

Source: AISI (1).

TABLE B-26. - Blast furnace gas consumption in steel plants, 1966-70

(Billion cubic feet, based on 95 Btu per cubic foot)

Year	Blast furnace area		Steel melting furnaces	Other	Total
	Blast furnaces	Other uses			
1966..............	1,330	[1]1,087	12	1,648	4,076
1967..............	1,440	[1]1,291	(2)	1,440	4,131
1968..............	1,542	[1]1,306	(2)	1,605	4,454
1969..............	1,734	[1]1,320	(2)	1,704	4,757
1970..............	1,592	[1]1,247	(2)	1,684	4,523

[1] Includes coke oven underfiring.
[2] Included with "Other".

Source: AISI (1).

TABLE B-27. - Electric power consumption in steel industry, 1964-70

(Million kilowatt-hours)

Year	Generated	Purchased	Total consumption		Estimated consumption in steelmaking[1]	
			Quantity	Related to steel shipments, kwhr per short ton shipments	Quantity	Related to raw steel production, kwhr per short ton raw steel
1964.......	12,816	26,049	38,865	458	8,683	68
1965.......	12,151	28,006	40,157	433	9,335	71
1966.......	12,096	29,891	41,987	467	9,964	74
1967.......	11,954	30,557	42,511	507	10,186	80
1968.......	12,865	33,470	46,155	502	11,157	85
1969.......	11,702	36,691	48,393	515	12,230	87
1970.......	11,749	37,833	49,582	546	12,611	96

[1] A study of the differential change in consumption of purchased electric power in relation to production of arc-melted raw steel revealed that in the 1964-70 period arc-furnace use accounted for one-third of the increase in purchased electric power consumption.

Source: AISI (1).

TABLE B-28. - Limestone consumption in steel plants, 1964-70

(Thousand short tons)

Year	Ironmaking			Steelmaking				Total iron and steel
	Agglomerated products	Blast furnace	Total	Open hearth	BOF process	Electric furnace	Total	
1964......	6,624	17,182	23,805	5,569	90	88	5,746	29,551
1965......	6,661	18,315	24,977	4,990	84	108	5,181	30,158
1966......	7,903	16,909	24,812	4,930	68	121	5,119	29,931
1967......	7,930	14,764	22,693	2,922	363	119	3,404	26,097
1968......	8,513	13,136	21,649	2,626	393	112	3,131	24,779
1969......	8,799	14,630	23,429	2,618	437	125	3,180	26,609
1970......	8,431	14,264	22,695	2,048	438	138	2,624	25,319

Source: AISI (1).

TABLE B-29. - Lime consumption in steel plants, 1964-70

(Thousand short tons)

Year	Steelmaking method			
	Open hearth	BOF process	Electric furnaces	Total
1964	925	1,130	366	2,422
1965	932	1,594	387	2,913
1966	818	2,293	385	3,496
1967	652	2,997	405	4,055
1968	614	3,519	465	4,598
1969	576	4,577	578	5,732
1970	440	4,857	611	5,907

Source: AISI (1).

TABLE B-30. - Fluorspar consumption in steel plants, 1964-70

(Thousand short tons)

Year	Steelmaking method			
	Open hearth	BOF process	Electric furnaces	Total
1964	161	96	48	305
1965	162	139	53	355
1966	150	198	56	405
1967	132	239	51	422
1968	109	307	69	485
1969	109	379	75	563
1970	95	373	87	555

Source: Bureau of Mines Minerals Yearbook.

TABLE B-31. - Oxygen consumption for iron and steelmaking in the steel industry, 1964-70

(Million cubic feet)

Year	Blast furnaces	Steelmaking			
		Total	Open hearth	BOF process	Electric furnaces
1964	8,894	90,626	58,036	30,017	2,573
1965	9,533	104,396	58,897	42,636	2,863
1966	9,041	128,681	62,672	62,855	3,154
1967	8,662	140,466	58,407	78,707	3,352
1968	6,659	151,157	55,147	86,850	9,160
1969	9,078	183,427	58,712	114,175	10,540
1970	13,528	186,169	51,640	120,336	14,193

Source: AISI (1).

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