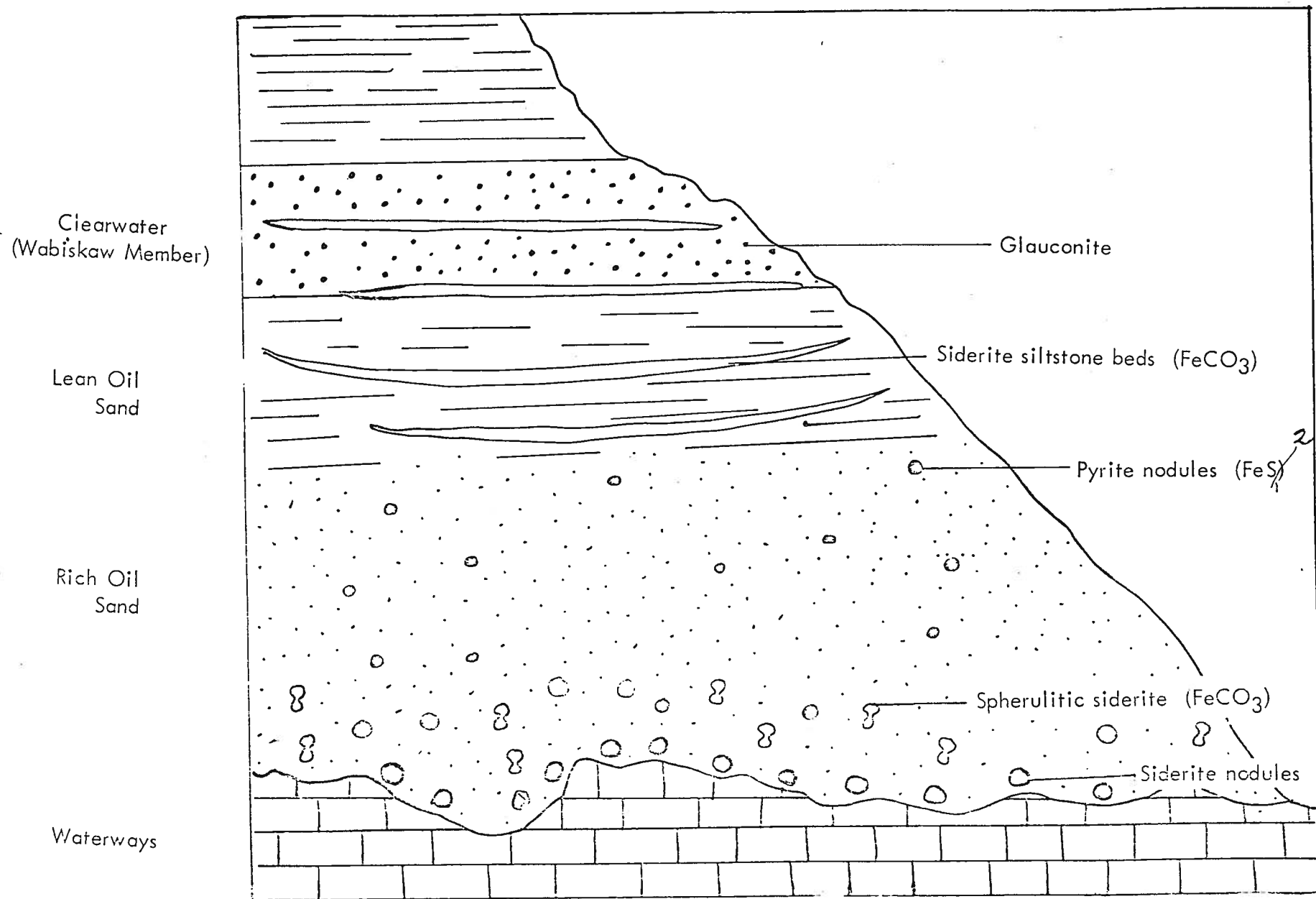


NOTES ON THE OCCURRENCE OF  
IRON-BEARING MINERALS ASSOCIATED  
WITH THE ATHABASCA OIL SANDS

Prepared by  
Geology Division  
Research Council of Alberta  
June, 1973

Alberta  
RESEARCH COUNCIL





IRON IN THE MCMURRAY FORMATION

## IRON-BEARING MINERALS IN THE ATHABASCA OIL SANDS

Iron-bearing minerals are known to occur in the McMurray Formation in the following forms:

1. Large siderite nodules on the unconformity at the base of the McMurray Formation on top of the Waterways limestone. Ellis (1926) made the following comments on this occurrence.

"It is of interest to note that fragments of iron ore have been found at a number of points throughout the McMurray area -- notably on Steepbank and on Ellis rivers. At one point on Steepbank river, approximately 5 miles from the mouth, two small excavations, 40 feet apart, were made in the northeast bank in 1914. In each instance a thin capping of bituminous sand overlies a compacted bed, 1 to 2 feet thick, consisting of fragments of siderite up to 20 pounds in weight. These fragments are not waterworn nor pitted, as would be the case with float that had been transported considerable distances. A bed of clay<sup>1</sup>, 1 to 4 feet thick, underlies the iron ore, and rests upon well-bedded Devonian limestones.

An analysis<sup>2</sup> of a representative sample of the iron ore showed: iron, 35 per cent; insoluble 18 per cent. So far as the writer's observation has gone, the occurrences referred to above, have no economic value. It may be added that clay ironstone, in the form of impure siderite, has a wide distribution, in association with rocks of Cretaceous age, in the western provinces of Canada. In some instances, the deposits appear to be due to the silting out of the fragments of ore, from the softer rocks of the formation. In no instance, however, have beds of economic importance been discovered."

---

<sup>1</sup> Residual clays are found throughout the McMurray area, and are probably derived from certain beds of highly argillaceous limestones. Reference to these clays will be found in "Notes on Clay Deposits of McMurray Area." by S. C. Ellis, Mines Branch Bull. No. 10, 1915.

<sup>2</sup> Analysis by Chemical Laboratories, Mines Branch.

2. Siderite cemented siltstones occur in the upper part of the McMurray Formation and in the Lower Clearwater Formation (Carrigy, 1966). The following notes were extracted from this report.

"Siderite-Cemented Siltstones

Minute crystals of siderite within the matrix of the argillaceous silts are believed to have grown in the organic muds soon after deposition. The genesis of these siderite-cemented beds can be explained as follows: the ferric iron in organic hydrosols brought in by freshwater streams is flocculated by electrolytes in quiet brackish water and settles to the bottom of the basin of deposition; the organic matter immediately begins to decompose, and the carbon dioxide and ferrous iron released during this process combine to form siderite ( $\text{FeCO}_3$ ). This lithification process proceeds until all of the organic matter has been destroyed and all of the iron has been released.

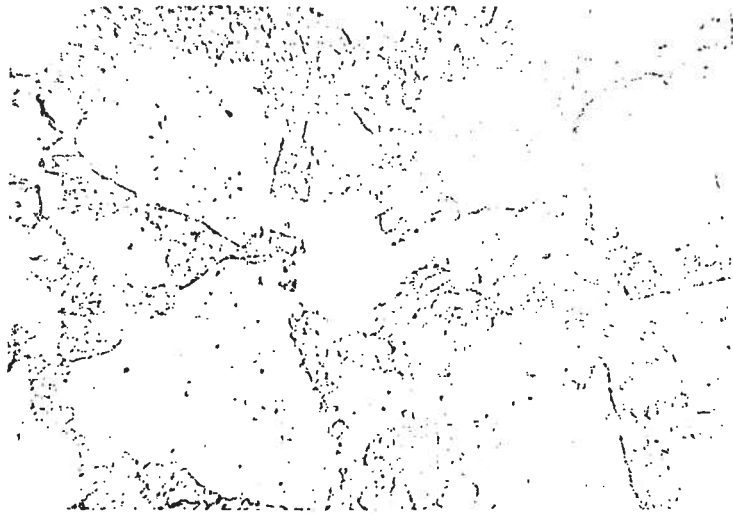
The McMurray Formation contains many beds of siderite-cemented siltstones. Thin sections of these beds (Pl. 13, Fig. 2) showed that the siderite is present in the form of small crystals, each probably growing from a single nucleus. In extreme cases siderite has eaten into the quartz grains, forming deep embayments in them. Small irregular bodies of pyrite also are scattered at random throughout these thin sections.

Siderite is considered indicative of littoral shallow-water strata containing abundant organic material (Teodorovich, 1961). The abundance of siderite-cemented beds in the upper part of the McMurray Formation and in the basal sands of the Clearwater Formation are thus probably the result of an increasingly saline environment of deposition in late McMurray -- early Clearwater time."

3. Siderite spherulites occurring in coarse-grained oil sands in the lower part of the McMurray Formation (Carrigy, 1966), (Allen and Sanford, 1973). Two photographs of the siderite found in Carrigy's report are reproduced on the following page.



*FIGURE 1. Photomicrograph of siderite spherulites from coarse-grained oil sands in the lower part of the McMurray Formation in the Mildred Lake Deposit. Magnification X300, plane polarized light.*



*FIGURE 2. Photomicrograph of a thin section of oil-stained, siderite-cemented siltstone of the McMurray Formation showing central pore space (P), quartz grains (Q), siderite (S) and pyrite (black). Magnification X300.*

Allen and Sanford of Great Canadian Oil Sands Ltd. make the following observations on the presence of hard (siderite-cemented) sandstones on Lease 86 within the rich oil sand deposit now being mined.

"The ore body consists of a basal fluvial sand overlain by lagoonal deposits which have been channelled into and refilled with silty beds which are now cemented with siderite.

The oil impregnation within the ore body is not homogeneous, but varies in richness from 0 to 18 percent by weight. The deposit also contains numerous thin beds of clay which contain no bitumen. Pockets of low pressure combustible gas have been encountered on the property within the ore body.

There is a noticeable increase in coarseness of the sediments and in bitumen saturation toward the base of the formation. In the basal unit the grain size varies from pea-sized pebbles to coarse silt and the bitumen content is high. Thin and discontinuous clay beds with dips of 5 to 8 degrees to the north are common. Fragments of wood up to a few cubic inches in size and occasional logs and stumps occur within these beds. Silt lenses up to 6 inches thick are also present.

Transition of the Basal Sand to the overlying fine-grained "Lagoonal" deposits is gradational. Clay bands varying from 1 inch to an occasional 6 feet in thickness, traceable for 100 to 200 feet, are characteristic of this unit and the dip of the beds varies from horizontal up to 5 degrees to the north.

A conspicuous old channel cuts through the "Lagoonal" deposits. The base of the channel dips to the north but massive (to 60 inches thick) clay beds within the channel dip to the north at steeper angles than the surrounding "Lagoonal" beds.

Within the channel there are two types of hard rock lenses:

- 1) A light brown-grey rock, rarely more than 12 inches thick, sometimes totally surrounded by tar sands. Microscopic examination shows that

these rocks are composed chiefly of quartz grains ranging in size from silt to fine sand cemented with calcite and siderite.

2) Hard, partly cemented oil-saturated sandstones.

A black, massive, very hard, sandstone lens composed of quartz grains cemented by siderite and calcite. This lens ranges in thickness from 3 to 42 inches thick and is impregnated with bitumen.

Observations at the mining faces have established that the rock lenses are invariably associated with minor channels within the major scour in the clay beds (Allen and Sanford, 1973)."

4. Pyrite, ( $\text{FeS}_2$ ) 46.6% Fe, occurs as nodules throughout the McMurray Formation (Carrigy, 1966). The following paragraph is an extract from this publication.

"Pyrite

Pyrite is found in the rich oil sands in the form of nodules up to 6 inches in diameter and as disseminated crystals surrounding fossil-wood fragments in the non-marine parts of the oil sands. In the basal Clearwater Formation pyrite replaces foraminifera, radiolaria, sponge spicules, hystrichospherids, diatoms, spores and pollen."

Conclusions

The amounts of siderite and pyrite present in the oil sands area are small and would not normally be worked. However, these hard rocks and nodules are currently being mined and segregated by Great Canadian Oil Sands Limited, and large amounts will be mined in the Syncrude operation. It would seem desirable, therefore, to make a study of the distribution of the iron-bearing minerals in the McMurray Formation to assess their economic potential.

NOTES ON SIDERITE  
(extracted from Lindgren, 1933)

"The Siderites of Marine and Brackish-water strata

Occurrence -- Siderite ( $\text{FeCO}_3$ )<sup>3</sup> is an iron ore of some importance, in both epigenetic and syngenetic deposits. It occurs in fissure Veins and as a replacement of limestone, but is also found in the sedimentary rocks as a product of the sedimentary processes. The sedimentary siderite ores are called clay ironstone, sphaerosiderite, or black band. A dense or fine-grained concretionary or spherulitic structure is characteristic of the "clay ironstone" occurring in clays or shales; and these concretions, more or less admixed with clay and sand and often inclosing vegetable remains, are found abundantly at certain horizons. The variety called "black band" forms continuous beds of dark-colored, compact appearance in the shales of the coal measures, often directly underneath or above the coal beds.

These ores contain less than 48 per cent of iron and must be calcined before smelting. Both sulphur and phosphorus are present, sometimes in considerable quantities.

Marcasite, pyrite, arsenopyrite, millerite, galena, sphalerite, and chalcopyrite are sometimes found along cracks in the concretions of siderite, indicating that the iron solutions carried small amounts of the less common metals, probably as sulphates. An analysis of siderite ore from Maryland<sup>4</sup> showed in percentage 36.0 Fe, 13.53  $\text{SiO}_2$ , 6.47  $\text{Al}_2\text{O}_3$ , 0.94 Mn, 0.08 P, and 0.42 S.

The economic importance of these ores, formerly great, is now small. Near the surface they are sometimes changed to limonite.

The origin of sedimentary siderites is explained along the same lines as that of the bog-iron ores. Solutions of ferrous bicarbonate or sulphate were supplied to the marshes along the sea coast or to the shallow sea

---

<sup>3</sup> Siderite ( $\text{FeCO}_3$ ) has a maximum iron content of 48.2% Fe.

<sup>4</sup> J. T. Singewald, Jr., Econ. Geol., 4, 1909, pp. 530-543.  
J. T. Singewald, Jr., Report on the iron ores of Maryland, Maryland Geol. and Econ. Survey, 9, pt. 3, 1911.



where organic matter was abundant. Precipitation of the normal insoluble carbonate took place through absorption of the solvent  $\text{CO}_2$  by vegetation. Free oxygen was absent, for otherwise the carbonate would have been transformed into limonite. But even if the iron had originally been deposited as limonite, a reduction and carbonation to siderite may have been effected by the limonitic precipitate being covered by mud containing organic matter.

The concretionary masses are not the products of primary precipitation, but are, probably in all cases, segregated into nodular form by the action of percolating solutions around a suitable nucleus while the sediments were still soft.

Examples -- In the United States sedimentary siderites are known in Pennsylvania, Ohio, West Virginia, Maryland, and Kentucky. Their present industrial importance is slight, but they were formerly mined on a more extensive scale. The production in 1930 was only 1,000 long tons from Pennsylvania, and this was used for the manufacture of red paint.

In Pennsylvania and adjacent States the upper barren Coal Measures contain abundant nodules of siderite in the shales and sandstones, but no valuable deposits. In the upper productive Coal Measures, or Monongahela River series, black band ore occurs, for instance, just below or above the Pittsburgh coal bed. In the lower Coal Measures the siderites are especially abundant; in Ohio 12 horizons of black bands and concretionary ores are distinguished by Orton.<sup>5</sup>

Siderite ores also occur in the Tertiary Claiborne formation of Mississippi.

The black bands are common in Germany. They were formerly actively worked in Westphalia and near Saarbrücken, where the ore formed flat lenticular masses as much as 1 1/2 meters thick and sometimes several hundred meters in extent.

In England the black bands were formerly of the highest importance and 50 years ago furnished four-fifths of the total iron output. They are

---

<sup>5</sup> Ohio Geol. Survey, 5, 1884, p. 378.

now mined only in North Staffordshire and in Scotland. In Wales the black bands occur in the lower Coal Measures. Kendall<sup>6</sup> enumerates 75 horizons of siderite ore.

In Scotland (Ayrshire) the black bands occur both in Coal Measures and in Carboniferous limestone. The ores contain 25 to 40 per cent Fe, and occur as thin strata, 1 1/2 feet or less thick; several of them are usually close together."

#### REFERENCES

- Carrigy, M. A. (1966): Lithology of the Athabasca Oil Sands, Res. Coun. Alberta Bull. 18, 48 pages.
- Ells, S. C. (1926): Bituminous sands of northern Alberta, Can. Mines Branch Rept. No. 632, 244 pages.
- Lindgren, W. (1933): Mineral Deposits, McGraw-Hill Book Company, Inc., New York, 930 pages.
- Reno, H. T. in Mineral Facts and Problems, U.S. Bureau of Mines Bull. 630, p. 455-279.

---

<sup>6</sup> J. D. Kendall, The iron ores of Great Britain and Ireland, London, 1893, pp. 145-199.

# IRON

By Horace T. Reno<sup>1</sup>

**T**HE IRON ore industry of the United States grew from an annual output of less than 5 million tons in 1870 to over 115 million tons annually in 1951. Since 1951, annual output measured in terms of usable ore shipped to the consumer has declined to about 80 million tons a year, but the industry has continued to grow in terms of capital invested and crude ore mined. There have been sweeping changes in almost every facet of the iron ore industry since World War II when the domestic industry ceased to be the sole source of ore and mining of low-grade magnetite taconite deposits was started in the Lake Superior district.

Sixty-eight countries of the world reported iron ore production in 1963, and more than 150 million tons of iron ore was sold outside the country of origin in 1962.

Sedimentary hematite deposits of primary origin, hematite and magnetite deposits of complex origin, and replacement vein deposits have been the most productive commercial iron deposits to date. However, Precambrian metamorphosed sediments, such as taconite deposits of Minnesota, the jaspilite deposits of Michigan, and the specular hematite and magnetite bearing iron formations which comprise the southern ranges of the Labrador-Quebec district are the principal type of deposits to be newly exploited in the last decade.

Open-pit mines produce approximately 90 percent of the iron ore in the United States because the cost of underground mining precludes expending funds for beneficiation to meet stringent market requirements.

Iron ores are beneficiated by crushing, sizing, washing, concentrating, and agglomerating. Concentration is accomplished by washing, by gravity separation in jigs, heavy-media cyclones, or Humphrey spirals, by magnetic separators, or by flotation. The ores are agglomerated principally by pelletizing at or near the mines and by sintering with other material at steel mills.

Blast furnaces have proved to be the most efficient tool for smelting iron ore and are used to smelt more than 93 percent of the iron ore consumed in the United States. Small furnaces have proved uneconomical principally because of the cost of labor. Coke is the most expensive material and the largest single cost item in iron ore smelting. Methods have been devised to save coke by injecting various gases, oils, and powdered coals into the smelting zone of the furnace.

Sponge iron processes in which the ore is reduced at temperatures below the fusion point of iron, and direct iron processes in which the ore is reduced at temperatures slightly higher than the fusion point, present possible alternative methods for producing iron, but they have been found to be applicable only in specific economic and physical environments. They are not used in this country because they cannot compete in production costs with blast furnaces.

Iron ore resources are reasonably well distributed around the world and unquestionably are sufficient for centuries. The United States uses between 120 and 125 million tons or more of iron ore a year. Most of it is smelted to produce iron, but small quantities are used in making cement, special high-density concrete, and pigments, and magnetite concentrate is used for the heavy-medium in coal processing plants.

Iron is obtained as a coproduct or byproduct in smelting copper, lead, zinc, and nickel sulfides and is a coproduct in mining and treating titanium minerals. The supply of scrap iron and steel fluctuates directly with the demand. Unrecoverable iron losses from the mines through the complete cycle of use to return scrap range from 16 to 31 percent.

The United States emerged from the era of peacetime self-sufficiency and high-grade iron ore in the latter part of the 1940's. In an emergency, however, the United States could be self-sufficient for 2 or 3 years.

<sup>1</sup> Commodity specialist.

Available iron statistical data present adequate coverage of the iron ore industry through the blast furnace. Industry, some States, educational institutions, and the Federal Bureau of Mines are conducting comprehensive iron ore research programs.

The outlook for the iron ore industry throughout the world is that the long-term trend in the price of iron ore in terms of constant value dollars will be downward, and that government actions will not influence the in-

dustry adversely. U.S. production for internal consumption will be 80 million tons of 60 percent iron ore by 1970 and 92 million tons by 1980. In addition 5 to 10 million tons will be produced for export. The principal iron mines of the world producing for international trade will have capacity to produce about 300 million tons of high-grade iron ore annually by 1980.

The principal problem of the domestic iron ore industry is to meet both price and quality competition from foreign producers.

## BACKGROUND

The iron ore industry of the United States is almost three and one-half centuries old. High-grade ore was produced in the Colonies and smelted in charcoal reduction plants distributed from Georgia to New Hampshire. Incomplete records indicate that less than 50 million tons was mined through 1870. The industry grew from an annual output of less than 5 million tons in 1870 to more than 50 million tons annually by 1910; it was producing 75 million tons annually by 1916, 100 million tons annually by 1942, and over 115 million tons by 1951. Since then the annual output of usable ore has declined to less than 80 million tons, but in terms of capital invested and crude ore mined the industry has continued to grow.

Discovery of the Lake Superior iron mining district and development of the Bessemer steel-making furnace in the 1850's and the smelting industry's change from charcoal to coal and then to coke in 1875 consolidated iron ore mining and smelting. In the same period, development of the Great Lakes transportation system led to establishment of the world's foremost iron and steel complex in the bituminous coal region of Pennsylvania, Ohio, West Virginia, and Illinois. Iron and steel plants based on local ores were established in Alabama, New York, New Jersey, Tennessee, and Colorado, but the Lake Superior district has accounted for about 80 percent of the iron ore mined in the United States.

Until the end of World War II, the domestic iron-ore mining industry was virtually the sole source of iron ore for the United States. Enriched ores of the Lake Superior district that contained 50 to 55 percent iron, were the accepted standard of high quality by which other ores were gaged. In fact, the industry was little changed from the pattern established 75 years before. The end of the war, however, marked two significant changes: First, the industry ceased to be the sole source of ore for the United States and second, mining of low-grade magnetic taconite deposits was started in the Lake Superior district. As a result there have been

sweeping changes in almost every facet of the iron ore industry. Foreign iron ore deposits supply about a third of U.S. needs for ore. Iron ore pellets, a processed product containing at least 63 percent iron, have become the standard of high quality. Most domestic underground iron mines have been shut down and open-pit iron mining has changed from a seasonal to a year-round operation. Only the Great Lakes transportation system and the preeminence of the Lake Superior district remain of the prewar iron mining industrial pattern.

## SIZE, ORGANIZATION, AND GEOGRAPHIC DISTRIBUTION OF THE INDUSTRY

Each year, the iron ore industry produces more than 500 pounds of iron ore for every person in the United States. In 1963, iron ore accounted for more than one-third the value of all the country's metal production. More than 21,000 men were employed directly in the industry; investment per man directly employed has exceeded \$100,000 if the costs of transportation facilities are included in the total.

There were 179 iron mines in the United States in 1963; 31 of these produced more than 1 million tons each and together they produced 78 percent of the crude ore and 71 percent of the usable ore; 23 mines produced more than 500,000 tons; 61 produced more than 100,000 tons and the remaining 64 produced less than 100,000 tons. Integrated iron and steel companies control 70 to 80 percent of the domestic iron ore output. Several of the larger of these companies control or have an interest in iron mines in Canada, Chile, Liberia, Peru, and Venezuela.

Sixty-eight countries of the world reported iron ore production in 1963, but 10 countries produced four-fifths of the total. The U.S.S.R. was the leading producer, followed by the United States, France, China, Canada, Sweden, United Kingdom, India, West Germany, and Venezuela in that order.

International trade in iron ore is a large and growing business. In 1962, more than 150 million tons of iron was sold in the world markets outside the country of origin. Conservatively, this ore was valued at the port of export at more than \$1 billion. That same year, 19 countries exported more than 1 million tons of ore. Measured by iron content, Canada, shipping mostly to the United States, was the principal exporter, closely followed by Sweden, shipping to Western European countries, and the U.S.S.R., shipping to its satellites. Australia and some of the smaller countries on the west coast of Africa are rapidly expanding their capacity to produce iron ore for export. If world trade in iron ore expands at the growth rate of the last 5 years, it will be more than doubled by 1980.

The Lake Superior district (Michigan, Minnesota, and Wisconsin) accounted for 77 percent of the crude and usable ore produced domestically in 1963; the Northeastern district (New Jersey, New York, and Pennsylvania) accounted for 7 percent of the crude and usable ore; the Western States (Arkansas, Idaho, Missouri, Montana, Nevada, New Mexico, Utah, and Wyoming) accounted for 5 percent of the crude and 6 percent of the usable ore; the Southeastern States (Alabama and Georgia) accounted for 4 percent of the crude ore and 3 percent of the usable ore; and Tennessee, Arizona, Arkansas, California, Colorado, New Mexico, and Texas accounted for 6 percent of the crude and 7 percent of the usable ore. Distribution of iron blast furnaces in the United States is given in table 1.

TABLE 1.—Location of U.S. iron-blast furnaces, 1964

Plant location and operating company	Number of stacks	Plant location and operating company	Number of stacks
<b>PITTSBURGH-YOUNGSTOWN DISTRICT</b>		<b>PITTSBURGH-YOUNGSTOWN DISTRICT—CON.</b>	
Kentucky:		Pennsylvania (Pittsburgh area):	
Ashland: Armeo Steel Corp.....	3	Braddock: United States Steel Corp.....	6
Ohio: (Youngstown area):		Chairton: United States Steel Corp.....	1
Campbell: Youngstown Sheet & Tube Co.....	4	Duquesne: United States Steel Corp.....	5
Hubbard: Valley Mould and Iron Corp.....	1	McKeesport: United States Steel Corp.....	4
Warren: Republic Steel Corp.....	1	Neville Island: Shenango, Inc.....	2
Youngstown:		Pittsburgh: Jones & Laughlin Steel Corp.....	6
Republic Steel Corp.....	5	Rankin: United States Steel Corp.....	6
United States Steel Corp.....	4	Total.....	30
Youngstown Sheet & Tube Co.....	2		
Total.....	17	West Virginia:	
Ohio (central and south):		Weirton: Weirton Steel, Division of National Steel.....	4
Canton: Republic Steel Corp.....	1	Total, Pittsburgh-Youngstown district.....	89
Jackson: Jackson Iron & Steel Co.....	1		
Massillon: Republic Steel Corp.....	1	<b>CHICAGO DISTRICT</b>	
Middletown: Armeo Steel Corp.....	1	Illinois:	
New Miami: Armeo Steel Corp.....	2	Chicago:	
Portsmouth: Detroit Steel Corp.....	2	Interlake Iron Corp.....	2
Steubenville: Wheeling Steel Corp.....	5	International Harvester Co.....	3
Total.....	13	Republic Steel Corp.....	1
Pennsylvania (western) (excluding Pittsburgh area):		United States Steel Corp.....	11
Aliquippa: Jones & Laughlin Steel Corp.....	5	Youngstown Sheet & Tube Co.....	3
Erie: Interlake Iron Corp.....	1	Granite City: Granite City Steel Co.....	2
Farrell: Sharon Steel Corp.....	2	Total.....	22
Johnstown: Bethlehem Steel Co.....	6		
Midland: Crucible Steel Co. of America.....	3	Indiana:	
Monessen: Pittsburgh Steel Co.....	3	East Chicago:	
Sharpsville: Shenango, Inc.....	2	Inland Steel Co.....	8
Total.....	22	Youngstown Sheet & Tube Co.....	3
		Gary: United States Steel Corp.....	12
		Total.....	23

TABLE 1.—Location of U.S. iron-blast furnaces, 1904—Continued

Plant location and operating company	Number of stacks	Plant location and operating company	Number of stacks
<b>CHICAGO DISTRICT—Continued</b>		<b>WESTERN DISTRICT</b>	
Minnesota:		California:	
Duluth: United States Steel Corp.....	2	Fontana: Kaiser Steel Corp.....	4
Total, Chicago district.....	47	Colorado:	
<b>CLEVELAND-DETROIT<sup>1</sup> DISTRICT</b>		Pueblo: The Colorado Fuel & Iron Corp....	4
Michigan:		Utah:	
Dearborn: Ford Motor Co.....	3	Geneva: United States Steel Corp.....	3
River Rouge: Great Lakes Steel Corp., Division of National Steel.....	4	Ironton: United States Steel Corp.....	2
Trenton: McLouth Steel Corp.....	2	Total.....	5
Total.....	9	Total, Western district.....	13
Ohio (Lake area):		<b>SOUTHERN DISTRICT</b>	
Cleveland:		Alabama:	
United States Steel Corp.....	2	Birmingham:	
Jones & Laughlin Steel Corp.....	3	Republic Steel Corp.....	2
Republic Steel Corp.....	6	United States Pipe & Foundry Co.....	2
Lorain: United States Steel Corp.....	5	Ensley: United States Steel Corp.....	5
Toledo: Interlake Iron Corp.....	2	Fairfield: United States Steel Corp.....	3
Total.....	18	Gadsden: Republic Steel Corp.....	2
Total, Cleveland-Detroit district.....	27	North Birmingham: United States Pipe & Foundry Co.....	1
<b>EASTERN DISTRICT</b>		Woodward: Woodward Iron Co.....	4
Maryland:		Total.....	19
Sparrows Point: Bethlehem Steel Co.....	10	Tennessee:	
New York:		Lyles-Wrigley:	
Buffalo:		Merritt-Chapman & Scott Corp.: Tennessee Products & Chemical Corp.....	1
Hanna Furnace Corp.....	4	Rockwood: Woodward Iron Co.....	2
Republic Steel Corp.....	2	Total.....	3
Lackawanna: Bethlehem Steel Co.....	7	Texas:	
North Tonawanda: Tonawanda Iron Di- vision.....	1	Houston:	
Troy: Republic Steel Corp.....	1	Sheffield Division of Armco Steel Corp.....	1
Total.....	15	Lone Star: Lone Star Steel Co.....	1
Pennsylvania (eastern):		Total.....	2
Bethlehem: Bethlehem Steel Co.....	5	Virginia:	
Fairless Hills: United States Steel Corp.....	3	Lynchburg: Lavino & Co., E. J.....	12
Sheridan: Lavino & Co., E. J.....	11	Total, Southern district.....	26
Swedeland: Alan Wood Steel Co.....	2	Total all districts.....	238
Total.....	11		
Total, Eastern district.....	36		

<sup>1</sup> Ferro-manganese only.

Source: American Iron and Steel Institute.

### DEFINITION OF TERMS, GRADES, AND SPECIFICATIONS

Iron ore is classified according to the principal mineral constituent as either hematite, magnetite, or limonite (brown ore). In the South-eastern district hematite ore is called red ore. The term "natural ore" is used to designate iron ore that contains moisture, in contrast to "dry

ore" that has been dried but not calcined. Iron ore is measured in long (gross) tons to the blast furnace, but pig iron, the blast furnace product, is measured in short (net) tons.

Iron ores are described as crude or usable. Crude ore is the material, as mined, prior to any processing for removing waste constituents, though it may be crushed and screened. Usable ore is the product of mine, beneficiating, or

agglomerating plant which is shipped without further processing to the consumer. In this category are included direct-shipping ore (the usable ore as mined), iron ore concentrate (ore from which waste constituents have been removed), and iron ore agglomerate (compact masses of either ore or fine-grained concentrate).

Beneficiated ores are usable ores that have been treated to improve either their physical or chemical characteristics. Thus ores that have been improved by simple sizing or crushing are among the beneficiated ores.

Grades of iron ore are established according to percentage and type of impurities and by physical characteristics; within limits, the percentage of iron is a secondary consideration. Iron ore delivered to Lake Erie ports is purchased on the basis of 51.5 percent iron; usable iron ore shipped in the Southeastern district in 1958 contained an average of 39 percent iron.

The five principal grades of iron ore are— (1) bessemer, containing not over 0.045 percent phosphorus; (2) low-phosphorous, nonbessemer, containing between 0.045 and 0.180 percent phosphorus; (3) high-phosphorous, containing over 0.180 percent phosphorus; (4) manganese, containing over 2 percent manganese; and (5) siliceous, containing over 18 percent silica. In addition, iron ore is often described as lump, fine, high sulfur, high silica or titaniferous. Buyers' specifications are rigid within the above named grades, and maximum impurity limits are always cited.

## TECHNOLOGY

### Geology

The iron content of the earth's crust has been calculated at 5.06 percent (13).<sup>2</sup> A fractional part of this iron has been concentrated, under varying geologic conditions, into widely distributed, multi-origin deposits formed in many rock types. Of the various commercial deposits, the most productive to date have been: (1) sedimentary hematitic deposits of primary ore enriched by weathering processes; (2) hematite and magnetite deposits of complex origin in metamorphic rocks; and (3) replacement and vein deposits.

Limonite, siderite, hematite, and magnetite are the principal iron-ore minerals. In sedimentary deposits these minerals have been deposited mechanically, chemically, or biochemically; the mineral species have been governed by the conditions of deposition. The iron was derived from weathering of igneous minerals such as hornblende, pyroxene, or mica. Silicate, alumi-

nate, and carbonate minerals, and iron and titanium mineral combinations thereof are common gangue.

Precambrian metamorphosed sediments comprise a major part of the world's low-grade iron-ore deposits. They were exploited first in Lake Superior district after World War II as a result of (1) imminent depletion of high-grade deposits, (2) growing demand for iron, and (3) development of more efficient mining and beneficiation techniques. The taconite deposits of Minnesota in which magnetite is the principal iron mineral and the jaspilite deposits of Michigan in which specular-hematite is the principal iron mineral have been proved commercial sources of iron only since 1954. The success of the mining companies exploiting these deposits, and the demand for the iron-ore pellets produced from them influenced others in the iron ore industry to prospect for and develop similar deposits. Precambrian metamorphosed specular-hematite and magnetite bearing iron formations which comprise the southern ranges of Labrador-Quebec district in Canada have been developed on a large scale in the last decade, and similar deposits have been developed recently in the Western United States and in the U.S.S.R.

Titaniferous iron deposits of sedimentary metamorphic, and magmatic origin are prevalent throughout the world, but few are exploited where other type iron deposits are available.

### Mining

Open-pit mines produce approximately 90 percent of the iron ore in the United States. The trend has been toward more open-pit mining and less underground mining because improvements in excavating equipment has permitted a steady increase in the overburden-to-ore ratio since World War II. In the last 5 years, however, underground mining has been decreasing steadily because the average ore as mined underground would not meet rigid market specifications, and the cost of underground mining precluded expending funds for beneficiation. Underground mines produced approximately 15 million tons of ore in 1963. It is significant that only 16 million tons of direct-shipping ore was produced in 1963.

### Open-Pit Mining

Mining methods in open-pit iron mines are similar but vary widely in detail. Overburden is stripped with power shovels, draglines, or scrapers, and is transported either by rail, trucks, conveyor belts, skips, or in the scrapers. The overburden on shallow, thin-bedded deposits often is double or triple cast with a dragline excavator. The choice of equipment is

<sup>2</sup> Italicized numbers in parentheses refer to items in the list of references at the end of this chapter.

controlled by the physical characteristics of the overburden, the depth and size of the ore body, and the nature of surrounding terrain.

In large pits, ore is loaded exclusively with power shovels, but in some thin-bedded deposits it is loaded with dragline excavators. Ore is transported from the pits by rail, trucks, skips, conveyor belts, or by combinations thereof; the choice with few exceptions is ruled by the grade of haul and the size of operation.

Drilling equipment used in large, open-pit iron mines includes churn drills, rotary drills, down-the-hole drills, jet-piercing apparatus, and air-driven percussion drills. Jackhammers and wagon drills are used in the smaller mines. Churn drills predominate in the Lake Superior district's soft residual-hematite mines, and jet-piercing apparatus predominates in taconite and jaspilite mines. However, roller-cone rotary drills and down-the-hole drills with tungsten-carbide-insert cutting edges have proved superior to churn drills and to jet-piercing equipment in some types of ground.

Mining benches in open-pit mines range in height from 20 to 50 feet; the average is about 35 feet. Drill holes spacing and burden (distance from first line of holes to face) range from 12 to 30 feet. Hole sizes range from 5 to 12 inches. Jet-piercing apparatus make an uneven diameter hole ranging in size from 8 to 20 inches or more. The usual practice is to take advantage of the flexibility to chamber the bottom or various depths of the hole to obtain the most efficient blasting. Field-mixed ammonium nitrate and fuel oil is now the most common explosive used in open-pit iron mines where moisture is not a problem. Waterproof free-flowing low-velocity blasting powders are used in wet ground. Some form of delay detonation is used in all except the smallest open-pit iron mines.

#### Underground Mining

There has been a concerted effort since 1960 to improve the efficiency and lower the cost of underground iron mining. Raise boring machines, a hard rock mole that drives 7-foot diameter openings, and continuous miners similar to coal mining machines have been used successfully. The larger underground mines have been mechanized to the same extent as the open-pit mines and wherever possible loaders, trammers, conveyors, samplers, and hoists have been fully automated. Closed circuit television is used to monitor isolated operations. These practices have stimulated the underground miners to modify and vary mining methods to the point where conventional nomenclature no longer completely describes the operation.

Sublevel caving has been the principal underground method of mining iron ore in the Lake

Superior district. Block and panel caving and variations thereof are used in large ore bodies where dilution is not a problem. Shrinkage stoping, open stoping, sublevel stoping, with many modifications and various other methods also are used depending on the size, shape, and character of the orebody, and the character of the enclosing rocks. Most bedded deposits are mined by room and pillar methods similar to those used in coal mining. Air-driven percussion and auger drills and electric driven auger drills are used in underground iron mines. Drifters on jumbos are used in large headings, jack-leg hammers in small headings, and jack-leg and stopers in stopes and raises. Long holes are drilled with air-driven drifters and rotary machines with auger-type drilling strings.

Ammonium nitrate and fuel oil, ammonium nitrate-TNT slurries, and gelatin dynamites are used in blasting underground. Cap and fuse regular delay and fast delay caps are used for detonation. Slushers are the principal means of loading. Room and pillar mines use conventional metal mine mechanical loaders and some coal loaders. Ore is transported underground on rails, on conveyor belts, and with trackless haulage units.

#### Beneficiation (30, 38)

Beneficiate, as applied to iron ore, is a broad general term that includes any process used to improve physical or chemical characteristics of the ore, that is any process used to increase the value of the ore after it is mined, but before it is smelted. Thus crushing, sizing, washing, concentrating and agglomerating are processes of beneficiation.

#### Crushing, Sizing, Washing, and Concentrating

High-grade, hard lump ores are crushed to about 8 inches if destined for use in an open-hearth furnace and a maximum of 4 inches if destined for use in a blast furnace. Within the last few years it has become common practice to remove minus ¼-inch material from all ore sold on the open market. The coarse material then is graded and sized to customer's specifications. Minus ¼-inch material is sold at a discount or agglomerated by one of several processes described later.

Soft, iron-bearing material containing clay and sand in which the iron is concentrated in a coarser and harder portion is beneficiated by washing. The ore is crushed, screened, and then washed in log washers or on screens and in various types of classifiers. In some plants, bowl classifiers are used for separating fine iron minerals from the log washer tailings. From 45 to



70 percent of the iron is recovered in a product ranging from 40 to 60 percent iron. Reject fines from washing plants contain from 10 to 45 percent iron (in extreme instances).

Gravity concentration by jigging or heavy-medium separation equipment is applied to concentrating coarse ore (usually plus  $\frac{1}{4}$ -inch and seldom finer than  $\frac{1}{8}$ -inch), and Humphrey spirals, and wet cyclone separators (both with and without suspension medium), are used for concentrating fine ore and the tails from jigs and heavy medium wash plants. Each type of gravity concentration equipment has certain advantages or disadvantages, depending on the physical characteristics of the ore and on the difference in the specific gravity of ore and waste. Heavy medium cyclone separators have high capacity and make a good separation. Humphrey spirals make a better separation of fine material than cyclones, but do not have as high capacity. Heavy-medium units make a sharper, more rapid separation on unsized coarse ore than do jigs. Among the various types of gravity-separation equipment, cyclones (heavy medium) and other types of heavy-medium plants seem to be most favored by the large producers.

Magnetic concentration would present the answer to iron-ore beneficiation if the ores contained only magnetite. Unfortunately, in the preponderance of so-called magnetite iron ore, including the taconites, the iron is distributed in magnetic and nonmagnetic iron minerals and in iron-bearing silicates. Consequently, the overall recovery of a typical magnetic concentration plant ranges from 30 to 95 percent of the iron in the feed. In many instances the tailings contain silicate minerals from which a desirable iron-bearing product cannot be recovered by present methods, but they also contain recoverable iron in the form of oxide minerals.

Essentially all types of magnetic separators have been applied to concentrating magnetite ore, but most operators have settled on the belt units for cobbing and rougher concentration and on drum units for finishing. If the ore is ground finely enough to liberate the mineral constituents, magnetic process plants recover 95 percent or more of the magnetic iron content of the ores in a 62 to 68 percent iron concentrate. The siliceous magnetite iron-bearing formations of the Lake Superior district require grinding to pass 100-mesh (75 to 92 percent minus 325-mesh); not even a 500-mesh grind, however, will liberate iron minerals from materials obtained from some parts of the district's slaty formation material.

The distribution of iron by mineral in the nonmagnetic cherty taconite on the Mesabi range

between Grand Rapids and Buhl, Minn., as determined by the Bureau of Mines, is as follows:

Mineral	Percent of total iron content	Range (percent)
Magnetite.....	21.3	0-66
Nonmagnetic oxides.....	74.8	5-100
Siderite.....	2.7	0-90
Silicate.....	1.2	0-90

<sup>1</sup> By difference.

Magnetic taconites currently mined contain 60 to 70 percent of their total iron in magnetite minerals and the remainder in nonmagnetic oxide and silicate minerals.

Nonmagnetic iron minerals can be concentrated with conventional magnetic separators by converting them to magnetite in a controlled reduction roasting atmosphere in shaft, multiple hearth, or rotating cylindrical furnaces.

Iron ore concentration with high-tension separation equipment that imparts differential movement of mineral particles with a grounded rotor and a concentration of mobile ions was reported in 1957 (18). Reportedly the equipment compared favorably with commercial magnetic and flotation separation equipment in semi-pilot plant tests on hematite, magnetite, and martite ores, but it has not yet been applied on a large scale commercially. Nevertheless, electrostatic separators continue to be of interest to researchers seeking profitable methods of concentrating complex iron ores.

The Mines Experimentation Station of the University of Minnesota is conducting a pilot-plant study of a process for beneficiating low-grade Mesabi range ores in which electrostatic and high-intensity wet magnetic separation circuits are used to concentrate part of the iron minerals.

Specular-hematite ores are concentrated efficiently with flotation, and flotation is applied to concentrating the fine-grained hematite minerals in material from which part of the iron minerals have been removed by other methods.

Flotation also has been applied successfully for upgrading iron ore concentrate by floating silica, apatite, and other mineral impurities away from the iron minerals. The art and science of applying flotation to concentrating iron ores has been advanced markedly in the last decade, but reagents and procedures have not been found that are commercially applicable to ores containing mixtures of limonite, goethite, and hematite.

#### Agglomeration (2, 5, 21, 27)

Fine-grained iron ore and iron ore concentrate is agglomerated before being smelted in a blast furnace by sintering, nodulizing, pelletizing, or briquetting. The fine ore is sintered with heat on traveling grates or in a batch ma-

chine, nodulized with heat in a rotary kiln, pelletized without heat in a rotating drum, pan, saucer, or cone, or briquetted without heat using some form of binder in pressure-roll machines. Hot ore briquetting processes have been successful on a laboratory scale using pressure rolls to form the briquettes, but a 2-year pilot-plant test on Lake Superior fine grained siliceous ore indicated that the operation would not be profitable because of high maintenance costs. Together the several types of materials produced is called agglomerate; individually they are called iron-ore sinter, nodules, pellets, and briquettes. Pellets and usually briquettes are indurated by some form of heat treatment after they are formed. The pellets are treated in updraft or downdraft traveling grate furnaces, in shaft furnaces, or in grate-kiln furnaces. Each method has its advantage. Data are not available to determine which is the better under all circumstances.

Self-fluxing agglomerates, wherein fuels, flux, and iron minerals are combined, present theoretical possibilities for saving in the cost of operating a blast furnace. The principal advantage is that the flux would be calcined before it reached the furnace. Lime sinter, which contains less than enough basic material to neutralize all the acidic materials in the ore, is in common use, but completely self-fluxing agglomerates are still not widely used.

Bureau researchers have produced partially reduced pellets in the laboratory and on a pilot plant scale. Partially reduced pellets are those in which most of the oxygen has been removed from the contained iron oxide minerals. These pellets were proved superior blast furnace feed in the Bureau's experimental furnace, and similar pellets have been tested in commercial furnaces, but the results have not yet been published.

### Smelting (1, 22, 24)

Blast furnaces are used to smelt more than 93 percent of the iron ore consumed in the United States, open-hearth furnaces are used to smelt about 6 percent, and electric furnaces producing ferroalloys are used to smelt less than 0.2 percent. Their proportions have been about the same since the turn of the century despite concerted efforts by many researchers to develop alternatives for the blast furnace. The fact is that the blast furnace is the most efficient tool for smelting iron ore yet developed. Its use over more than three centuries has progressed from crude art to highly sophisticated metallurgical technology. Probably more has been done to increase its efficiency in the last 10 years than was done in the preceding 100.

The average blast furnace in the United States

is 95 feet high and 23 feet in diameter at the hearth, it has a working volume of 33,200 cubic feet, and will produce about 1,200 tons of pig iron (hot metal) per day. The largest furnace in the United States is the Armco Steel Corporation's "Amanda" at Ashland, Ky. The "Amanda" is 104 feet high, 30 feet 6 inches in diameter at the hearth, has a working volume of 68,510 cubic feet, and capacity to produce 3,310 tons per day. Record monthly production, however, was held in 1964 by the Bethlehem Steel Co.'s "J" furnace at Sparrows Point, Md., with 104,435 tons of iron produced in October 1963. The "J" furnace is 165 feet 3 inches high and has a hearth diameter of 23 feet 9 inches and working volume of 50,522 cubic feet.

Nor is the Amanda the world's largest blast furnace. This distinction is claimed by Tokai Iron & Steel Co. Ltd.'s No. 1 blast furnace at Nagoya Harbor, Japan, which has a hearth diameter of 22 feet 2 inches, working volume of 71,371 cubic feet, and daily capacity of over 3,500 tons.

The smallest iron blast furnace in the United States has a height of 55 feet, hearth diameter of 7 feet, working volume of 3,316 cubic feet, and capacity of about 100 tons per day. It has been used principally to produce ferroalloys but was not operating in 1964.

Small blast furnaces have proved uneconomic principally because of the cost of labor. It takes about the same crew to operate a small furnace as it does a large one. Therefore, there has been an unbroken trend since World War II to build larger furnaces. Apparently the structural limit has not yet been reached as Russian metallurgists have announced plans to build a furnace with a 36-foot hearth diameter and 95,000 cubic feet of working volume.

The chemistry of the blast furnace is extremely complex. At least 27 chemical reactions are possible, but simply stated the furnace performs two functions: (1) it reduces iron oxide to metal, and (2) it fuses the charge so that metal and slag will separate. Coke is the principal fuel and reductant, and limestone and/or dolomite is used for flux. These materials are charged with the ore into the top of the furnace. Coke is the most expensive material, and the largest single cost item in iron ore smelting. Within the last decade, methods have been devised to save coke by injecting part of the fuel and reductant needed into the smelting zone of the furnace. Various gases, oils, and powdered coals have been used successfully for this purpose. Availability and cost determine the choice. Natural gas has been the principal alternative fuel used in the United States. Fuel oil has been the principal alternative in European countries. Theoretically, more coke can be saved using powdered coal, but reliable tech-

niques for injecting the coal were not developed until 1962. Coal injection was reported to the Bureau for the first time in 1963 when 29,303 tons of bituminous coal and some anthracite, 43.9 million gallons of oil, 3.8 billion cubic feet of coke oven gas, and 31.6 billion cubic feet of natural gas were used in blast furnaces.

Blast furnace efficiency is judged by the ratio of fuel consumed to the iron produced. Recovery of the iron in the feed is over 93 percent. Capacity or productivity is related to efficiency and varies widely depending on the quality and characteristics of the charge in addition to depending on the operation of the furnace. Furnace capacities were published until 1960, but the practice was discontinued because the figures were widely misunderstood and misinterpreted. Furthermore, advancing technology made the capacity figures all but meaningless in terms of the metal that could be produced in a given size furnace.

Blast furnace operations have been greatly improved in the last two decades: (1) by grading and sizing the burden (charge without fuel); (2) by increasing the temperature and oxygen content of the blast; (3) by the fuel injection discussed above; (4) by increasing the rate and pressure of the blast; and (5) by using a burden that contains more iron per unit volume. Iron ore pellets have been accepted in the United States as the best material to obtain optimum furnace operation. However, in Europe, sized and graded sinter prepared from high-grade ore is considered superior to pellet by some furnace operators. Relative reducibility, tempered by length of experience with each, probably is responsible for the choice. Use of either high-grade pellet or sinter leads to better furnace operations and their physical and chemical characteristics set the standards by which other iron raw materials are measured.

Theoretically, use of partially reduced pellets will improve blast furnace operation and increase capacity as much as have pellets and sinter. Furthermore, the advantage of using them has been demonstrated practically in the Bureau experimental blast furnace, so there is little doubt that they will be used commercially if their cost is not prohibitive. Preliminary estimates indicate that the cost of iron in partially reduced pellets delivered to most blast furnaces will be little more than the cost of iron delivered in pellets; therefore, partially reduced pellets probably will replace pellets for feed to furnaces in which there is need to increase output. That is, additional iron ore smelting capacity will be obtained by using prerduced pellets, rather than by building new blast furnaces.

Electric-furnace smelting has proved marginally competitive with the blast furnace in

areas of inexpensive electricity a long distance from a supply of coke. Almost any carbonaceous material will serve for the reductant in an electric furnace. The Bureau has had marked success with wood chips. Flux requirements are essentially the same as for a blast furnace.

Sponge-iron processes, in which the ore is reduced at temperatures below the fusion point of iron, and direct iron processes, in which the ore is reduced at a temperature slightly higher than the fusion point, present possible alternative methods of producing iron. Scarcity of coke, or in some areas impending depletion of coking coal and high relative prices of coke in others, and changing economic and technologic conditions, often make these processes exceptionally attractive. Periodically since 1910, research institutions and industrial organizations have shown great interest and activity in developing processes to replace blast furnace smelting. A great deal of research effort has been expended on direct reduction possibilities. Several hundred processes have been developed through successful laboratory tests, and a dozen or more have been successfully tested in semi-commercial pilot plants. At least five and possibly more are being applied commercially in specific physical and economic environments (11, 12, 23, 28).

It is at times impossible to distinguish between semicommercial pilot and commercial operations. Höganäs and Wiberg-Soderfors, true sponge iron processes developed in Sweden, have long records of successful continuous commercial applications in that country. The Krupp-Remm, and "H-Iron" processes, have been applied commercially but in some instances have been found inapplicable with changing economic environments. Since its inception the Hy-L process has been used successfully and continuously to make sponge iron at Monterey, Mexico, and the Beheverria process has been used the same way at Legazpia, Spain. The R-N, S-L, and Strategie-Udy processes have been tested successfully in semicommercial plants and are offered as processes commercially applicable to processing selected iron ores under some conditions. In addition, several fluidized bed processes for obtaining iron from high-grade concentrate have been tested on a large scale. These processes also are offered as commercially applicable under some conditions.

Table 2 presents an elementary comparison of selected direct-reduction processes. The reader is referred to the work of Barrett, of the Bureau of Mines (4); Brown, of Jones and Laughlin Steel Corp.; (7) and Chase and McBride, of the United States Steel Corp. (10) for comprehensive discussion and review of the principal sponge iron and direct iron processes.

TABLE 2.—Comparison of principal iron ore direct reduction processes

Item compared	Krupp-Renn	R-N	Strategic-Udy	E-Iron	Hy-L	Echoverria	S-L
Possible ore feed	Low-grade high silica but low in sulfur and phosphorus.	Any-grade lump sulfur and phosphorus not critical.	Any-grade—but ¼ inch or finer Low in sulfur and phosphorus.	High-grade fine	High-grade lump	High-grade lump, sinter, or pellet.	High-grade lump ore or pellets.
Flux	None	Limestone—for sulfur only.	Limestone	None	None	Limestone—for sulfur only.	Dolomite for sulfur only.
Reductant	Solid carbonaceous, fairly low-grade.	Solid carbonaceous, excess recycled.	Solid carbonaceous	Hydrogen	H <sub>2</sub> -CO-gas	Solid carbonaceous, excess recycled.	Coal.
Reducing temperature	1,250° C.	852° to 1,055° C.	1,100° to 1,200° C.	480° C to 535° C.	About 1,100° C.	1,050° C.	1,050° C.
Pressure	Atmosphere	Atmosphere	Atmosphere	400 psig	Atmosphere	Atmosphere	Atmosphere
Sources of heat	Solid carbonaceous, fairly low-grade, or fuel oil.	Oil, gas, or solid burner fuel.	Gas from electric furnace in circuit plus other gas.	Any	Natural gas	Fuel oil, natural gas, producer gas, etc.	Gas.
Equipment	Rotary kiln	Rotary kiln	Rotary kiln Short-arc electric furnace.	Fluidized-bed pressure vessels, at least three.	Four retorts Heat accumulator.	Vertical retort, external heat.	Rotary kiln.
First product	Mixture of slag and lumps.	Mixture of fuel-slag and iron.	Partially reduced ore-flux mixture.	Iron powder with slight impurities.	Sponge, 85 percent iron.	Mixture of fuel slag and iron.	Mixture of fuel slag and iron.
Second treatment	Magnetic separation	Gravity separation for fuel then ground, wet, magnetic separation.	Short-arc electric furnace.	Compression mechanism.	None	Screening and magnetic separation.	Screening and dry magnetic separation.
Second product	Iron (lumps)	Iron briquets over 85 percent iron.	Pig iron or semi-steel	Iron chips or powder	None	Sized sponge iron	Sponge iron pellets and briquets.
Apparent advantages	Low-grade ore Low-cost fuel Iron recovered from silicas.	Flexibility Low-grade ore Low-cost fuel Removes sulfur and phosphorus.	Low-grade ore Produces semi-steel Sulfur and phosphorus can be removed selectively Flexibility.	No trouble with fine concentrate Wide degree of reduction possible Product will replace all or any part scrap and ore charge to steel furnace.	Replaces scrap Most sulfur eliminated.	Replaces scrap Simplicity—small units are efficient Most sulfur eliminated.	Removes sulfur and phosphorus.
Apparent disadvantages and operating problems	Sulfur and phosphorus remain with iron.  Ring formation in kiln.	Low recovery in silicate iron mineral ore.	Must have inexpensive source of electricity.  Ring formation in kiln.	Must have high-grade fine ore Does not remove any contaminants. No choice of reductants.	Requires high-grade ore and low-cost gas and power.  Does not remove phosphorus Batch system.	Must have high-grade ore Does not remove phosphorus. Batch system.	Process not developed to process low-grade or siliceous ore.  None.

The Krupp-Renn process probably should be classified as a beneficiating process rather than a sponge iron process because it has been used almost exclusively to upgrade siliceous ores. It is a rotary kiln process to which fuel ore mixtures are fed to a internally heated kiln. The iron oxides are reduced to metal and the iron gathers in nodules or lumps at the lower end of the kiln. The product is cooled and fed to a ballmill and then to a magnetic separator. The lumps, called "Luppen" contain 90 to 95 percent iron. Availability of high-grade ores has made the Krupp-Renn process obsolete in most parts of the world. Krupp-Renn plants are still being operated in Czechoslovakia, but those in West Germany where the process was developed have been shut down or are operating on high-grade ore.

The R-N process is a refinement of the Krupp-Renn process. It also is an internally heated rotary kiln process, but the temperature is carefully controlled so that at no point in the kiln does it exceed the fusion point of iron. The grade and grain-size of ore fed to an R-N kiln are not significant except that retention time becomes excessive if the ore lumps exceed 1½ inches in diameter, or the reduction time is excessive at smaller diameters if the ore is very dense. Limestone or dolomite is added in small quantities to arrest sulfur. The kiln can be fired with either an oil, gas, or solid-fuel burner, and the temperature gradient throughout the kiln is closely controlled by limiting the quantity of air available for combustion. Kiln products are separated by screening, gravity, or magnetic processes; and the unused solid-carbon reductant is cleaned and returned to the circuit. The iron-bearing portion is pulverized and separated magnetically and the iron is pressed into metallic briquets of high strength and density.

The S-L process is essentially the same as the R-N process except that it has been applied only to high-grade lump ore and pellets.

Recognizing this similarity the proprietors of the R-N and S-L processes have agreed to license their joint technology to Lurgi Gesellschaft für Chemie und Huttenwesen m.b.h. of Frankfurt (Main), West Germany, for an improved direct reduction process, known as the SL/RN process.

The Strategic-Udy process can utilize any grade iron ore, but the particle grain size should be one-fourth inch or less because the economy of the process is dependent on rapid throughput. The ore is partially reduced in a rotary kiln at 1,100° to 1,300° C, and fed directly from the kiln into a short-arc electric furnace. Solid carbonaceous material and gas from the electric furnace partially reduce the ore in the kiln. The solid carbon not used in the kiln is "cooled"

and passes through to finish reducing the ore in the electric furnace. Limestone or dolomite flux as needed is fed to the kiln with the iron ore.

The Hy-L and Echeverria processes are true sponge iron reductions in that the temperature is never permitted to exceed the melting point of iron and in that the end product is used as is in steelmaking. Both processes require high-grade iron ore or concentrate because all impurities are carried through to the iron end product.

In the Hy-L process, the ore is reduced in four identical reduction reactors each with a capacity of approximately 100 tons of raw ore. The system operates on a 12-hour cycle during which the reactors pass through four stages of 3 hours each. In the first stage, the ore is preheated with hot gas and the reduction process is started. Most of the ore is reduced in the second stage. The remainder is reduced and the charge takes on approximately 2 percent of combined carbon in the third stage. In the fourth stage, the ore, now sponge iron, is cooled and the heat is recuperated and used to preheat the ore in the first stage. The final product is a sponge iron averaging about 85 percent metal from which 85 percent of the sulfur has been removed. The sponge is suitable for use wherever cold iron melting stock is normally employed.

Although the chemistry and metallurgy of the Hy-L and Echeverria processes are similar the mechanics are completely different. Ore in the Echeverria process is charged with any low volatile carbonaceous fuel into externally heated shaft-retorts. A small amount of limestone is mixed to the ore to pick up the sulfur. Retorts are about 10 meters high with a circular horizontal section slightly tapered to permit free descent in the column. The retorts are installed within a refractory-lined oven which is heated by combustion of producer gas. Time from charge to discharge is approximately 48 hours depending on the reducibility of the ore. Each retort has a capacity of approximately 1.4 tons of iron product per day. The product is screened into three sizes and then separated from the excess coal and limestone magnetically. The screened sponge products are used in any cold melting stock operation similar to the Hy-L sponge.

The II-Iron process is a fluidized-bed reduction and therefore requires high-grade, fine-grained iron ore or concentrate. As in the Hy-L and Echeverria processes, most impurities are carried through the process to the end product. The ore is reduced with hydrogen at 480° to 538° C, under 400 pounds per square inch, gage pressure (31). The product is an impure iron powder that can be compressed to

form chips suitable for a steel-furnace charge, or the powder can be fed directly into an electric furnace by a method developed cooperatively in Bureau laboratories (3).

Electric-furnace smelting of iron ore, and the various sponge-iron and direct-iron processes are not used in most instances in this country because they cannot compete in production costs with the blast furnace, but they have the following advantages that make them attractive in some geographic areas: (1) they would not require as large a capital investment as a blast furnace; (2) impurities, such as sulfur in coke, would not be introduced in the same extent; (3) they apparently can recover iron from complex minerals with a byproduct slag enriched in other metals; and (4) they can afford better product purity control.

### USES

Iron ore, in addition to supplying the metal for iron and steel products, is used in paint pigments, cement, basic refractories, as a fluxing agent in nonferrous smelting and as a constituent of some catalytic agents. Lump magnetite ore is used for heavy aggregate in concrete for covering underwater pipelines, as a shielding material in nuclear powerplants, for the medium in jig beds and sink floatplants, and during World War II it was used for ship ballast.

### BYPRODUCTS AND COPRODUCT RELATIONSHIPS

Iron is obtained as a coproduct in the mining of copper, lead, zinc, and nickel in operations whereby iron sulphides are separated from other metal minerals and then roasted to drive off the sulfur, leaving a residue of high-grade iron oxides. The residue, called iron cinder, is sintered to make an iron product which commands a premium price.

Iron is also obtained from the magnetite produced with the mining of titanium minerals, and as a byproduct when titaniferous ores are smelted to recover  $TiO_2$ . Magnetic iron minerals are separated in an iron concentrate, and if the concentrate contains too much titanium, it may be blended with other iron-bearing material to form suitable blast-furnace feed.

Many heavy mineral placer concentrates contain some magnetite. If the operation is large enough, and the mine location is favorable, the magnetite is separated and marketed.

Titanium-bearing iron ores are not utilized for blast-furnace feed in the United States at present because under normal furnace operation titanium forms oxide accretions in the bottom of the furnace. Few domestic mineral deposits

contain enough titanium to be mined at present for that element alone.

### SECONDARY SOURCES AND RECOVERY

Secondary iron is recovered from flue dust, mill scale, and from scrap iron and steel that is unsuitable for steel furnaces. Iron and steel scrap comprises about 50 percent of steel furnace feed and is a raw material often considered vital to the operation of ferroalloy furnaces.

The scrap supply follows the demand, but data have not been developed to predict accurately the supply that will be available under specific circumstances.

Unrecoverable losses of iron from the mine or beneficiation plant through its cycle of use range as follows: Loss in shipments from the mines to the steel mills is believed to be small. Blast-furnace loss ranges from 1 to 1.5 percent in plants that have dust collectors and Cottrell precipitators. Without this equipment, the loss is about 7 percent. Iron loss in ferroalloy and steel furnaces ranges from 2 to 3 percent. In addition to these furnace losses, there is also a loss of about 1 percent, which cannot be accounted for between the feed to the blast furnace and steel mill shipments. Estimates of irretrievable fabricated steel losses range from 12 to 25 percent or more. Thus, total unrecoverable iron losses through a complete cycle from mine to use and secondary recovery range from 13 to 36 percent.

### RESOURCES

The total resources of iron ore available to industry have increased sharply in recent years, in particular because improved beneficiation can now produce high-grade materials economically from the very abundant low-grade metamorphosed sedimentary iron formations. Formerly only those parts of the iron formations that had been concentrated by natural geologic processes could be used. However, availability of high-grade, physically desirable blast-furnace feed has reduced the demand for certain natural ores, causing substantial shifts in the sources of iron ore.

Resources are unquestionably sufficient for centuries; they are reasonably well distributed around the world, and the major factors to be weighed in selecting particular areas to develop are those of costs (mining, beneficiation, transportation, and taxation), political stability, and security. Nevertheless, very real differences exist in the geologic settings (continuity, thickness, attitude, etc.), which affect mining costs, and in the mineralogy of the ores, which determine the feasibility of economical ungrading.

The resource figures in the following tables were compiled by the Geological Survey from many sources. They are approximations of quantities and grades known to exist in selected areas of the world that are either in exploitation now or for which there is reason to believe that development may take place in the relatively near future. No attempt is made to break them into the traditional measured, indicated, and inferred categories. Most of the material, even of the highest grade, will undergo some form of beneficiation before use; the grade figures give a general idea of the concentration ratio between ore in the ground and the quantity of "usable iron ore" that can be produced.

CONSERVATION

If it must be removed from the pit, low-grade iron ore is saved at most open-pit mines by stockpiling it in spoil banks so that it can be recovered when changing technologic or economic conditions make such recovery profitable. A few concentrating plant operators have constructed their tailing ponds so that the tailings can be retreated. Substandard iron ore is mixed with high-grade ore to produce a greater tonnage of usable product if buyer's specifications allow it.

SOURCES OF STATISTICAL INFORMATION

The Bureau of Mines canvasses major iron-ore producers monthly, and all producers annually. These canvasses are conducted in close cooperation with State agencies and industry trade associations. Export and import data are compiled by the Bureau of Mines from records of the Bureau of the Census, Department of Commerce. The Bureau of Mines also compiles iron-ore production statistics for foreign countries from official foreign government publications and from consular reports of the Department of State.

Bureau coverage of the domestic industry is practically 100 percent; mine production figures for small mining operations that fail to report are obtained from consumer's purchase records. Coverage of foreign iron-ore statistics is complete except for the U.S.S.R. and its satellites, and the figures are as accurate as the limited number of mineral attaches in foreign countries permits. The Bureau publishes iron-ore statistics monthly in Mineral Industry Surveys and annually in the Minerals Yearbook.

The American Iron Ore Association publishes monthly Lake Superior iron-ore shipments from United States and Canadian ports, monthly stocks of iron ore and agglomerates at U.S. docks and furnace yards, U.S. and Canadian monthly consumption of iron ore and agglomerates by districts and processes, and an annual statistical report of shipments of Lake Superior iron ore to upper Lake ports and all-rail shipments to consumers. U.S. production of pig iron and steel, with corollary statistics, are published weekly, monthly, and annually by the American Iron and Steel Institute. Together, these statistical data present completely adequate coverage of the iron ore industry through the blast furnace, but beyond the blast furnace many pertinent data on iron production, consumption, and stocks are lacking.

TABLE 3.—Iron ore resources of the United States<sup>1</sup>

[Million long tons]

Region	Quantity	Percent Iron	Type
Northeast (New York, New Jersey, Pennsylvania).	300 1,000	30-50+ 25+	Magnetite. Magnetite, hematite.
Southeast (Alabama, Georgia, Tennessee).	8,000 50	33-39 33-57	Red (hematite) ore. Brown (limonite) ore.
Lake Superior (Minnesota, Michigan, Wisconsin).	500 >100,000	50-54 22-30+	Direct shipping. Taconite, jaspilite.
South Central (Missouri, Texas).	250 150	40-60 49+	Magnetite, hematite. Limonite and siderite.
Rocky Mountain (South Dakota, Wyoming, Colorado, New Mexico, Utah).	500 2,000	48-60 25-40	Hematite and magnetite. Taconite.
Northwest (Montana, Idaho, Washington, Oregon).	15 1,000	40-60 25-40	Limonite, magnetite, hematite. Taconite.
Southwest (Arizona, California, Nevada).	100 2,000	60+ 25-40	Magnetite. Magnetite and taconite.

<sup>1</sup> Compiled by Geological Survey, U.S. Department of the Interior

TABLE 4.—Iron ore resources of selected countries<sup>1</sup>

[Million long tons]

Country	Quantity	Percent Iron
Australia.....	10,000	55-65
Brazil.....	2,400 600 25,000	>60 58-61 40-58
Canada.....	4,000	43-61+
Chile.....	24,000	22-37
France.....	1,000	53-50
Gabon.....	8,000 600	30-55 60-61
India.....	>100 21,000	40-45 75-81+
Iberia.....	400	20-68
Malaya.....	300	37+
Mauritania.....	150	65-80
Norway.....	200	65
Peru.....	1,000	32-35
Sierra Leone.....	1,000	45-55
Sweden.....	100	65
U.S.S.R.....	3,500 8,200 50,000 32,700	55-65 >45 40-46 <40
Venezuela.....	100 3,500 >300	45 58-65 40-50

<sup>1</sup> Compiled by Geological Survey, U.S. Department of the Interior.

## PRODUCTION, CONSUMPTION, AND TRADE

The relative position of the iron producing districts and the changes in quality and the extent of concentration practiced in each are shown in table 5.

The Lake Superior district has been the principal source of domestic iron ore. Its production of crude ore has remained about the same for the last 10 years, while its production of usable ore has declined steadily. The grade of usable ore produced, however, has increased steadily.

TABLE 5.—Crude and usable iron ore produced in the United States, grade of usable ore, and ratio of concentration, by districts

Year	Crude ore mined (thousand long tons)	Usable ore produced		Ratio of crude ore to usable ore
		Quantity (thousand long tons)	Grade (percent)	
Lake Superior district				
1949.....	70,306	68,494	50.77	1.2:1
1950.....	66,641	70,627	49.75	1.2:1
1951.....	115,845	93,647	51.10	1.2:1
1952.....	84,933	77,095	53.35	1.2:1
1953.....	120,425	95,655	59.49	1.3:1
1954.....	80,725	60,991	59.69	1.3:1
1955.....	109,118	83,255	51.28	1.3:1
1956.....	110,050	77,817	59.60	1.4:1
1957.....	122,763	83,530	52.43	1.5:1
1958.....	81,445	51,777	51.89	1.6:1
1959.....	74,021	43,959	53.91	1.7:1
1960.....	123,652	71,792	54.13	1.7:1
1961.....	105,565	53,207	55.27	2.0:1
1962.....	111,829	55,556	55.78	2.0:1
1963.....	117,314	59,132	56.51	2.1:1
Southeastern district				
1949.....	11,495	7,692	36.64	1.5:1
1950.....	11,910	7,598	37.43	1.6:1
1951.....	14,450	8,587	37.57	1.7:1
1952.....	12,975	7,624	37.95	1.7:1
1953.....	11,663	7,092	38.13	1.6:1
1954.....	10,737	6,150	37.72	1.7:1
1955.....	11,010	7,166	36.77	1.5:1
1956.....	11,117	6,635	39.09	1.8:1
1957.....	12,668	6,749	33.33	1.8:1
1958.....	5,898	3,827	37.89	1.5:1
1959.....	8,194	4,350	38.60	1.9:1
1960.....	7,627	4,365	39.27	1.7:1
1961.....	6,159	3,520	36.61	1.7:1
1962.....	7,357	3,186	29.70	2.3:1
1963.....	6,547	2,419	36.79	2.7:1
Northeastern district				
1949.....	8,405	3,864	61.45	2.2:1
1950.....	9,573	4,475	61.14	2.1:1
1951.....	10,787	5,151	61.34	2.1:1
1952.....	10,182	4,425	61.47	2.3:1
1953.....	12,025	5,162	61.58	2.3:1
1954.....	9,719	4,684	62.51	2.4:1
1955.....	11,608	4,629	67.85	2.4:1
1956.....	11,621	4,667	62.65	2.4:1
1957.....	12,116	4,922	62.89	2.4:1
1958.....	8,626	3,412	62.03	2.5:1
1959.....	9,634	3,679	62.22	2.5:1
1960.....	11,124	4,125	61.85	2.7:1
1961.....	9,966	4,015	62.13	2.4:1
1962.....	11,222	4,254	63.65	2.5:1
1963.....	11,311	4,672	63.13	2.3:1

TABLE 5.—Crude and usable iron ore produced in the United States, grade of usable ore, and ratio of concentration, by districts—Con.

Year	Crude ore mined (thousand long tons)	Usable ore produced		Ratio of crude ore to usable ore
		Quantity (thousand long tons)	Grade (percent)	
Western district				
1949.....	6,655	4,442	52.25	1.3:1
1950.....	7,653	5,891	50.97	1.3:1
1951.....	10,952	8,181	53.43	1.3:1
1952.....	10,158	8,020	53.82	1.2:1
1953.....	12,184	8,859	57.93	1.4:1
1954.....	8,663	6,065	53.60	1.3:1
1955.....	11,114	6,658	51.63	1.6:1
1956.....	10,335	8,073	51.68	1.7:1
1957.....	6,750	6,457	48.63	1.0:1
1958.....	5,572	5,178	50.24	1.1:1
1959.....	4,751	4,350	50.76	1.1:1
1960.....	5,327	4,683	62.19	1.2:1
1961.....	5,329	4,810	52.78	1.2:1
1962.....	6,350	4,438	62.79	1.4:1
1963.....	7,805	4,531	55.21	1.7:1
Other districts				
1957.....	7,155	3,650	37.41	2.0:1
1958.....	5,254	2,751	52.59	1.9:1
1959.....	6,491	3,169	54.69	2.1:1
1960.....	5,733	3,127	59.76	1.9:1
1961.....	9,255	5,097	52.83	1.9:1
1962.....	6,535	3,455	53.53	1.9:1
1963.....	9,766	4,833	55.12	2.0:1

<sup>1</sup> Includes 29,219 tons of ore from Puerto Rico in 1951; 153,613 tons in 1952.

The Southeastern district was the second ranked source of domestic iron ore until 1957, but since then its production of crude and usable ore have declined, and in 1963 it produced less than any of the other recognized districts. The tenor of usable ore produced there has remained about the same, but the grade of crude ore mined has declined.

The Northeastern district has maintained its position among the iron ore districts, producing about the same quantity of crude and usable ore. The average grade of usable ore produced in the district has increased slightly in the last decade.

The Western district also has maintained its position while producing an increasingly better grade of usable ore.

The United States uses from 120 to 125 million tons or more of iron ore per year, or roughly 1,300 pounds of iron in ore for each ton of steel produced. Most of it is smelted to produce iron, but small quantities are used in making cement, special high-density concrete, and paint pigments, and magnetite concentrate is used for heavy-medium in coal processing plants.



Iron ore has become a significant part of the foreign trade of the United States as domestic production has fallen steadily, and imports have increased to supplant domestic mines in supplying the country's needs, figure 1.

The chart, figure 2, showing the average grade of imports and the average grade of iron ore produced in the United States in the last two decades provides insight into this competition for the domestic market. It is apparent that the average grade of usable ore produced in the United States ultimately will equal or exceed that of imported ore.

Most of the U.S. foreign trade in iron ore has been with Canada. Venezuela supplanted Canada as the principal supplier for a short time, but considering both exports and imports, iron

ore trade with Canada has always been the larger.

From 1960 to 1963 Canada supplied 44 percent of iron ore imports; Venezuela supplied 35 percent; Chile 10 percent; and Peru about 4 percent. Most imported blast furnace ore originates in these four countries. Most of the open-hearth, lump ore originated in Brazil and Liberia, with lesser amounts from Venezuela and Chile.

The United States sells about 5 million tons of iron ore per year to Canada and more than 1 million tons to Japan. Sales to Canada are essentially trades made to cut down the transportation costs in each country.

Iron ore is not subject to tariffs.

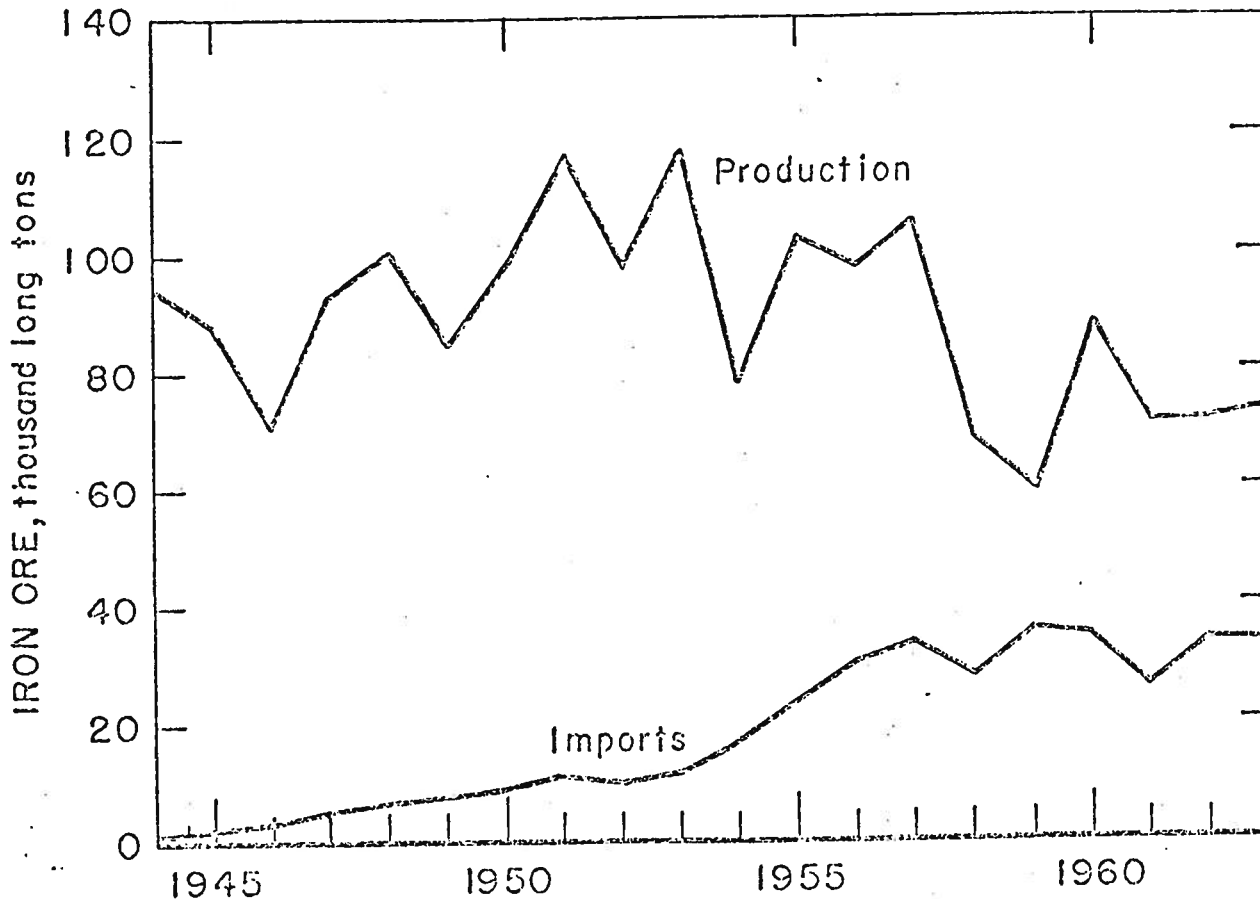


FIGURE 1.—United States Iron Ore Production and Imports for Consumption.

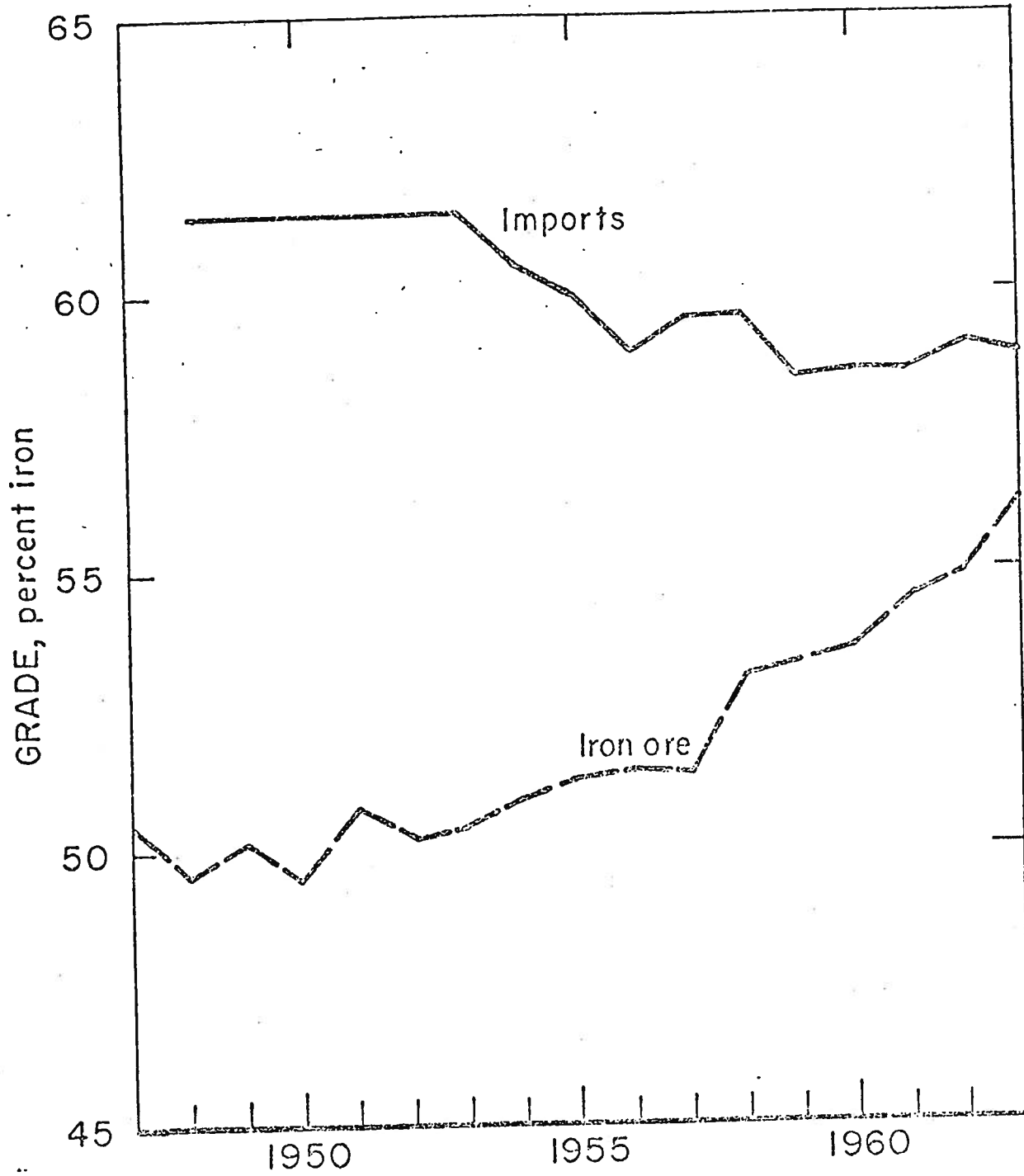


FIGURE 2.—Average Grades of Domestic and Imported Usable Iron Ore Consumed in the United States.

## STRATEGIC CONSIDERATIONS

Iron is absolutely essential to the economic well-being and safety of the United States. The principal danger to supply is vulnerability of the transportation system. Most of the Lake Superior district iron ore moves to markets through the Great Lakes, and this movement is essential if the country is to have an adequate supply of iron ore because railroads do not have enough capacity to replace the Lake transportation system. Furthermore, the St. Lawrence Seaway carries 10 to 15 million tons of iron ore annually from Canada to the steel-producing centers on the lower Great Lakes, and the United States is partially dependent on iron ore from South America. Stockpiling iron ore, to date, has been deemed impractical.

The United States emerged from the era of peacetime self-sufficiency in high-grade iron ore about the latter part of the 1940's. In an emergency, however, the United States could be self-sufficient for 2 or 3 years. This does not mean that there is not enough iron ore in the country to supply our needs, only that its geographic distribution is such that the output cannot be easily increased. If ore from Canada were available, the two countries probably could be self-sufficient indefinitely.

## GOVERNMENT PROGRAMS

The Defense Production Act of 1950 included provision for government assistance in exploration and development of iron-ore deposits, and the Internal Revenue Act of the same year provided accelerated tax amortization for new and expanded iron-ore production facilities. Iron-ore exploration assistance was continued until May 15, 1953, when it was suspended. It was reactivated again by order of the Secretary of the Interior on July 24, 1961, and is still available January 1965. Rapid tax amortization incentives were continued through September 29, 1955. During the time the expansion goal permitting rapid tax amortization of capital invested in iron-ore facilities was in effect, planned investments under the program totaled over \$1.25 billion.

## PRICES AND COSTS

Table 6 gives the Lake Erie price for iron ore, 1955-59 average and 1960-61. Lake Erie base prices are established each year by publication of a major contract between a prominent iron ore producer and a steel corporation. Other companies follow this lead and negotiate contracts accordingly. Lake Erie base prices are published each year before the start of the Lake

Superior shipping season by several trade journals and by leading mining companies.

Current iron-ore mining costs range from about \$2.50 per ton in open pits to \$10 or more per ton in underground mines. The average production costs of iron ore produced in underground and open pit mines in Minnesota, 1952-56 average and 1957 to 1961, are given in table 7.

TABLE 6.—Lake Erie base prices of iron ore, per long ton, 51.5 percent iron, natural

Year	Old range lessemer	Old range nonlessemer	Mesabi lessemer	Mesabi non- lessemer
1955-59 (average).....	\$11.41	\$11.29	\$11.21	\$11.05
1960.....	11.65	11.70	11.60	11.45
1961.....	11.63	11.70	11.60	11.45
1962.....	11.05	10.90	10.60	10.65
1963.....	11.05	10.60	10.60	10.65

TABLE 7.—Average cost per long ton of mining and beneficiating iron ore in Minnesota<sup>1</sup>

Year	Develop- ment	Labor and supplies	Other <sup>2</sup>	Royalty	Total
1952-56 (average).....	\$0.625	\$0.905	\$9.915	\$0.433	\$2.878
1957.....	.691	.959	1.115	.474	3.239
1958.....	.632	.691	1.622	.413	3.753
1959.....	.737	1.212	1.932	.451	4.415
1960.....	.755	1.131	1.701	.523	4.170
1961.....	.787	1.150	2.618	.537	4.622

<sup>1</sup> Bulletin of the University of Minnesota, Mining Directory Issue, V, 63, No. 9, May 1, 1963.

<sup>2</sup> Includes beneficiation.

## TAXES

Federal tax laws allow iron-ore miners a 15 percent depletion deduction from gross income to arrive at net taxable income. Direct State taxes are levied on reserves, both developed and undeveloped. In some instances, however, reserve tax laws for low-grade deposits have been relaxed, and now only low-grade ore production is taxed.

## EMPLOYMENT AND PRODUCTIVITY

The number of men employed at domestic iron mines and beneficiating plants has declined about one-third since World War II. Employment has been related to usable ore production but has not fluctuated with it directly because mining companies have planned operations to maintain a stable labor force. The mining companies have also kept most men employed year round. These practices have obscured productivity measurements so that year to year comparisons are not significant. For example, data reported to the Bureau indicates that output per man in 1955 was 1.73 tons of usable ore per hour, and in 1962 it was 1.72 tons per hour.

There is no doubt, however, that the trend in productivity is upward. Output was only 0.75 ton per man-hour in 1923, the first year employment figures were reported to the Bureau.

TABLE 8.—*Employment and productivity at iron ore mines and beneficiating plants*

Year	Average number men employed	Productivity, tons usable ore per man-hour
1925.....	35,767	.717
1930.....	33,075	.816
1935.....	14,987	1.162
1940.....	25,123	1.512
1945.....	26,777	1.455
1950.....	31,687	1.402
1955.....	29,000	1.75
1960.....	27,543	1.63
1962.....	21,010	1.72

## TRANSPORTATION

More than 75 percent of the iron ore produced in the United States is transported in ore carriers on the Great Lakes. The Great Lakes' fleet in 1964 numbered 170 vessels. Their average age was 41 years. The quantity of ore that the fleet can move in any one year varies according to the length of the shipping season; the annual carrying capacity under the most favorable circumstances is 76.3 million long tons.

Iron ore transported over the Great Lakes system is transferred a minimum of 3 times (rail, to loading dock, to ship, to railroad) and a maximum of 5 times (mine truck, to railroad, to loading dock, to ship, to stockpile, to railroad). Each transfer generates additional fines that detract from the value of the ore. Blending of ore from various mines to assure a guaranteed analysis is an integral part of the mine-to-rail-to-ship transportation system.

The St. Lawrence Seaway carries over 12 million long tons of foreign iron ore annually to Great Lakes ports of the United States. This ore comes principally from the Quebec-Labrador iron belt of Canada via rail to river ports and thence through the Seaway following a transfer pattern identical to that of ore transported on the Great Lakes system. Seaway locks limit ore carriers to 25-foot 6-inch draft, 700-foot length, and 75-foot beam. Iron ore in transoceanic trade is carried in special bulk cargo ships ranging in carrying capacity from 25,000 to 70,000 long tons. Oceangoing iron ore cargo ships with carrying capacity over 100,000 long tons are being planned.

Iron ore from mines in the Southeastern, Northeastern, and Western States including Texas and Missouri normally moves all-rail to

the furnaces, and 1 to 2 million tons annually is transported all-rail from the Lake Superior district. Less than 1 percent of the iron ore produced domestically is moved from mines to furnaces by truck.

Transportation costs of delivering iron ore from mines to the furnaces range from 40 to 50 percent of the value of the ore. In 1963, charges over the Great Lakes system from the Mesabi range to the Pittsburgh Steel district were \$6.60 per long ton; and all-rail charges were \$10.23 per ton.

## RESEARCH

Since World War II, private industry has been heavily engaged in iron research, principally to develop ore dressing techniques for beneficiating the taconites of Minnesota, and the jaspilites of Michigan. The industry supports research laboratories, with a total annual budget estimated at more than \$5 million. Total industry expenditure for iron ore and associated research is believed to range between \$15 and \$25 million annually. The Federal and State annual total is about \$1 million.

The Minnesota State Mines Experiment Station at the University of Minnesota has been conducting a small but comprehensive iron-ore research program since 1911.

The Michigan Bureau of Mineral Research was established on the campus of the Michigan College of Mining and Technology in 1955, principally to conduct research projects applicable to the State's iron-ore resources.

The Bureau of Mines has had an iron-ore research program since establishment of Bureau stations at the University of Minnesota in 1917 and at the University of Alabama in 1921. Until World War II, the Bureau's program was conducted without urgency and only to develop basic scientific technical data to expand and develop the base of the country's non-ore resources, and to encourage development of iron industries in new areas. During the war, the Bureau explored many iron-ore deposits. Since then, the Bureau has been concerned with more immediate problems of increasing domestic iron supply and of devising mining and ore-dressing techniques that would enable profitable exploitation of complex iron-ore deposits. A small hearth, low-shaft experimental blast furnace is operated at Bruceton, Pa., by the Bureau in cooperation with private industry to study material substitution and operating techniques applicable to conservation and development of the Nation's iron resources.

## OUTLOOK

The iron ore industry will be a vital part of the expanding industrialization brought about by rising living standards and a growing population. New mines will be opened to share in the markets created by the iron and steel industries now being planned for the recently independent, less developed nations. Others will be opened to help supply the demands foreseen for industrial areas now in existence. Those mines producing high-grade, low-silica pellets or equivalent will tend to capture the world markets. When most of the existing blast furnace capacity using high-grade pellets is utilized, partially reduced agglomerates will tend to supplant the pellets. That is when more blast furnace capacity is needed, it will be obtained through use of partially reduced agglomerates in preference to building more furnaces.

Technology will continue to exert strong influence on the course of the iron ore industry. Except in unusual circumstances, iron ore will be mined in open pits from the large low-grade, easily beneficiated deposits. The trend toward larger equipment and automation of transportation and crushing plants will continue. Drilling and blasting practices in the taconite mines will improve but not at the fast rate of the last decade.

By 1970 essentially all iron ore produced for consumption by the industrialized nations will be beneficiated. The conventional gravity and magnetic separation and flotation ore dressing processes will be refined and used more in series or combinations to produce a higher-grade product with decreasing silica-alumina limits. Electrostatic separation and roasting to obtain iron minerals susceptible to magnetic attraction probably will be applied commercially within the next decade.

Pelletizing will continue to be the preferred method of iron ore agglomeration in the United States and will be used more in other countries, but it will not replace existing sintering plants. Partial reduction in conjunction with pelletizing will be applied increasingly. However, researchers eventually will find a method to bypass the agglomeration process so that fine grain concentrate can be used directly to produce iron.

General economic and political activities probably will have little effect on the structure of the domestic iron ore industry, but production and transportation relative costs will trend downward. Common market countries may regulate the iron and steel industries to some extent but, other than in Luxembourg and the Lorraine district of France, competition even-

tually will force establishment of a free iron-ore market in Europe.

The outlook for economic and political activities related to the world iron-ore industry is that the long-term trend in the price of iron ore in terms of constant value dollars will be downward, and that future government actions will not adversely influence the industry and in some instances will actually favor it.

Worldwide capacity to produce iron ore probably will continue greatly to exceed requirements. Nevertheless, many mining districts now supplying ore to restricted markets may not have capacity to supply all ore of the grade and quality needed.

Mine capacity is distinguished from probable production which is related to but not numerically identical to requirements. In North America mine capacity to produce high-grade agglomerates in the United States will increase steadily. The Lake Superior district will continue to be the principal source of domestically produced iron ore. The district's capacity to produce high-grade taconite pellets will reach 30 million tons annually by the late 1960's and 40 to 50 million tons by 1980. By then the district also will have capacity to produce 10 million tons of high-grade pellets annually from semitaconite or soft ores. The district's capacity to produce direct shipping ores and the conventional 51 to 60 percent iron-ore concentrate probably will decrease rapidly through the next 5 years, and may be only 5 to 10 million tons by 1980. Capacity to produce these conventional ores in the Lake Superior district will be fixed by the domestic steel industry's need for flexibility in output.

The Northeastern district including Pennsylvania probably will maintain capacity to produce at least 6 million tons of high-grade iron ore agglomerates annually until 1980, although new deposits will have to be developed to do so.

The Southeastern district's productive capacity probably reached bottom when most of the underground mines in the Big Seam of the Clinton formation were shut down in 1959. Capacity to produce 2 to 3 million tons annually more than likely will be maintained in the southeast through 1970, but unless technology develops, competition from foreign operations will close most of the mines within the next few years.

Iron-ore productive capacity in the Western district, which includes Missouri, will expand to keep pace with Western markets, probably reaching 14 million tons annually within 5 years. It is just a question of time before the large

low-grade iron resources of Arizona, Nevada, and Montana are exploited on a large scale. Even assuming no radical change in technology or in transportation costs, it is expected that at least one deposit in each of these States will be producing ore by 1975. If transportation costs can be halved, deposits in South Dakota probably will be exploited for the Eastern market.

Alaskan iron ore deposits may be exploited for export to Japan or for local use. In either case their impact on the world's iron ore industry will not be significant.

Accordingly, it is expected that United States iron ore production for internal consumption will be 80 million tons of 60 percent iron ore by 1970 and 92 million tons by 1980. In addition 5 to 10 million tons will be produced annually for the export market.

Canadian iron ore productive capacity without doubt will be expanded at a rate to supply all the iron ore the U.S. and Canadian markets will absorb. In addition, Canadian ore will be mined for export to both Asiatic and European markets. The Japanese probably will continue to buy ore from Canada at a rate commensurate with other trade between the two countries. Japan bought 1,545,000 tons of Canadian ore in 1962. Canadian producers will be at a cost disadvantage competing with South American and African producers for the European markets, but high quality, reliability, and preferential treatment by the British may enable the Canadians to maintain substantial exports eastward. Canada sold 2,850,000 tons of iron ore to European countries in 1962. Canada's capacity to produce high-grade iron ore probably will exceed 60 million tons per year by 1980. Actual output, however, may range substantially below the growth rate indicated by that figure.

Mexico will produce iron ore for its own needs but probably will not export significant quantities. Almost certainly, Mexican iron ore will not affect U.S. markets.

The outlook is for iron ore producers in South America actively to continue supplying ore to the United States, Japan, and European countries. The only readily apparent conditions that could prevent their doing so are political instability and confiscatory taxes. Large, easily mined, high-grade deposits, year-round moderate climate, and in most instances proximity to salt water ports give the South American producers an inherent economic advantage over most other producers.

Transportation probably will continue to be the bottleneck that limits iron ore output in the Minas Gerais district of Brazil. This situation may be alleviated within 5 years by a new rail line from the district to Rio de Janeiro. The outlook is for favorable government action to

permit building of such a line. A new line, and enlarged capacity through the part of Vitória will increase Brazil's potential for iron ore exports to 30 million tons per year. Iron ore needs of the Brazilian iron and steel industry will not affect significantly Brazil's capacity to export ore.

Chile's iron ore productive capacity more than likely will remain above its own needs and ability to find markets. Export capacity could reach 20 million tons per year by 1980, but export shipments probably will not increase at a comparable rate.

Peru's iron ore productive capacity is expected to change very little in the next decade or two. Considering the planned developments in Australia and potential developments in the Western United States there is much doubt that there will be incentive for Marcona to install a new plant to obtain more production. Increased efficiency and minor plant additions may increase Peru's export capacity to 10 million tons per year. Output will depend on markets. The Peruvian iron ore industry should be competitive around the world; therefore, an aggressive sales policy could result in exports much higher than the estimated 10 million tons.

The Venezuelan iron ore industry may be on the threshold of a revolutionary technical change that will put it far ahead of its competitors in supplying merchant ore to the world's markets. The government has been asked to approve plans to lay a pipeline from the oilfields of Eastern Venezuela in the State of Anzoategui to the mines in Piar District of Guayana area in the State of Bolivar. The line is to transmit natural gas for use in an iron ore reduction plant to upgrade Guayana ore from 60 to 85 percent iron. The plans call for initial plant annual capacity of 1 million tons of finished product which can be increased readily to 10 million tons.

The natural gas reduction plans greatly enhance the outlook for the Venezuelan iron ore industry. The combination of inexpensive reductant and high-grade, low-silica ore favor a successful operation. An 85 percent iron bearing material with suitable physical properties and stability to stand long-distance transportation would make its own market if offered at prices competitive with the contained iron in pellets and high-grade ore.

Accordingly, it is expected that by 1970 the Venezuelan iron ore industry will have annual capacity to produce 10 million tons of partially reduced ore plus 10 million tons of high-grade ore and that by 1980 the production capacity for partially reduced ore will be increased to 20 million tons.

European iron ore mines, with the exception of those in the Soviet Bloc and on the Scandinavian Peninsula, in the future will not be as significant a source of ore for the European iron and steel industry as they have been in the past. The iron ore industries in Great Britain, West Germany, France, Luxembourg, Spain, Austria, Italy, and Yugoslavia in all probability will either remain static or decline in relation to the size of their cohabitant steel industries.

Iron mines in Sweden, Norway, and Finland do not compare favorably in inherent cost of production with open-pit mines in more temperate and tropical climates. Nevertheless, the iron ore industry of these northern countries will continue to produce on a large scale, although individual small mines may not be able to meet world competition. The outlook is for total mine capacity of 30 million tons annually by 1970 and 40 million tons by 1980.

Among the Soviet Bloc countries only the U.S.S.R. appears to have potential for a growing iron ore industry to serve a market that is demanding higher and higher grade ore. The need of the steel industries of Bulgaria, Czechoslovakia, East Germany, Poland, Hungary, and Rumania for quality raw material to increase output will probably make them part of this market. Thus the outlook for the iron ore industry of the Soviet Bloc is for the mines in U.S.S.R. to expand capacity to supply most of the needs of the Soviet satellites and for many of the low-grade mines of the satellites to close.

It is doubtful that Soviet Bloc ore will move outside the Bloc and probable that free world ore will be shipped into the Bloc. The quantity of free world ore entering the Bloc will be determined by trade agreements similar to those now existing between Brazilian and Indian mining companies and communist governments. Therefore, the iron ore and iron and steel industries in the Soviet Bloc countries will have little if any influence on free world trade in iron ore.

African iron mines are destined to assume a larger role in the iron ore trade of the world. Political stability and economic responsibility probably will be the prime factors influencing the direction of growth. The Liberian industry, judging by past government performances, is the most favorably situated to expand at a rate compatible with potential markets. By 1980 the industry should have capacity to produce 20 million tons per year.

The Mauretania and Sierra Leone industries have established markets in world trade, and there is no reason to believe that internal circumstances will be altered sufficiently to jeopardize external relations. The industry of

Mauretania probably will have iron ore productive capacity of 8 to 10 million tons annually, by 1980. That of Sierra Leone probably will have 3- to 4-million ton capacity.

Gabon has the resources to support a substantial merchant iron ore industry. The extent of development in capacity to produce iron ore will be dependent on the activity in the European steel industry and on government stability. If the government encourages free industrial enterprise through 1970, development of iron ore resources will be dependent on markets for iron ore then existing.

Guinea also has the resources to support substantial merchant iron ore industries, but the apparent course of its government makes it unlikely that private companies will invest the necessary funds.

India is the only Asiatic country expected to increase significantly its capacity to produce iron ore for export. Goa's capacity probably will remain around 6 million tons per year while capacity to produce for export in Malaya and the Philippines will decline. The iron ore industry of India will increase its capacity well in excess of domestic requirements and in addition will maintain capacity to produce 2 to 3 million tons annually more than its export market. The total capacity of the Indian industry is expected to exceed 30 million tons of iron ore per year by 1980.

There is not much doubt that an active, aggressive iron ore export industry will be developed in western Australia by 1970. Its size will be limited only by its competition around the world. Trade agreements with Japan and European countries probably will be instrumental in developing capacity to produce at least 5 million tons per year for export by 1970 which may be increased to 10 million tons per year by 1980. However, if markets can be found for the ore, capacity could reach 20 million tons or more per year by 1970 and 40 million by 1980.

Assuming that super ore carriers are built to minimize the ocean transportation disadvantage in supplying European markets that Australian iron ore producers will have with those on the east coast of South America and the west coast of Africa, Australian capacity to produce iron ore for export should reach 8 million tons by 1970 and 15 million by 1980.

Thus the integrated capacity outlook is that the principal iron mines producing for international trade, excluding those in Communist countries, probably will be able to produce 200 to 300 million tons of high-grade iron ore per year by 1980.

Barring a major war that restricts freedom of the seas, every industrialized nation seems as-

sured of an adequate supply of high-grade iron ore easily available for a price equal to or less than that now established.

The United States is assured of the iron ore it needs under practically any circumstance as long as the North America transportation system is left intact.

The outlook for the domestic industry has bettered each year since innovation of the taconite industry. This improving situation has been brought about by technologic advance and increasing knowledge. Thus the thesis that the best key to the future is record of the past provides assurance that the domestic industry will flourish in the next decade with current research and development substantiating this outlook. More than likely producers of high-grade pellets will tend to capture the markets and the producers of partially reduced pellets will take over from them as all the excess blast furnace capacity for smelting standard pellets is utilized. Domestic iron mines are in an excellent position to be in the forefront of this pattern.

Figure 3 shows the U.S. iron ore supply 1940-64 and a forecast of the sources of supply and the rate of consumption 1964 through 1980.

The forecast was made on the basis of anticipated U.S. steel production, which was converted to iron in ore requirements assuming that 0.67 ton of iron from ore would be used to produce each ton of steel. This figure discounts the impact that basic oxygen converters, and continuous casting units could have on the scrap to hot metal ratio. Iron requirements were converted to iron ore assuming an average grade of 60 percent iron for both domestic and foreign ore. U.S. steel production was projected in accordance with the historical use of steel per capita, assuming that it would increase at the 1.6 percent compound annual rate forecast by the Bureau of Mines, for the growth rate of population and labor force. This projection then was modified by consideration of technologic, economic, political, and social elements to forecast an iron and steel industry growth rate slightly above that expected for the U.S. population. The principal elements considered in making the forecast were—(1) better steel, (2) use of substitutes, (3) development of new uses, (4) imports of foreign steel, (5) expansion of foreign markets, (6) less expensive production methods, and (7) shifting U.S. population.

Better quality steel greatly slowed the rate of steel consumption in the last decade, but to the presently produced quality level this factor apparently has exerted maximum influence and

therefore will not change the trend significantly in the future.

Use of substitutes and development of new uses for steel have by and large offset one another in the past. Now better quality steel and the steel industry's comprehensive, application research program should begin to bear fruit. New steel uses in the future probably will more than offset use of steel lost to substitutes.

Steel imports probably will exceed exports for the short term (5 years). The determining factor in the balance will be cost and quality. Here again quality and research favor the U.S. industry. Furthermore, the technologic advances and capital improvements of recent years and the probability of continuing advance and improvement put the domestic industry in an increasingly better competitive cost position. This leads to the conclusion that for the long term, steel exports will exceed imports, and the per capita output of steel will tend to increase accordingly.

Changing distribution of people in the United States will tend to cut down per-capita steel consumption because a larger percentage of the people will live outside the Chicago-Pittsburgh industrial complex where steel is the leading structural material.

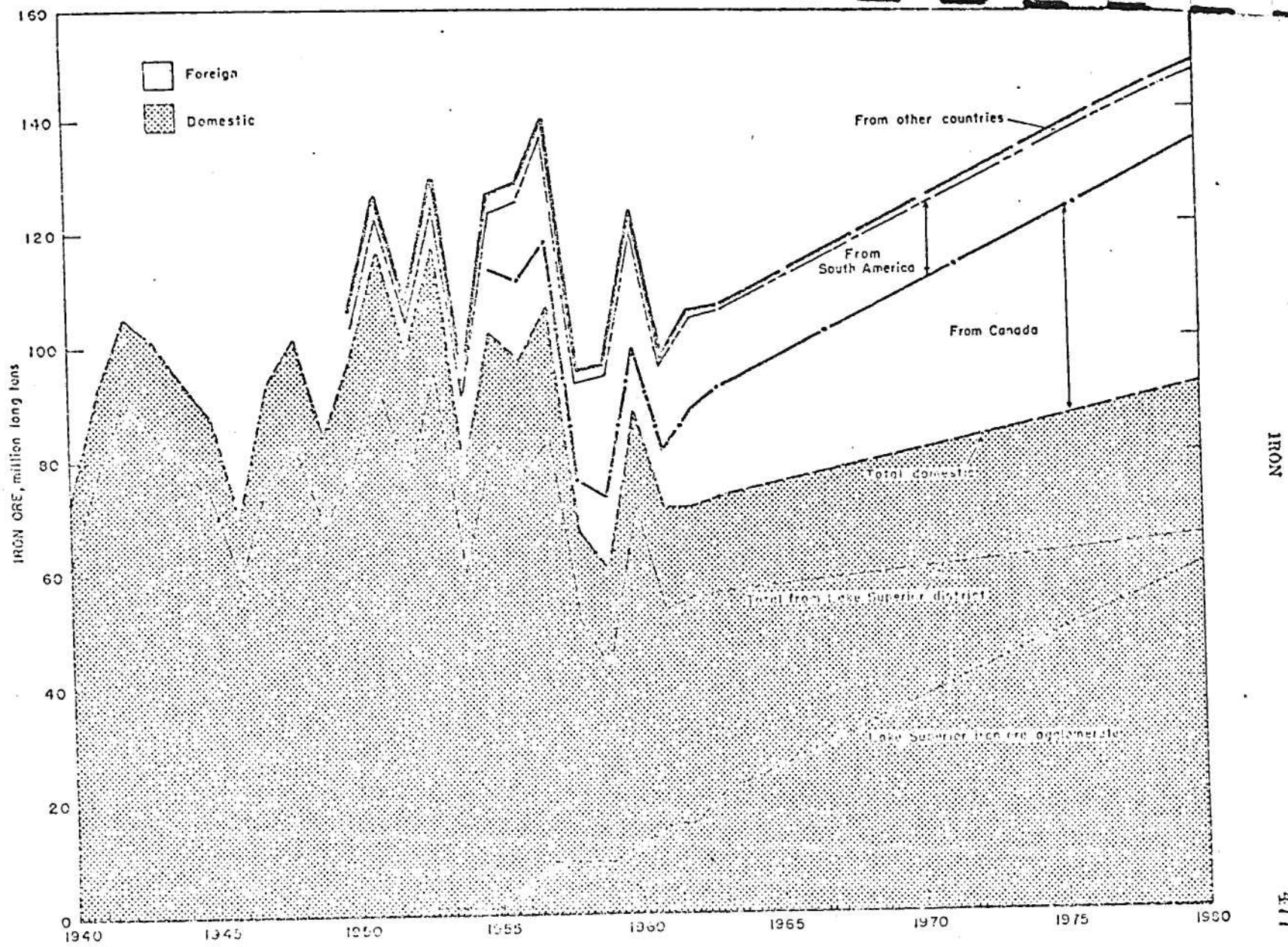
Reinforced concrete and timber are preferred to steel in the Pacific Coast States, where the population is expected to increase 62 percent between 1960 and 1980, and the Mountain States, where it is expected to increase 55 percent. These increases are in contrast to the total expected population increase of only 37 percent.

These seven elements expected to influence the rate of steel production in large measure offset each other. However, time will tend to strengthen those elements that can increase steel output and weaken those that could decrease it. With this in mind the forecast of a growth rate only slightly higher than rate of population growth is considered conservative.

The forecast of iron ore requirements is a mean from which actual consumption is not expected to vary more than 15 percent, and the total supply—domestic production, plus imports, minus exports—is not expected to vary from actual consumption more than 10 percent. Domestic and Canadian mines producing high-grade iron ore pellets for consumption in the United States are in a position to maintain output near capacity. Those producing lesser quality will necessarily provide most of the flexibility needed to adjust supply to consumption. Iron ore imports from Africa and South American countries are not expected to vary significantly from the quantities shown on figure 3.



FIGURE 3.—Sources of United States Iron Ore Supply 1910-63 and Predicted Sources 1961-80.



IRON

## PROBLEMS

The principal problem of the domestic industry is to meet both price and quality competition from foreign producers. It must do so if it is to continue to exist. The domestic industry has proximity in its favor, but all other elements of iron ore production favor one or the other of foreign operations producing iron ore for sale in the United States. This leads to many specific operating problems.

The iron formation in the Lake Superior region is exceptionally hard and fine-grained; consequently, both mining and grinding costs are high. Use of jet piercing equipment for drilling and scientifically designed blasting have been partial solutions to the problem, but the fact remains that mining costs in the Lake Superior district are not competitive with those in Canada.

Loss of the iron minerals not susceptible to magnetic attraction in taconite processing operations in Minnesota and some other districts is a problem. Researchers seem to be approach-

ing an economical solution, but the problem is not yet solved.

More than two-thirds of the iron formation that is equal in grade to that being mined is not profitably amenable to any known method of concentration. Thus, inability to mine and process nonmagnetic taconite is a problem. The same is true of partially oxidized iron formation and soft hematite ores.

Transportation of iron ore is a problem, particularly from the Lake Superior district because there it is a seasonal operation. Not only are transportation costs high, but periodic operation forces consumers to maintain a large iron ore inventory. Agglomeration of fine-grained ore and iron ore concentrate is a solution to smelting these materials but because of the cost, it is not a completely satisfactory solution. Exploitation of titaniferous iron ore deposits is a problem because iron ores containing more than 1 percent of titanium cannot be easily smelted in a blast furnace without excessive operating difficulties and high fuel consumption.

## REFERENCES

1. AMERICAN IRON AND STEEL INSTITUTE. Directory of Iron and Steel Works of the United States and Canada, 1964, 409 pp.
2. BANKS, G. N., R. A. CAMPBELL, AND G. E. VIENS. Iron Ore Pelletizing, a Literature Survey. Canada Dept. of Mines and Tech. Surveys, Ottawa. Mines Branch Inf. Circ. 152, August 1963, 23 pp.
3. BANNING, LLOYD H., AND OLIVER C. FURSMAN. Melting Pyrophoric Hydrogen-Reduced Iron Powder for Production of Steel. BuMines Rept. of Inv. 6105, 1964, 37 pp.
4. BARRETT, EDWARD P. Sponge Iron and Direct-Iron Processes. BuMines Bull. 519, 1951, 143 pp.
5. BECKHAIN, ROBERT W., AND DANIEL M. URICH. Grate-Kiln Pelletizing Process at Humboldt. Min. Cong. J., v. 47, No. 12, December 1961, pp. 61-64, 68.
6. BISHANES, G., AND T. L. JOSEPH. Topochemical Aspects of Iron Ore Reduction. J. Metals, v. 7, No. 5, May 1955, sec. 3, pp. C39-C45.
7. BROWN, DWIGHT C. Direct Reduction of Iron Ores. A Review Presented at a Meeting of the Amer. Inst. of Chem. Eng., New York, Dec. 3-7, 1961, 97 pp.
8. BUREAU OF MINES AND GEOLOGICAL SURVEY. Materials Survey—Iron Ore. Compiled for National Security Resources Board. 1956, 335 pp.
9. CHAPMAN, H. H. The Iron and Steel Industries of the South. Univ. of Alabama Press, University, Alabama, 1953, 427 pp.
10. CHERVALL, G. The Echeverria Ore Reduction Process. Pres. at United National Interregional Symp. on The Application of Modern Technical Practices in the Iron and Steel Industry to Developing Countries, Prague, Czechoslovakia, Nov. 11-26, 1963, 15 pp.; Steel Symp. 1963, Tech. Paper B.7, Prague, Czechoslovakia, Sept. 16, 1963, 15 pp.
11. CELADA, J., AND J. SKELLY. The HyL Process. Pres. at United Nations Interregional Symp. on the Application of Modern Technical Practices in the Iron and Steel Industry to Developing Countries, at Prague, Czechoslovakia, Nov. 11-26, 1963, 17 pp.; Steel Symp. 1963, Tech. Paper No. B.6, Prague, Czechoslovakia, Oct. 15, 1963, 17 pp.
12. CHASE, P. W., AND D. L. McDRIBE. Present and Future of Direct Reduction Processes in Latin America. Pres. at Third Latin American Congress of the Iron and Steel Industry at Caracas, Venezuela, July 8-13, 1963. Blast Furnace and Steel Plant, October 1963, pp. 868-878, 897.
13. CLARKE, F. W. Data of Geochemistry. Geol. Survey Bull. 770, 1924, 841 pp.
14. CORE, S. G. The Reduction of Iron Ores—The Possibilities of an Alternative to the Blast Furnace. Murex Rev., v. 1, No. 17, 1957, 34 pp.
15. DAVIS, E. W. The Evaluation of Iron Ore. Univ. of Minnesota Inst. Technol., Inf. Circ. 1, 1940, 23 pp.
16. DEAN, R. S., AND C. W. DAVIS. Magnetic Separation of Iron Ores. BuMines Bull. 425, 1941, 417 pp.
17. DeVANEY, F. D. Pelletizing in Shaft Furnaces. J. Metals, v. 10, No. 2, February 1958, pp. 118-128.
18. DYLENFORTH, W. P. Electrical Concentration of Iron Ore. Pres. at AIME meeting, Tampa, Fla., October 1957.
19. ENGLISH, ALAN, AND M. F. MORGAN. Downdraft Taconite Pellet Hardening. J. Metals, v. 10, No. 2, February 1958, pp. 118-128.
20. FEDERAL TRADE COMMISSION. Control of Iron Ore. 1952, 157 pp.

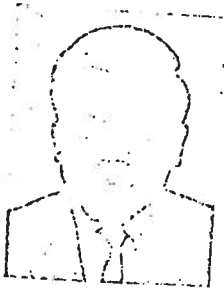
21. FINE, M. M., J. P. HANSEN, AND NORWOOD B. MELCHER. Prereduced Iron Ore Pellets: A New Blast Furnace Raw Material. BuMines Rept. of Inv. 6152, 1962, 19 pp.
22. FINE, M. M., P. L. WOOLF, AND N. BERNSTEIN. Experimental Production and Smelting of Prereduced Iron Ore Pellets. BuMines Rept. of Inv. 6523, 1964, 28 pp.
23. HAINS, D. J. The SL Direct Reduction Process. Pres. at United Nations Interregional Symp. on the Application of Modern Technical Practices in the Iron and Steel Industry to Developing Countries, Prague, Czechoslovakia, Nov. 11-25, 1963, 15 pp.; Steel Symp. 1963, Tech. Paper B.5, Czechoslovakia, Sept. 19, 1963, 15 pp.
24. HAYWARD, CARLE R. An Outline of Metallurgical Practice. D. Van Nostrand Co., Inc., New York, 2d ed., 1946, 689 pp.
25. IRON AGE. Controlled Reoxidization of Artificial Magnetite to Gamma Hematite. V. 172, No. 1, July 2, 1953, pp. 142-146.
26. KALLING, B., AND P. JOHANSSON. Reduction of Iron Ore Without Melting in Rotary Furnaces. J. Iron and Steel Inst., v. 177, May 1, 1954, pp. 76-85.
27. KNEPPER, WILLIAM A. Agglomeration, International Symp. on Agglomeration. 1st, Philadelphia, 1961. Amer. Inst. of Min. Met. and Petrol. Eng. 1, 109 pp.
28. MCANENY, COLIN C. Iron--How Is Direct Reduction Doing Commercially? Eng. and Min. J., v. 161, No. 12, December 1960, pp. 84-89.
29. REBE, L. Development of Chemical Treatment of Low-Grade Iron Ores at Appleby Fordingham. J. Iron and Steel Inst. (London), v. 181, pt. 1, pp. 26-40.
30. ROE, L. A. Iron Ore Beneficiation. Minerals Pub. Co., Lake Bluff, Ill., 1957, 305 pp.
31. SQUIRES, A. M., AND C. A. JOHNSON. The H-Iron Process. J. Metals, pt. 1, v. 9, No. 4, April 1957, pp. 586-590.
32. STEWART, ALEX. Direct Reduction of Iron Ores. Min. Cong. J., v. 44, No. 12, December 1958, pp. 34-38, 58.
33. THOENEN, J. R., A. H. REED, AND B. H. CLEMMONS. The Future of Birmingham Red Iron Ores, Jefferson, Ala. BuMines Dept. of Inv. 4988, 1963, 71 pp.
34. UDY, M. J., AND M. C. UDY. The Strategic-Udy Process, Direct Iron Reduction. Western Miner and Oil Rev. (Vancouver, B.C.), v. 31, No. 6, June 1958, pp. 49-42.
35. UNIVERSITY OF MINNESOTA MINES EXPERIMENT STATION. Iron Ore Beneficiation. Oct. 1, 1949, 171 pp.
36. VIENS, G. B., R. A. CAMPBELL, AND R. R. ROGERS. Experimental Electric Smelting of Ores and Related Materials at Department of Mines and Technical Surveys. Can. Min. and Met. Bull., v. 50, No. 538, February 1957, pp. 70-77.
37. VIOLETTA, D. C. Updraft Pelletizing of Specular-Hematite Concentrates. J. Metals, v. 10, No. 2, February 1958, pp. 118-128.
38. WHALEY, HENRY P. Milling Methods at Erie Mining Co. Twenty-Fourth Annual Mining Symp., Record of the Proceedings, Duluth, Minn., Jan. 14-16, 1963, pp. 7-14.



## HYDROMETALLURGY AT SHERRITT GORDON

# Economics of Iron and Sulphur Recovery from Pyrites

B. R. MEHTA, Development Engineer,  
P. T. O'KANE, Manager, Development,  
Research and Development Division,  
Sherritt Gordon Mines Limited,  
Fort Saskatchewan, Alberta



MEHTA



O'KANE

B. R. MEHTA was born in India and graduated from the Department of Chemical Engineering of the University of Bombay in 1962. After working for one year with National Rayon Corporation, Bombay, he joined the graduate school of chemical engineering of the University of Alberta, Edmonton, and graduated with an M.Sc. in chemical engineering in 1965. He then joined the Research Council of Alberta, Edmonton. On completion of one year of project work at the Research Council, he joined Sherritt Gordon Mines Ltd. He is now a development engineer in the Development Department.

P. T. O'KANE was born in Flin Flon, Manitoba and graduated in chemical engineering from the University of Saskatchewan in 1955. He joined Sherritt Gordon Mines Limited following graduation, working in their Pilot Plant and Engineering Department at Fort Saskatchewan.

He left Sherritt Gordon to spend one year at Nicaro, Cuba and another year with Atomic Energy of Canada Limited; then rejoined Sherritt Gordon in 1960 as head of Process Engineering. He became Lead of Development in 1964 and currently is manager, Laterite Project, Sherritt Gordon Mines Limited.

THE PAPER WAS PRESENTED: as "Economics of Iron and Elemental Sulphur Recovery from Pyrite Using Low-Temperature Thermal Decomposition and Aqueous Oxidation" at the C.I.M. Conference of Metallurgists, King's on, Ont., August, 1967. It will appear in the C.I.M. Transactions for 1968.

KEYWORDS IN THIS PAPER: Iron, Sulphur, Pyrites, Thermal decomposition, Aqueous oxidation, Hydrometallurgy, Dissolution, Hydrolysis, Economics, Sherritt Gordon Mines Ltd.

### ABSTRACT

The increasing trend of the world price of sulphur has necessitated the exploitation of sulphide minerals for the production of elemental sulphur. Technological advances in hydrometallurgy have now provided technically feasible processes for the recovery of elemental sulphur and for the production of high-purity iron from a pyrite feed containing non-ferrous metals and non-metallic impurities.

The economics of such a venture are largely dependent on the location of pyrite with respect to the accessibility of the markets for elemental sulphur and iron. The freight rates and long-term price trends for both sulphur and iron are important factors influencing the viability of such a project. In addition to the credits for sulphur and iron values, the recovery of the non-ferrous metals such as copper, zinc, cobalt, nickel, lead and precious metals in the raw material improves the over-all economics.

The process involves, in addition to other optional steps, thermal decomposition of pyrite to approximately iron monosulphide and elemental sulphur, followed by aqueous oxidation of the monosulphide to hydrated iron oxide and elemental sulphur. The cost estimates for this process are presented for three plant capacities: 250,000 stpy, 500,000 stpy and 1,000,000 stpy pyrite. Two grades of raw material, their price and the sales price of the products are varied to illustrate different situations and locations. The over-all economics and the profitability of the different cases are discussed.

### I. INTRODUCTION

THE LARGE INCREASE in the world price of sulphur in the past three years has prompted a great deal of activity in the exploitation of sulphide minerals for the recovery of elemental sulphur as well as for sulphuric acid production.

The economics of sulphuric acid production from pyrite are influenced markedly by several factors in addition to the price of iron tonne. One factor is the marketability of the by-product iron oxide, which is dependent upon contained impurities and accessibility to market. Another important factor is the cost of the

pyrite and its transportation from mine to plant site. The location of the plant site would also influence the sales price of sulphuric acid manufactured in excess of the captive consumption.

The advantages of shipping elemental sulphur rather than pyrite or sulphuric acid are obvious and this has resulted in the development of several processes for the recovery of elemental sulphur. A commercial example is the Outokumpu Oy plant (1) in Finland, in which the labile atom of sulphur is liberated by flash smelting. The resultant iron sulphide matte is roasted to give sulphur dioxide for sulphuric acid manufacture and an iron oxide calcine.

Purification of the iron oxide calcines from pyrite or pyrrhotite roasters with respect to silica content and with respect to non-ferrous metals is practised commercially by Montecatini (2) in Italy and the Dowa Mining Company (3) in Japan. The Lurgi Company in Germany has developed a process for removal of non-ferrous metals from the roasted calcines by volatilization of the chlorides (4). However, none of the above processes, either alone or in combination, yield all the sulphur in the elemental form and an iron product of acceptable purity.

Sherritt Gordon Mines Limited has developed a new process (5) in which essentially all of the sulphur is converted to the elemental form and all impurities can be separated to give very pure iron.

The next step in further development of the process is to examine the economics using preliminary cost estimates based on the laboratory results. The decision to prove the process on the pilot-plant scale would be based on this preliminary economic study. This paper is concerned with these economics and the influence on the economics of such variables as plant capacity, plant location, raw materials cost, sales value of the products, form of the final iron product and impurities.

The foregoing is accomplished by estimating capital and operating costs for three plant capacities — 250,000, 500,000 and 1,000,000 tons\* per year of pyrite. Two process schemes are considered at each capacity level. The first scheme would process a 'clean' or relatively pure pyrite to produce sponge iron and elemental sulphur; the second would treat an impure pyrite containing assorted non-ferrous metal impurities to produce high-purity sponge iron or high-purity iron powder as well as elemental sulphur and concentrates containing the non-ferrous metals.

The material and energy balances and process flow sheets upon which the estimates are based are also presented. The process is being assessed in broad terms, although it has been necessary to fix certain design parameters, particularly the analysis of the pyrites with respect to non-ferrous metal content and the unit operating costs for a particular location. The authors wish to emphasize that such assumptions are made only to illustrate one example and adjustments must be made to consider specific cases.

## II. PROCESS DESCRIPTION AND CONDITIONS

The process and the laboratory work to develop the process have been described in detail elsewhere (5), and thus will be discussed only briefly here.

\*Short tons (2000 lbs.) are used throughout this paper unless otherwise designated.

The process consists essentially of four major steps:

1. Low-temperature thermal decomposition of the pyrite to elemental sulphur and iron monosulphide.
2. Aqueous oxidation of the iron monosulphide to hydrated iron oxide and elemental sulphur.
3. Dissolution of the hydrated iron oxide and non-ferrous metal values, purification and hydrolysis of pure basic ferric sulphate.
4. Processing to a final iron product.

As mentioned above, two processing schemes are considered, one treating a relatively clean pyrite containing few impurities, whereby step 2 can be eliminated, and the other processing an impure pyrite containing substantial impurities. The process conditions and design parameters for clean pyrite processing are given in Table I and in Figures 1 and 2; those for impure pyrite processing are shown in Table II and Figures 3 and 4.

### 1. Thermal Decomposition

Decomposition of pyrite into artificial pyrrhotite or iron monosulphide plus elemental sulphur is an endothermic reaction requiring, theoretically, 525 BTU per pound of pyrite ( $\text{FeS}_2$ ). It is proposed to carry out the decomposition in a fluidized bed reactor, essentially following the system proposed by Heath and Graves (6).

Material and energy balances have been calculated for 1 ton of pyrite feed; these are shown in the preliminary process flow diagram, Figure 1.

Pyrite concentrates are withdrawn from storage to be dried in a fluid-bed dryer. The dried pyrite is then combined with unreacted sulphides from the aqueous oxidation step (described below) and fed to the thermal decomposition reactor.

The endothermic heat of reaction is satisfied by the combustion of Bunker 'C' fuel oil directly in the fluid bed. It is necessary to control the oxygen so as to add only the stoichiometric quantity required to achieve complete combustion of the fuel.

The 1,300°-1,500° F operating temperature combined with 30 minutes retention time should result in an iron monosulphide product with a sulphur to iron molar ratio of approximately 1 to 1.15, which is adequate for the subsequent processing steps. The solids discharge from the reactor into a quench tank, where they are slurried with a recycle solution for feed to the aqueous oxidation autoclave.

The combustion gases leaving the reactor contain the elemental sulphur distilled in the reaction together with small quantities of hydrogen sulphide, sulphur dioxide and possibly carbonyl sulphide,  $\text{COS}$ . These gases pass through dust cyclones, a waste heat boiler, an electrostatic precipitator and then a sulphur recovery section consisting of a catalytic converter to convert  $\text{HS}$  plus  $\text{SO}_2$  to elemental sulphur and a sulphur condenser generating low-pressure steam. The combustion gases are then water-scrubbed and vented to atmosphere.

Any arsenic contained in the pyrite is also evolved and can be expected to report with the elemental sulphur.

Lime treatment of the elemental sulphur, as practised by Outokumpu Oy (7), is one method of removing arsenic from the sulphur.

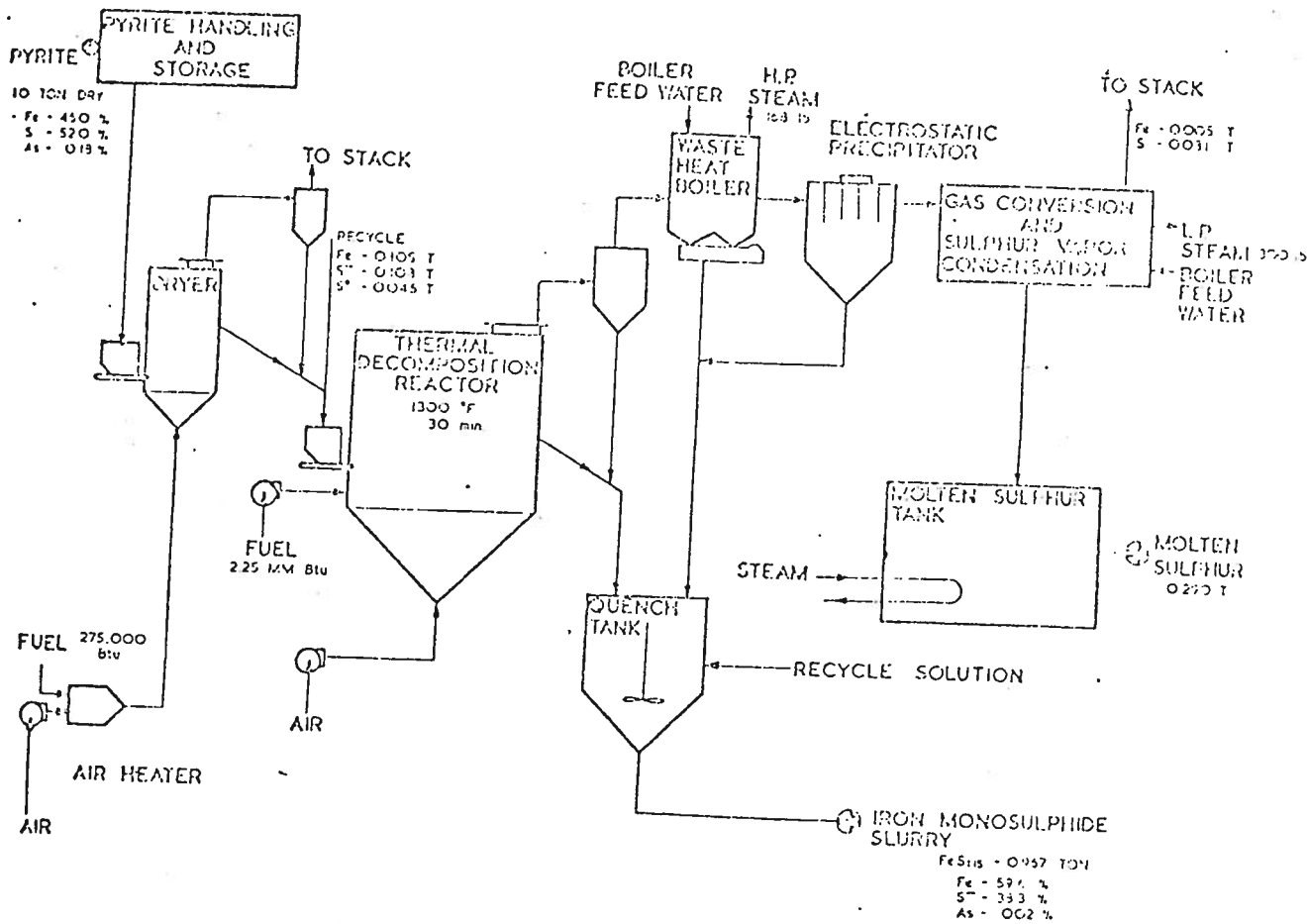


Figure 1.—Schematic Equipment Flow Diagram for Low-Temperature Thermal Decomposition.

Table I — Basic Design Parameters for Treatment of Clean Pyrite  
(See also Figures 1 and 2)

1. Pyrite Feed							
Chemical Analysis							
	Fe	S	Cu	Zn	Pb, Ni, Co	As	Insol.
% by Weight, Dry Basis	46	52	0.05	0.07	<0.01	0.18	1.6
Moisture	10%						
Size	70% minus 200 mesh						
2. Over-all Recoveries							
Iron	98%						
Sulphur (Elemental)	91%						
3. Thermal Decomposition							
Sulphur Recovery	94% of S evolved 99% of S <sup>2</sup> recycled						
Arsenic Evolved	90%						
(S/Fe) in Iron Monosulphide	1.15 molar						
4. Aqueous Oxidation							
Oxidant	Air (100% excess)						
Oxygen Partial Pressure	150 psi						
Temperature	230°F						
Retention Time	1.5 hours						
Slurry Density	600 gpl solids						
Recycle Solution	20 gpl H <sub>2</sub> SO <sub>4</sub>						
Sulphur Conversion to S <sup>2</sup>	70% per pass						
Non-Ferrous Metal Extraction	90%						
5. Product Analysis (% By Weight, Dry Basis)							
	Fe	S	Cu	Zn	As	Insol.	
Iron Monosulphide	59.6	33.3	0.052	0.073	0.005	1.8	
Elemental Sulphur		9.5					
Sponge Iron	0.1						

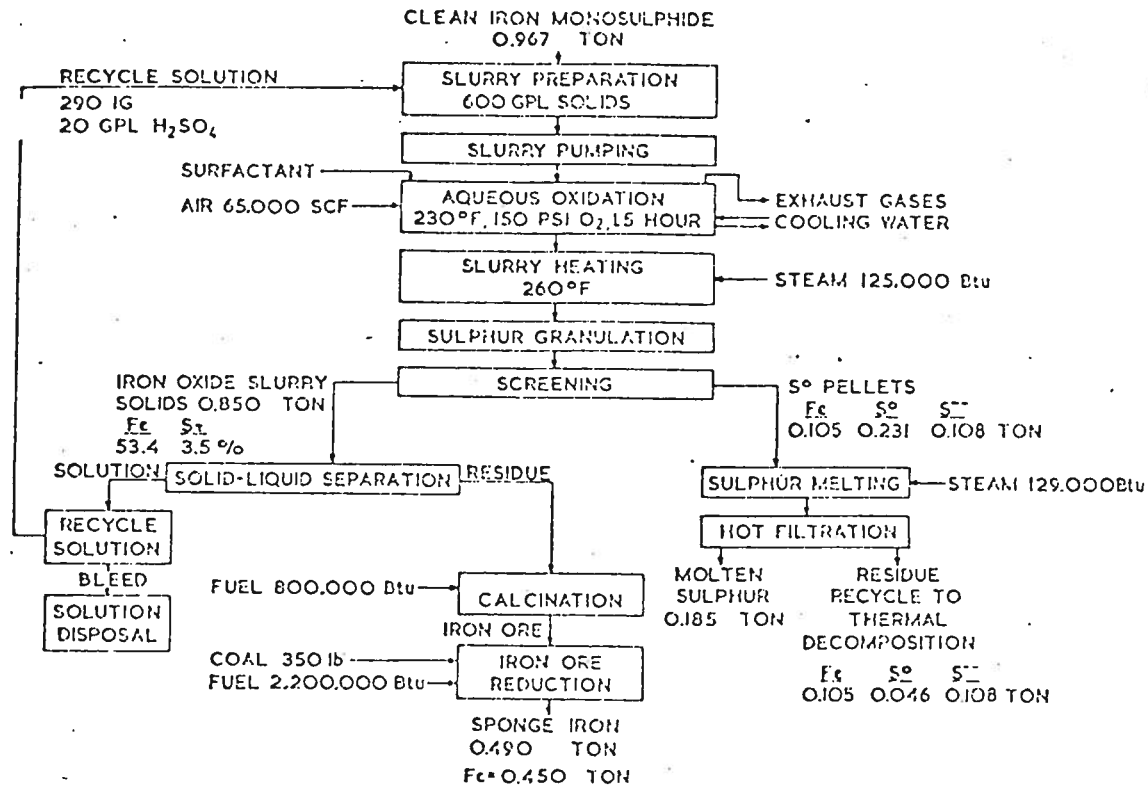


Figure 2.—Process Flow Diagram for the Aqueous Oxidation of Clean Iron Monosulphide.

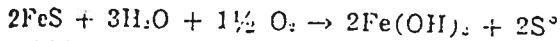
Table II — Basic Design Parameters for Treatment of Impure Pyrite  
(See also Figures 1 and 4)

1. Pyrite Feed	Fe	S	Cu	Zn	Ni	Co	Pb	Ag(1)	As	Insol.
Chemical Analysis										
% By Weight, Dry Basis	43.1	50.5	0.3	2.2	0.03	0.05	1.4	1.76	0.4	18
2. Over-all Recoveries										
Iron.....	98%									
Sulphur (as Elemental).....	91%									
Non-Ferrous Metals.....	90%									
3. Thermal Decomposition										
As per Table I										
4. Aqueous Oxidation										
As per Table I										
5. Iron Dissolution										
80 gpl Fe dissolved										
$\frac{S(SO_2) + S(Fe_2SO_4)}{Fe(Fe_2O_3)} = 1.1$ Molar Ratio										
$\frac{S(SO_2)}{S(Fe_2SO_4)} = 1.0$										
6. Metal Stripping										
Fe (ground sponge iron) and S° = 1.1 Stoichiometric										
7. Hydrolysis										
100% Excess Air										
100 gpl Fe in Feed Solution										
80 gpl Fe Precipitated										
8. Product Analysis (% by Weight, Dry Basis)										
	Iron Monosulphide		Elemental Sulphur		Sponge Iron		High-Purity(3) Iron Powder			
Fe.....	55.10				91.5		99.9			
S.....	36.50		99.5		0.005		0.007			
Cu.....	0.30				0.002		0.002			
Zn.....	2.50				0.005		0.005			
Ni.....	0.01				**		**			
Co.....	0.05				**		**			
Pb.....	2.50				**		**			
Ag(1).....	2.50									
As.....	0.05				0.01		0.002			
Insol.....	2.70				(2)		0.0004			

(1) Ounces per Ton (2) Dependent upon coal analysis  
 (\*\*) Less than 0.001% (3) Carbon, 0.003%  
 (4) Si

## 2. Aqueous Oxidation

This step is an oxidation reaction converting iron monosulphide to hydrated iron oxide and elemental sulphur according to the following over-all reaction:



This reaction is carried out in a recycling aqueous

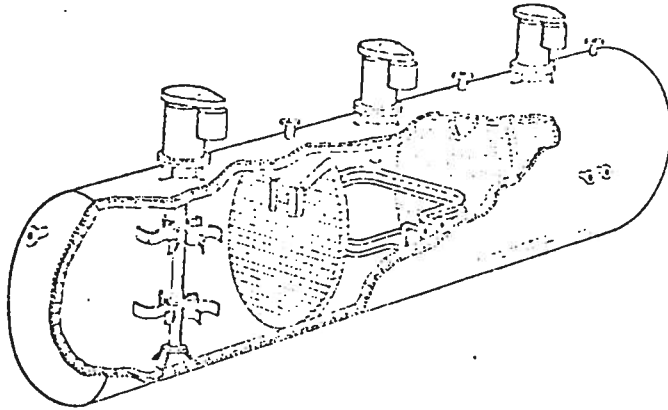


Figure 3.—The Aqueous Oxidation Autoclave.  
 Design Pressure ..... 1000 psig  
 Design Temperature ..... 300° F  
 Material of Construction .... carbon steel shell, lined with lead and acid brick, with titanium internals.

medium and is exothermic, generating 1,525 BTU per pound of FeS. The calculated material and energy balances are shown in Figure 2 for the clean pyrite scheme; those for the impure pyrite scheme are given in Figure 4:

The aqueous oxidation autoclave shown schematically in Figure 3 is a three-compartment vessel of carbon steel construction lined with lead and acid-resistant brick. Agitators and other internals may be fabricated from titanium. This vessel would be similar in construction and service to that used commercially by Sherritt Gordon at Fort Saskatchewan for acid leaching (8).

Iron monosulphide from the thermal decomposition reactor is repulped in recycle solution from either the liquid-solids separation step following sulphur granulation or following hydrolysis, depending on the treatment scheme. This slurry is then pumped into the autoclave by means of a suitable high-pressure slurry pump. Several pump designs have been used for applications similar to this (9), although the proven Galligher 'Airdrex' pump has been assumed for the purpose of this preliminary estimate. This estimate is based on using 800 psig air as the source of oxygen, with the air compressor driven by a gas turbine. A waste heat boiler on the gas turbine exhaust generates all process steam requirements. Pure oxygen or oxygen-enriched air might prove to be economic alternatives to the use of high-pressure air.

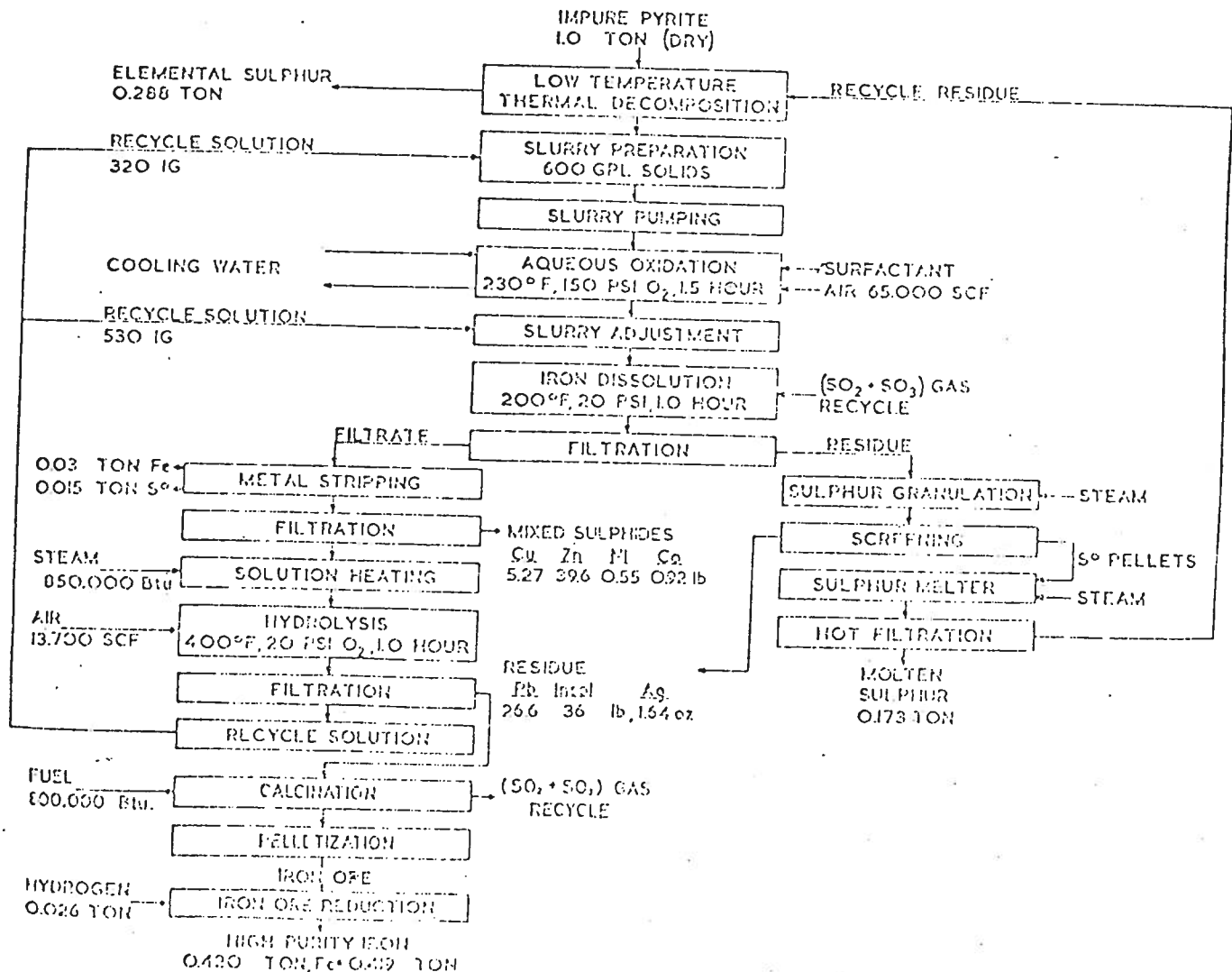


Figure 4.—Process Material and Energy Balances



The exothermic heat of reaction is removed by cooling coils installed in the autoclave. Exhaust gases depleted in oxygen leaving the autoclave are finally water-scrubbed to remove acid mist before venting to atmosphere.

In the case of clean pyrite treatment, the slurry discharging from the aqueous oxidation autoclave is steam-heated to a temperature of approximately 260°F (slightly above the melting point of sulphur), and then flash-cooled under controlled conditions to form pellets of elemental sulphur and unreacted sulphides. Little or no oxides or sulphates are associated with the elemental sulphur. The resultant slurry is next passed over a 25-mesh screen to separate the pellets from solution and hydrated iron oxide.

The elemental sulphur pellets are then treated in the sulphur recovery circuit. This circuit consists of a sulphur melter where pellets are agitated and heated in water at a temperature of 300°F; this hot slurry is then filtered in a pressure filter to recover approximately 95 per cent of the elemental sulphur present as a pure product. The hot filtration residue, consisting of unreacted pyrite, unreacted pyrrhotite and some elemental sulphur, is ball-milled for recycle to the thermal decomposition step.

The undersize from the sulphur pellet screen is filtered on disc filters without washing. The hydrated iron oxide solids still contain about 3.5 per cent sulphur, essentially in the form of basic ferric sulphate. The solution is recycled to the aqueous oxidation autoclave; it will likely be necessary to bleed some of this recycle solution in order to remove small quantities of impurities such as copper and zinc. This bleed solution would be treated with lime before disposal.

Processing after the autoclave in the case of impure pyrite treatment is described below.

### 3. Iron Dissolution and Hydrolysis of Basic Ferric Sulphate

This description refers to the treatment of impure pyrite only, but it can also be considered for processing clean pyrite if high-purity iron powder is desired.

The aqueous oxidation autoclave discharge slurry is first flashed from 230°F to atmospheric pressure. This slurry is then diluted to approximately 200 gpl solids by the addition of recycle solution from the hydrolysis step and then charged directly to the iron dissolution vessel. This vessel is fabricated from mild steel and lined with rubber and acid brick. Internals may be titanium or a 'Hastelloy' alloy. The slurry is contacted with sulphur dioxide gases generated in the calcination step. The SO<sub>2</sub> is absorbed to totally dissolve iron as ferrous sulphate; the elemental sulphur, pyrite, pyrrhotite, precious metals and lead sulphate remain unattached.

The slurry following the iron dissolution step can be readily filtered on a drum filter, but it may possibly be advantageous to first thicken this slurry. The residue is heated above the melting point of sulphur, flash-cooled and screened to recover unreacted sulphides and elemental sulphur in a pellet form as described above. These pellets pass then to the sulphur recovery circuit, also as described above. The remaining solids (those not included in the pellets) contain all of the lead as lead sulphate, the gangue materials and any precious metals. This material should be a suitable feed to a lead smelter.

Table III — Basis for Capital Cost Estimate

1. Battery limit plant costs are calculated as a function of purchased equipment cost, as follows:
  - a. Installation cost at 25 per cent of purchased equipment cost.
  - b. Piping cost at 20 per cent of purchased equipment cost.
  - c. Instrumentation cost at 12 per cent of purchased equipment cost.
  - d. Electricals cost at 10 per cent of purchased equipment cost.
  - e. Site preparation and building cost at 30 per cent of purchased equipment cost.  
Physical plant cost = Purchased equipment cost + Items (a) to (e).
  - f. Engineering and Construction cost at 25 per cent of Physical plant cost.  
Direct plant cost = Physical plant cost + Item (f).
  - g. Contingency at 15 per cent of Direct plant cost. Battery limit plant cost = Direct plant cost + Item (g).
2. Off-site facilities for the grass-root plants include:
  - Utility distribution
  - Yard piping
  - Land
  - Maintenance shop
  - Laboratory and office buildings
  - Railway siding and roads
  - Fire protection
  - Etc.
3. Process Development Costs are not included.
4. Royalties are not included and would be extra.
5. A hypothetical plant site is assumed in the Great Lakes area.
6. No provision made for escalation.

The filtrate consists of a solution containing approximately 100 gpl dissolved iron as well as any nickel, cobalt, copper or zinc. It is assumed for this estimate that the non-ferrous metal values are stripped as a bulk precipitate; selective precipitation could also be considered. Copper, nickel and cobalt are cemented by the addition of finely divided sponge iron. Zinc is precipitated as the sulphide. This bulk precipitate can be easily filtered in a pressure filter and dried for shipment.

The solution now goes to the hydrolysis step, which is carried out at a temperature of 400°F in a tower lined with lead and acid brick. Only slight agitation is required; this is provided by the air added to convert ferrous to ferric iron. A mixture of hydrated iron oxide and basic ferric sulphate is precipitated; this slurry is filtered on a drum filter, with the filtrate recycling to the iron dissolution step and/or the aqueous oxidation step. The residue is ready for further iron treatment.

### 4. Iron Processing

In the consideration of clean pyrite treatment, the hydrated iron oxide is calcined at a temperature of 1,800°F to drive off the remaining sulphur. The calcines are pelletized and are then reduced to sponge iron, using, for example, the Steleo-Lurgi process (10).

The basic ferric sulphate - hydrated iron oxide mixture from the impure pyrite scheme is very pure. It can be treated as in the case of the clean pyrite, except that the SO<sub>2</sub> - SO<sub>3</sub> gases driven off in calcination would be recycled to the iron dissolution step, but the calcine may also be reduced to high-purity iron powder if desired.

### III. PRELIMINARY COST ESTIMATES

The capital cost and operating cost estimates are based on the pre-pilot-plant data and design variables described in Tables I and II. The broad basis for these cost calculations are reported for the capital and for the operating costs in Tables III and IV respectively.

A proposed plant is composed of two major sections — thermal decomposition and aqueous oxidation. The calcination and iron ore reduction plants form a part of the latter section. The capital cost for a particular section is determined by grouping the

equipment costs for different operations and adding other costs as a percentage of equipment cost. These cost calculations are illustrated for a plant capacity of 500,000 tons per year of pyrites.

The costs for a thermal decomposition plant of 500,000 tons per annum capacity are shown in Tables V and VI. These cost figures compare with similar cost data reported elsewhere (6). As the thermal decomposition operation is essentially identical for treating either a clean or an impure pyrite, the capital and operating costs of such a plant, at the same capacity level, are assumed to remain unaltered for both kinds of pyrite.

**Table IV — Basis for Direct Operating Cost Estimate**

<b>1. Labour (Including Fringe Benefits)</b>	
Operating.....	\$30,500/Man/Shift/Year* \$3.66 per man-hour
Supervisory.....	\$18,000/Man/Shift/Year \$5.77 per man-hour
<b>2. General Plant Overhead Expenses</b> 50% of Labour	
<b>3. Utilities</b>	
Power.....	0.8c/kwh
Natural Gas.....	40c/Million BTU
Bunker 'C' Oil.....	40c/Million BTU
Cooling Water.....	1.1c/1,000 IG
Process Water.....	45c/1,000 IG
Boiler Feed Water.....	60c/1,000 IG
Surfactant.....	35c/lb
Filter Aid.....	\$1.25/lb
Hydrogen.....	\$150/ton
<b>4. Maintenance Supplies and Labour</b> Thermal Decomposition: 3% of fixed capital per annum Aqueous Oxidation: 4% of fixed capital per annum	
<b>5. Property Taxes and Insurance</b> 1.25% of fixed capital per annum	

\*Canadian dollars are used throughout this paper

**Table V — Capital Cost Estimate**

PLANT: Thermal Decomposition of Pyrite  
CAPACITY: 500,000 tpy Pyrite

No.	Item	Cost \$
1.	Total Purchase Equipment Cost.....	1,300,000
	a. Concentrate Handling and Storage.....	\$ 70,000
	b. Drying Station.....	140,000
	c. Thermal Decomposition System.....	380,000
	d. Dust Removal and Gas Cooling.....	240,000
	e. Sulphur Conversion and As Removal.....	370,000
	f. Sulphur Handling and Storage.....	160,000
	Sub-Total.....	\$1,300,000
	Battery Limit Plant Cost.....	
2.	Off-site and Auxiliaries at 15% of Battery Limit Cost.....	\$3,831,000
	Limit Cost.....	574,000
	Total Plant Cost.....	\$1,405,000
3.	Interest during Construction at 6% p.a.	198,000
4.	Plant Start-up Costs.....	85,000
	<b>TOTAL FIXED CAPITAL COST</b> .....	<b>\$1,688,000</b>
5.	Working Capital at 10% of Fixed Capital Cost.....	470,000
	<b>TOTAL CAPITAL COST</b> .....	<b>\$5,158,000</b>
	Say.....	\$5,200,000

**Table VI — Direct Operating Cost Estimate**

PLANT: Thermal Decomposition of Pyrite  
CAPACITY: 500,000 tpy Pyrite  
OPERATION: 330 days/year

No.	Item	Quantity	Qty/Ton Pyrite	Cost \$/Year	Unit Cost \$/Ton Pyrite
1.	Operating Labour	4 Men/Shift			
2.	Supervision	1/2 Man/Shift	0.07 hr	122,000	0.24
3.	Plant Overhead	59% (1 + 2)	0.603 hr	24,000	0.05
4.	Power	315 kw		73,000	0.15
5.	Natural Gas	2.8 scfm	5.0 kwh	20,000	0.04
6.	Bunker 'C' Oil	534.4 lb/d	274 scf	56,000	0.11
7.	Boiler Feed Water	50 Igpm	120 lb	450,000	0.90
8.	Maintenance (Supply & Labour)	47 IG		14,100	0.03
9.	Taxes and Insurance	3% of Fixed Capital		149,700	0.28
10.	Misc. Plant Supplies	1.25% of Fixed Capital		59,600	0.12
11.	Technical Services	Nominal		35,000	0.07
12.	Contingency	Nominal		25,000	0.05
		10% of 1-11		101,500	0.20
	<b>TOTAL DIRECT OPERATING COST</b>			<b>\$1,120,500</b>	<b>\$2.24</b>
	Say			\$1,120,500	\$2.24

Table VII — Capital Cost Estimate

PLANT: Aqueous Oxidation of Clean Iron Monosulphide  
CAPACITY: 500,000 tpy Pyrite

No.	Item	Cost \$
1.	Total Purchased Equipment Cost.....	\$ 1,840,000
a.	Slurry Handling and Pumping.....	\$ 250,000
b.	Aqueous Oxidation Autoclave.....	550,000
c.	Sulphur Granulation and Hot Filtration.....	150,000
d.	Solid-Liquid Separation.....	600,000
e.	Sulphur Handling and Storage.....	110,000
f.	Recycle Residue Handling.....	100,000
g.	Recycle Solution Storage and Disposal.....	80,000
	Sub-Total.....	\$1,840,000
	Battery Limit Plant Cost.....	\$ 5,422,000
2.	Air Compressor Unit (80,000 scfm at 850 psia, 32,000 hp).....	4,650,000
3.	Calcination Plant (1,200 tpd).....	3,360,000
4.	Iron Ore Reduction Plant (750 tpd).....	4,875,000
	Total Battery Limit Plant Cost.....	18,307,000
5.	Off-sites and Auxiliaries at 15% of Battery Limit Cost.....	2,746,000
	Total Plant Cost.....	\$21,053,000
6.	Interest during Construction at 6% P.A.....	917,000
7.	Plant Start-up Cost.....	150,000
	<b>TOTAL FIXED CAPITAL COST</b> .....	\$22,150,000
8.	Working Capital at 10% of Total Fixed Capital.....	2,215,000
	<b>TOTAL CAPITAL COST</b> .....	\$24,365,000
	Say.....	\$24,400,000

Table IX — Capital Cost Estimate

PLANT: Aqueous Oxidation of Impure Iron Monosulphide  
CAPACITY: 500,000 tpy Pyrite

No.	Item	Cost \$
1.	Total Purchased Equipment Cost.....	\$ 3,186,000
a.	Slurry Handling and Pumping.....	\$ 216,000
b.	Aqueous Oxidation Autoclave.....	507,000
c.	Iron Dissolution and L/S Separation.....	465,000
d.	Sulphur Granulation and Hot Filtration.....	170,000
e.	Metal Stripping and Sulphide Filtration.....	180,000
f.	Hydrolysis.....	970,000
g.	Hydrated Iron Oxide Separation.....	372,000
h.	Sulphur Handling and Storage.....	120,000
i.	Recycle Residue and Solution Handling.....	186,000
	Sub-Total.....	\$3,186,000
	Battery Limit Plant Cost.....	9,331,000
2.	Air Compressor Unit (95,000 scfm at 850 psia, 38,000 hp).....	5,320,000
3.	Calcination Plant (1,200 tpd).....	3,500,000
4.	Iron Ore Reduction Plant (750 tpd).....	4,875,000
	Total Battery Limit Plant Cost.....	\$23,079,000
5.	Off-Sites at 15% of Battery Limit Cost.....	3,461,000
	Total Plant Cost.....	\$26,540,000
6.	Interest during Construction at 6% P.A.....	1,190,000
7.	Start-up Cost.....	\$190,000
	<b>TOTAL FIXED CAPITAL COST</b> .....	\$27,920,000
8.	Working Capital at 10% Fixed Capital.....	2,792,000
	<b>TOTAL CAPITAL COST</b> .....	\$30,712,000
	Say.....	\$30,700,000

Table VIII — Direct Operating Cost Estimate

PLANT: Aqueous Oxidation of Clean Iron Monosulphide  
CAPACITY: 500,000 tpy Clean Pyrite  
OPERATION: 330 days/year

No.	Item	Quantity	Qty/Ton Pyrite	Cost \$/Year	Unit Cost \$/Ton Pyrite
<b>A. Autoclave Operation and Sulphur Recovery Section</b>					
1.	Operating Labour	4 Men/Shift			
2.	Supervision	1/2 Man/Shift	0.07 hr	122,000	0.24
3.	Plant Overhead	50% (1 + 2)	0.03 hr	24,000	0.05
4.	Power	1,136 kw		73,000	0.15
5.	Natural Gas	4,000 scfm	18 kw-hr	72,000	0.14
6.	Boiler Feed Water	60 Tons	4,372 scf	875,000	1.75
7.	Cooling Water	57 IG		117,100	0.23
8.	Process Water	14,000 lpm	13,300 IG	73,200	0.15
9.	Surfactant	400 lpm	380 IG	85,000	0.17
10.	Filter Aid	80 lbs/day	0.05	10,000	0.02
11.	Maintenance (Supply & Labour)	80 lbs/day	0.05	33,000	0.06
12.	Taxes and Insurance	4% of Fixed Cost		434,000	0.87
13.	Misc. Plant Supplies	1.25% of Fixed Cost		151,000	0.30
14.	Technical Services	Nominal		40,000	0.08
15.	Contingency	10% of 1-14		20,000	0.05
				200,000	0.42
	<b>B. Calcination Plant Cost (at \$1.50/ton, 1,200 tpd)</b>		<b>SUB-TOTAL</b>	\$2,236,000	\$1.50
	<b>C. Iron Ore Reduction Plant Cost (at \$1.00/ton, 750 tpd)</b>			712,000	1.42
	<b>TOTAL DIRECT OPERATING COST</b> .....			1,540,000	3.76
				\$4,988,000	\$9.77
	Say.....			\$4,990,000	\$9.77

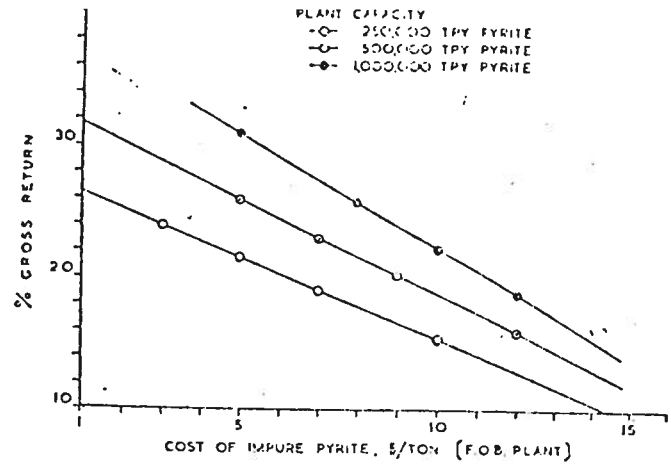
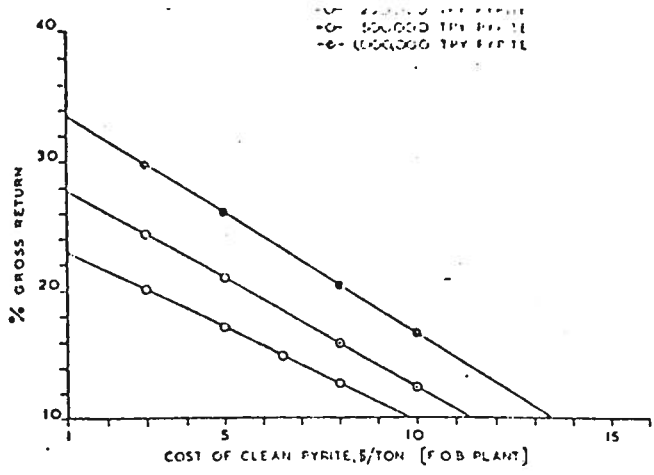


Figure 5.—Effect of the Cost of Clean Pyrite on the per cent Gross Return.

Sponge Iron Price ..... \$30.00/ton  
 Sulphur Price ..... \$31.25/ton  
 \$35.00/lt

Figure 6.—Effect of the Cost of Impure Pyrite on the per cent Gross Return.

Sponge Iron Price ..... \$30.00/ton  
 Sulphur Price ..... \$31.25/ton  
 \$35.00/lt  
 Non-Ferrous Metals Value from Pyrite ..... \$10.10/ton py

Table X — Direct Operating Cost Estimate

PLANT: Aqueous Oxidation of Impure Iron Monosulphide  
 CAPACITY: 500,000 tpy Pyrite  
 OPERATION: 330 days/year

No.	Item	Quantity	Qty/Ton Pyrite	Cost \$/Year	Unit Cost \$/Ton Pyrite
<b>A. Autoclave Operations and Sulphur Recovery Section</b>					
1.	Operating Labour	6 Men/Shift	0.10 hr	183,000	0.35
2.	Supervision	1 Man/Shift	0.01 hr	48,000	0.10
3.	Plant Overhead	50% (1 + 2)		115,000	0.23
4.	Power	1,200 kw		80,000	0.16
5.	Natural Gas for Air Compressor	5,260 scfm	5,000 scf	1,000,000	2.00
6.	Boiler Feed Water	70 lpgm	67 IG	20,000	0.04
7.	Cooling Water	18,000 lpgm	17,270 IG	94,000	0.19
8.	Process Water	700 lpgm	660 IG	150,000	0.30
9.	Surfactant	120 lbs/day	0.07	14,000	0.03
10.	Filter Aid	100 lbs/day	0.10	65,000	0.13
11.	Recycling Iron & Sulphur	Fe <sup>o</sup> & S <sup>o</sup> charged at selling price		528,000	1.06
12.	Maintenance (Supply & Lab)	4% of Fixed Cost		700,000	1.41
13.	Insurance and Taxes	1.25% of Fixed Cost		221,000	0.44
14.	Misc. Plant Supplies	Nominal		50,000	0.10
15.	Technical Services	Nominal		40,000	0.08
16.	Contingency	10% of 1-15		331,000	0.66
SUB-TOTAL.....				\$3,646,000	\$7.29
B. Calcination Plant (\$1.80/ton, 1,200 tpd).....				713,000	1.42
C. Iron Ore Reduction Plant (\$7.60/ton, 700 tpd).....				1,755,000	3.51
TOTAL (A, B & C).....				\$6,114,000	\$12.22
TOTAL DIRECT OPERATING COST.....				\$6,114,000	\$12.22
Say				\$6,100,000	12.20

Table XI — Summary of Cost Estimates

Plant Capacity tpy pyrite	Type of Pyrite	CAPITAL COST			DIRECT OPERATING COST		
		Thermal Decomposition Cost \$	Aqueous Oxidation Cost \$	Total Capital Cost \$	Thermal Decomposition Plant \$/year	Aqueous Oxidation Plant \$/year	Total Direct Operating Cost \$/year
250,000	Clean	3,200,000	13,400,000	16,600,000	650,000	2,600,000	3,250,000
	Impure	3,500,000	17,500,000	20,700,000	650,000	3,200,000	3,850,000
500,000	Clean	5,200,000	24,500,000	29,700,000	1,100,000	4,900,000	6,000,000
	Impure	5,200,000	29,500,000	35,000,000	1,100,000	6,100,000	7,300,000
1,000,000	Clean	8,500,000	45,100,000	51,300,000	2,000,000	9,000,000	11,000,000
	Impure	8,500,000	55,100,000	63,300,000	2,000,000	11,000,000	15,000,000

The battery limit costs of the pressure hydrometallurgical operation in the aqueous oxidation plant, as calculated for clean and impure pyrite at a plant capacity of 500,000 tons per year, are illustrated in Tables VII and IX, respectively. The costs for air compressor units (11) and calcination (12), as well as iron ore reduction (12) plants, are reported on a lump-sum basis. The operating costs on a similar basis are shown in Tables VIII and X for clean and impure pyrites, respectively.

The cost estimates for each capacity and for both kinds of pyrites are summarized in Table XI. The difference in the cost of aqueous oxidation for the treatment of clean and impure pyrite feed material is obvious in Table XI. The iron produced in both cases is in the form of sponge iron; all of the sulphur is in the elemental form.

#### IV. ECONOMICS

The evaluation of the economics of each case is made using the gross return on total capital investment. The direct operating costs, as reported in Table XI, are exclusive of the cost of pyrite and of capital amortization and interest charges. The sales revenue from iron and sulphur products assumed in illustrating the economics is shown in Table XII. The credit for non-ferrous metals is assumed at 60 per cent of the market value as reported in Table XII.

If pyrite can be delivered to the plant site at \$5 per ton, the economics of a plant treating 500,000 tons of pyrite annually are as shown in Table XII. The comparison of the economics of using clean and impure pyrite feed favours the use of impure material because of additional revenue accruing from the non-ferrous metal values.

Starting with the same impure pyrite feed, if the final iron product is in the form of high-purity iron powder, its economics compared to a sponge iron product look quite attractive, as shown in Table XIII. The \$100-per-ton sales price for high-purity iron powder has been arbitrarily assumed, and it is also assumed that hydrogen is used for its manufacture. This comparison shows that gross returns would increase if iron is produced as a specialty product of very high purity.

Using the aforementioned method for evaluating economics, the effect of a variation of pyrite cost on gross returns is shown in Figures 5 and 6 for clean and impure pyrites respectively. At a pyrite cost of \$1 to \$5 per ton and at a plant capacity level of 500,000 tons per year of pyrite and higher, the economics of the process are attractive. A similar trend is observed for the 500,000-tpy pyrite plant by altering the selling price of sulphur and sponge iron, as shown in Figures 7 and 8 respectively. At selling prices of \$30 per ton for sponge iron and \$34/lt of elemental sulphur, the economics of the 500,000-tpy plant are attractive. Again, the preference for the treatment of impure material is apparent.

	Cu	Zn	Ni	Co	Pb	Ag
	0.40	0.145	0.92	2.00	0.14	1.95/oz
	Clean Pyrite	Impure Pyrite				
1. Direct Operating Cost/Year	\$ 6,000,000	\$ 7,300,000				
2. Cost of Pyrite/Year	2,500,000	2,500,000				
<b>TOTAL</b>	<b>\$ 8,500,000</b>	<b>\$ 9,800,000</b>				
3. Sales Revenue/Year						
a. Sulphur	7,300,000	7,200,000				
b. Iron	7,300,000	6,300,000				
c. Non-Ferrous Metals — at 60% of Market Value	--	5,000,000				
<b>TOTAL</b>	<b>\$14,700,000</b>	<b>\$19,100,000</b>				
4. Gross Profit/Year	6,200,000	9,300,000				
5. Total Capital Cost	29,000,000	35,000,000				
6. % Gross Return	21%	26%				
7. Gross Profit/Year						
8. Total Capital Cost						

	Cu	Zn	Ni	Co	Pb	Ag
	0.40	0.115	0.92	2.00	0.14	1.95/oz
	High-Purity Iron Powder Production	Sponge Iron Production				
1. Direct Operating Cost/Year	\$ 9,000,000	\$ 7,300,000				
2. Cost of Pyrite/Year	2,500,000	2,500,000				
<b>TOTAL</b>	<b>\$11,500,000</b>	<b>\$ 9,800,000</b>				
3. Sales Revenue/Year						
a. Sulphur	7,200,000	7,200,000				
b. Iron	20,500,000	6,300,000				
c. Non-Ferrous Metals — at 60% of Market Value	5,000,000	5,000,000				
<b>TOTAL</b>	<b>\$33,150,000</b>	<b>\$19,100,000</b>				
4. Gross Profit/Year	21,650,000	9,300,000				
5. Total Capital Cost	60,000,000	35,000,000				
6. % Gross Return	36%	26%				
7. Gross Profit/Year						
8. Total Capital Cost						

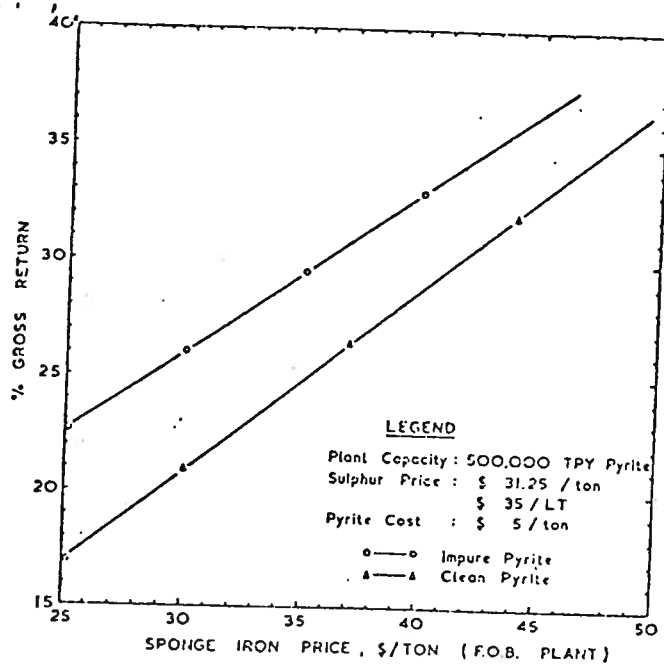


Figure 7.—Effect of Sponge Iron Price on the per cent Gross Return.

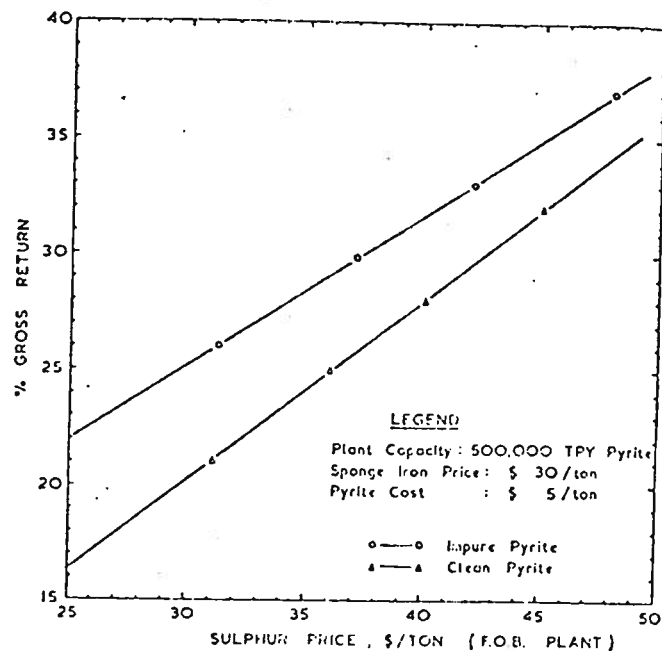


Figure 8.—Effect of Sulphur Price on the per cent Gross Return.

## V. CONCLUSIONS

This preliminary evaluation of the economics of various cases leads to the following conclusions:

- 1.—The venture is viable under the right circumstances. Ample raw material availability at low cost, accessibility of markets for sulphur and sponge iron, and a suitable location where energy costs are not excessive would be prerequisites for an economically attractive project.
- 2.—Annual plant capacities of 500,000 tons of pyrite and higher are preferred.
- 3.—The use of impure pyrite is favoured. The recovery and revenue will depend upon the form and quantity of impurities present in the feed material.
- 4.—Production of all the iron in pyrite as a high-purity iron powder is attractive. However, as the market for iron powder is limited (at least at the present time), a plant producing both high-purity iron powder and sponge iron could also be an attractive project.
- 5.—The process should be applicable to the treatment of other materials in addition to pyrite ores and concentrates. Sulphide ores containing small quantities of copper and zinc as well as pyrite could be treated directly without first going to flotation to make separate concentrates. A second example is nickel-containing pyrrhotite concentrates, in which case the thermal decomposition step would not be required.
- 6.—The foregoing conclusions lead to the over-all conclusion that the process shows sufficient promise to justify proceeding to the pilot-plant stage.

## ACKNOWLEDGMENTS

The authors wish to thank the management of

sent this paper. The assistance and contributions of the staff of the Research and Development and the Metal and Chemical Divisions are greatly appreciated. In particular, the authors wish to acknowledge the assistance of Mr. W. Kunda, head, Chemical Metallurgy Research Department.

## BIBLIOGRAPHY

- (1) Argall, George O., Jr., "Outokumpu Adds Second Catalyst to Raise Pyrite-to-Sulphur Conversion to 91 percent," *World Mining*, 20, 3, p. 42, (1967).
- (2) Colombo, U. P., Heath T. D., Sironi, G., and Tomassichio, G., "Fluosolids Reduction of Hematite by Montecatini," *J. of Metals*, 17, 12, p. 1317, (1965).
- (3) "Kova Seiko Process for Over-all Utilization of Pyrites," *Sulphur*, 69, p. 29, (1967).
- (4) Pietech, H. B., "Elimination of Non-ferrous Metals from Iron Oxides by Chlorination," Annual General Meeting, CIM, Quebec City, April 25-27, (1968).
- (5) Kunda, W., Rudyk, B. K., and Machiw, V. N., "Treatment of Pyrite by Low-Temperature Thermal Decomposition and Aqueous Oxidation," presented at Conference of Metallurgists, CIM, Kingston, Ontario, August 28-30, (1967). Published as "Iron and Sulphur from Sulphidic Iron Ores," pp. 819-835, this issue.
- (6) Graves, J. T., and Heath, T. D., "Sulfur Dioxide and Sulfur from Fluosolids Systems," AIME meeting, Los Angeles, February 21, (1967).
- (7) Gaccione, E., "From Pyrite: Iron Ore and Sulfur via Flash Smelting," *Chem. Eng.* p. 122, February 14, (1968).
- (8) Machmeyer, D., and Benson, B., "Hydrometallurgical Treatment of Oxidized Nickel-Cobalt Concentrate," *C.I.M. Bulletin*, Vol. 58, No. 644, pp. 931-938, September (1965).
- (9) O'Kane, P. T., "Pressure Leach Autoclave Design," 13th Chemical Engineering Conference, CIC, Montreal, October 15-23, (1963).
- (10) Praeger, M. J., and Grieg, C. R., "The SLURRN Process — Its Place in the Iron and Steel Industry," *Engineering Journal*, p. 29, June (1965).
- (11) Private Communication with Canadian Ingersoll-Rand, Ltd.

tion in the Tri-State district and Washington and more recently at Santander, Peru. Underground methods employing either open or supported slopes are used in most lead mines. Underground stoping includes block caving, room-and-pillar with and without rock bolts, shrinkage, cut-and-fill, and timbered stoping methods.

Improvements in mining practice in the past 40 to 50 years have been based largely on the development and extensive use of power equipment. Power shovels, scrapers, and mucking machines have replaced hand loading. Transportation also has undergone great changes; hand tramping and mule power have been replaced by motor trains operating on heavy-gauge track. More recently trackless mining, which utilizes electric- or diesel-powered units, is finding wide usage in the lead and lead-zinc mines of Washington, the Tri-State (4), the Upper Mississippi Valley (1), and southeast Missouri (3, 8). Mechanization is well adapted to the high backs, single-level mines that characterize so many of the lead and lead-zinc replacement ore bodies.

Other changes in equipment that have done much to improve mine output per man-shift include electric cap and floodlights at working faces, improved ventilation (including air conditioning), more efficient pumps, and powerful, lightweight rock drills using alloy steel or tungsten carbide bits.

### Milling

Simple lead ores, such as coarsely disseminated lead or zinc-lead minerals occurring with a low-specific gravity gangue, are treated in heavy-medium equipment, jigs, and on tables after being crushed and rolled in closed circuit with screens or classifiers to give properly sized feed. Bulk or differential flotation of the slime products (5) or of a regrind middling product completes the flowsheet. Ores of this kind are common in the mines of the Mississippi Valley and Eastern United States, but in some instances the ores are concentrated wholly by flotation.

Complex sulfide ores such as those of the Western United States consist of disseminated mixtures of fine-grained lead and zinc sulfides, usually accompanied by pyrite, copper sulfides, and gold and silver in a quartz or quartz-calcite gangue. Such ores may be complicated further by partial oxidation of the sulfides and presence of high-specific-gravity gangue minerals, such as barite, sphalerite, and rhodochrosite. The usual procedure on such an ore is to crush and grind in closed circuit with classifying equipment to a size at which the ore minerals are

freed from the gangue minerals. When the ore minerals are interlocked, the usual practice is to make a bulk sulfide concentrate, followed by regrinding and selective flotation.

Low capital and operating costs have extended the field of the sink-float method to include pretreatment of certain ores, permitting upgrading of ores diluted by nonselective mining methods. Present milling practices result in recovery of 85 to 94 percent of the sulfide lead and up to about 88 percent of the oxidized lead. Sulfide losses consist largely of the extremely fine particles, and although much research has been done and improvements have been made in the recovery of fines the results are still unsatisfactory.

### Smelting

Lead is recovered from its ores almost exclusively by smelting in blast furnaces or ore hearths employing carbon fuels. Ores or concentrates that contain few impurities may be reduced to metal in roasting hearths. Air is used to oxidize the sulfides and coke or coal to reduce the oxides. The ore hearth practice is followed at Galena, Kans., smelter, where (Newman) roasting hearths are used primarily in manufacture of lead oxide. The same process is employed at the New Broken Hill Smelter of Rhodesia, but is being replaced by blast-furnace methods.

In preparing the charge for blast-furnace smelting, the sulfur in the ores and concentrates is removed by a roasting-sintering process, usually on a Dwight-Lloyd sintering hearth (10). The sintering equipment eliminates most of the sulfur and produces a blast-furnace feed of desirable characteristics from the mechanically mixed concentrate, undersized sinter particles, and byproduct dusts and fumes collected in the smelter. Normally the charge to the lead blast furnace consists of lead sinter, coke, fluxes (such as silica and lime), and some lead-bearing furnace byproducts (13). Air is blown through the charge burning the coke to CO and CO<sub>2</sub> and producing a temperature of approximately 1,400° C. The carbon monoxide formed and the hot solid carbon reduce the oxidized lead compounds to bullion, which is tapped from the bottom or crucible of the furnace. Any copper, iron, cobalt, or nickel present in the ore combines with sulfur in the charge to form mattes which are tapped from the front of the blast furnace for subsequent treatment. Zinc present in the ore accumulates in the slag. When such slags contain 6 percent or more zinc, they are retreated in slag-fuming furnaces to recover the zinc and any remaining lead. The lead bullion contains precious metals present in the ore and metallic impurities which are recovered in the