4 Iron

The chemical element iron is the fourth most common element in the Earth's crust and the second most abundant metal. About five percent of the Earth's crust is composed of iron. The metal is chemically active and is found in nature combined with other elements in rocks and soils. In its natural state, iron is chemically bonded with oxygen, water, carbon dioxide, or sulfur in a variety of minerals.

Forms of Iron Minerals, Ores, and Rocks

Iron occurs mainly in iron-oxide ores. Some ores are a mixture of minerals rich in iron. Other iron ores are less rich and have a large number of impurities. The most important iron ore-forming minerals are:

- Magnetite - Magnetite (Fe_3O_4) forms magnetic black iron ore. There are large deposits of magnetite in Russia and Sweden.
- Hematite - Hematite (Fe_2O_3) is a red iron ore. Hematite occurs in almost all forms, from solid rock to loose earth. It is the most plentiful iron ore and occurs in large quantities throughout the world.
- Goethite - Goethite (Fe_2O_3.H2O), a brown ore, contains iron.
- Limonite - Limonite (Fe_2O_3.H2O) is a yellow-brown iron ore. Limonite is a collective term for impure goethite and a mixture of hydrated iron oxides.

Taconite contains low-grade iron in fine specks and bands. It is an extremely hard and flinty - containing about 25 - 30 percent iron. The iron in taconite occurs principally as magnetite and hematite and finely dispersed with silica in sedimentary deposits. Taconite is found in large quantities in the Upper Peninsula of Michigan, northeastern Minnesota, and Canada.

Sources of Iron

Iron is found in every state in the United States and in almost every country in the world. However, the ore must contain commercially recoverable amounts of iron in relatively large deposits or ranges if it is to be mined economically. The characteristics of iron-bearing ores vary geographically. Specifically, magnetite and hematite are the main iron-bearing ores in the Lake Superior district and in the northeastern United States, while hematite and hematite-magnetite mixtures tend to be found in ores in Alabama and the Southwest.

4.1 Process Overview

4.1.1 Iron Ore Mining

There are two basic methods of mining iron ore. These are:

- Surface mining or open-pit mining
- Underground or shaft mining

To be competitive, iron mining must be done on a very large scale. Surface mining is the preferred choice, although there are exceptions. Small, low-capacity mines have rapidly disappeared.

In 2000, twelve iron ore production complexes with 12 mines, 10 concentration plants, and 10 pelletizing plants were operating in Minnesota, Michigan, and six other States. The mines included eleven surface and one underground operation. Virtually all ore was concentrated before shipment. Nine mines operated by five companies accounted for 99 percent of production.[1]

4.1.1.1 Surface Mining

When the iron ore lies close to the surface, it often can be uncovered by stripping away a layer of dirt, sometimes only a few feet thick. The ore is mined from large open pits by progressive extraction along steps or benches. The benches provide access to progressively deeper ore, as upper-level ore is removed. After the soil and overlying rock are cleared, the ore is drilled and blasted. The portion of the ore body to be removed is first drilled in a specific pattern, and the holes are loaded with explosive mixtures and blasted. Following blasting, the fractured ore is loaded by huge electrical shovels, hydraulic excavators, or front-end loaders onto large dump trucks. The wide holes in the ground created by drilling, blasting, and ore removal are referred to as "open pits".

[1] U.S. Department of Interior, U.S. Geological Survey, *Mineral Commodity Summary*, Iron Ore, 2001

4.1.1.2 Underground Mining

Underground mines are established in areas with promising ore deposits. Iron ore deposits may lie deep underground. A shaft must be dug from the surface and an elevator or hoist must be installed. The shaft is the primary vertical channel through which people and ore are transported in and out of the mine. It may be desirable to sink a vertical shaft in barren wall rock at one end or to one side of the ore deposit to keep haulage and hoisting facilities clear of actual underground mining while minimizing haulage of ore underground to the mine exit. The miner's elevator is called a cage and the ore reaches the surface via a car called a skip. A ventilation system near the main shaft ensures that miners receive fresh air and prevents the accumulation of dangerous gases. Miners cut tunnels (drifts) branching out from the shaft at various levels to access the veins of ore. These levels are, in turn, connected by openings called raises. Stopes are the chambers in which ore is broken and mined. Cars or other conveyors carry the ore to the shaft, where it is hoisted to the surface.

The basic mine plant for underground mining operations consists of headframe, hoist, timber framing and storage area, miner's change house, compressor house, machine shops, warehouse, office, ore storage, ore loading, and shipping facilities.

Most iron ore leaves the mine by rail, after which, much is transferred to ships. A much larger proportion of ore is moved by water in the United States than elsewhere because of the proximity of the mines to the Great Lakes, which offer low-cost transportation. No U.S. taconite mine is more than about 100 miles from the Great Lakes, and most are much closer. A lesser-used method of transportation is an iron ore slurry pipeline.

4.1.2 Iron Ore Beneficiation

Iron ore occurs naturally in a variety of forms, from sand-like iron fines to solid rock masses. Crude ore, or ore mined in the natural state, seldom occurs in a pure state and requires some form of beneficiation. Crude ore is commonly mixed with other minerals (gangue), which reduce the iron content. Concentrations of as little as 30 percent may be of commercial interest, provided other factors such as gangue content, the size of the deposit, and accessibility are favorable. Crude iron ore is classified in three general categories:

- **Direct Shipping -** Direct shipping ores are transported as mined or possibly after screening. Direct shipping ores are generally hematite, magnetite, or goethite. Reserves of these ores are rarely found in North America because they have been mostly depleted. There are many grades of direct shipping ores, including lump ores usually crushed to 20 - 30 mm and sinter fines with a maximum grain size of 6 - 10 mm. The prices of direct shipping ores are often related to the historical Mesabi standard of 51.5 percent iron.

- **Concentrates -** Iron ore that requires beneficiation to upgrade the iron content is called low-grade, intermediate, taconite, or concentrating ore. “Concentrating” or otherwise treating iron ore to remove impurities and improve its quality is referred to as beneficiating.

- **Agglomerated -** The development of techniques of mining and concentrating taconite led to the introduction of the iron-ore pellet. Pellets are comprised of ore that has been agglomerated into balls. The pellet is the major form of introducing iron into the steel-making blast furnace. The effect of pelletizing taconite iron has been to encourage mines throughout the world to grind, concentrate and pelletize otherwise low-grade ores. Another form of agglomeration commonly used is briquetting.

Iron ores often contain impurities, undesirable chemical components such as phosphorous, sulfur, sodium, potassium (alkalis), alumina, silica and sometimes titanium. Other components such as calcium and manganese, may be considered desirable, depending on the composition of other raw materials used in the individual iron or steel producer's process.

There are a variety of beneficiation methods that can be used to prepare iron ores, depending on the iron content in the ores. Some ores contain greater than 60 percent iron and require only crushing and blending to prepare them for further beneficiation. In other cases, operations including screening and concentrating are necessary to prepare the raw materials. Generally, the operations required before the iron ore is considered a finished product include:

- Crushing & Screening
- Grinding
- Concentration
- Agglomeration

4.1.2.1 Crushing and Screening

Following blasting, the fragmented ore is loaded on a mining truck and hauled to the crusher for primary crushing. Many mines employ two to three stages of crushing. Some mines have the primary crusher located in the mine, using conveyors to transport the crushed ore to the secondary and tertiary crushers or directly to the mills. The crushing stages will reduce the iron ore from several feet in diameter at the primary stage to six inches down to one-half or three-eighths of an inch as a final product. The crusher product is fed to the milling operation for further size reduction.

4.1.2.2 Grinding

In the grinding circuit, rod, ball, or autogenous mills grind the taconite down into even smaller uniformed-sized particles. The ore is ground less than 325 mesh, and in some cases less than 500 mesh (45 - 25 microns) to help facilitate the liberation of the iron minerals from the rock.

4.1.2.3 Concentration

The product from the milling circuit is fed to the concentration circuit, where the valuable mineral is recovered and concentrated. Worthless gangue (sand and rock) is then separated. Using the magnetic properties of magnetite, magnetic-separation is the principal choice for taconite. Hematite ores are concentrated using conventional flotation. The concentrate is then filtered to remove water and passed to pelletizing and sintering operations.

In actual practice, concentration may be simple or complicated depending upon the exact nature of the ore. With some ores, the beneficiation may be very complicated. For instance, in concentrating taconite, the rock first must be crushed to a fine powder. Next, magnets are used to separate the useful ore from the gangue. Then the concentrate is rolled into one-half inch balls and roasted in a furnace to make pellets. Finally, the pellets are shipped to iron and steel mills.

When magnetite occurs in lower-grade deposits, the ore is ground, and the concentrate is separated magnetically from the gangue with the ore in a water suspension. Low-grade ores that cannot be separated magnetically may need to be concentrated through washing, jigging, heavy media separation, or flotation.

Magnetic separation is used to separate iron ores from less magnetic material and can be classified as either high- or low-intensity (requiring as little as 1,000 gauss or as much as 20,000). Particle size and the solids content of the ore determine which type of magnetic separator system is used.

Flotation uses a chemical reagent to make one or a group of minerals adhere to air bubbles for collection. Chemical reagents include collectors, frothers, antifoams, activators, and depressants. The type of reagent used depends on the characteristics of a given ore.

A typical flotation process sometimes requires desliming. In clusters of cyclones, the ultrafine material is removed to permit beneficiation of the ore. Waste material, such as silica, is then separated from the iron particles in the flotation circuit. The final adjustment in the physical and chemical characteristics of the ore is achieved through regrinding and column flotation.

4.1.2.4 Agglomeration

Iron ores, coke, and limestone that will be sent to blast furnaces for ironmaking need to be permeable to allow for an adequate flow of gas through the system. Additionally, concentrates in crude ores that are very fine need to be agglomerated before they can be used as feedstock for the blast furnaces. The three major processes used for agglomeration include:

- Sintering
- Pelletizing
- Briquetting

Sintering - Sintering involves mixing the iron-bearing material such as ore fines, flue dust, or concentrate with fuel. The mixture is then spread on surface beds, which are ignited by gas burners. The high temperature heating process, at approximately 1100^{o} Celsius, fuses the fine particles. The resulting product is lumpy material known as sinter. The sinter is sized and the fines are recycled. Sintering operations are also used to recycle wastes from other iron and steel manufacturing processes.

Pelletizing - After the taconite has been ground to a powder and concentrated, it is ready for pelletizing. Pelletizing involves forming pellets from concentrates, then hardening the pellets by heating. Pelletizing produces small marble-sized balls approximately one-half inch in diameter. To accomplish this, the concentrate is fed into a balling machine, usually a large, rotating steel drum. Solid fuel (coal dust) is sometimes combined with the concentrate to promote the heating necessary to harden the pellet. Common binders added to strengthen the pellets include soda ash, bentonite, and organic compounds. As the drum rotates, the concentrate and binder agglomerate into pellets of a consistent size. After the pellets are sized, any remaining fraction of materials are recycled back through the indurating process. The appropriately-sized marbles or balls are strong enough to retain their shape when shipped to the blast furnaces where they are used to make iron.

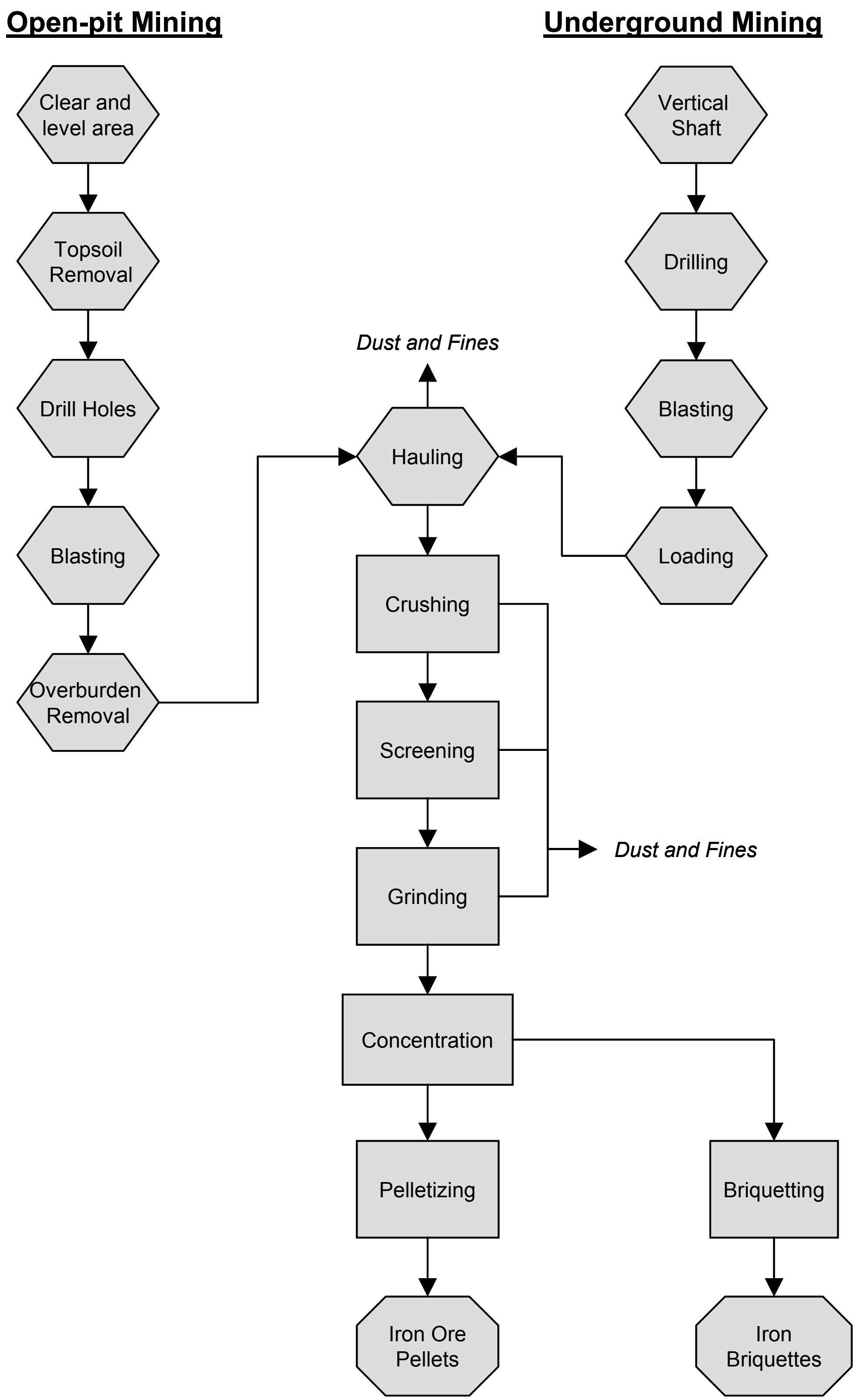
Briquetting - Briquetting, another form of agglomeration, involves heating the ore and pressing it into briquettes while the materials are still hot. Once the briquettes are cooled, they are sent directly to the blast furnaces.

4.2 Summary of Inputs/Outputs

The following lists the inputs and outputs for iron extraction and beneficiation. Figure 4-1 illustrates iron extraction and beneficiation with its major inputs and outputs.

Inputs	**Outputs**
Electricity	Iron Pellets
Fuels	Waste Rods
	Overburden
	Acid Mine Water
	Engine Fumes
	Dust and Fines
	Carbon Dioxide
	Sulfur Compounds
	Chlorides
	Fluorides
	Nitrogen Dioxide
	Tailings

Figure 4-1. Iron Ore Mining Flow Diagram

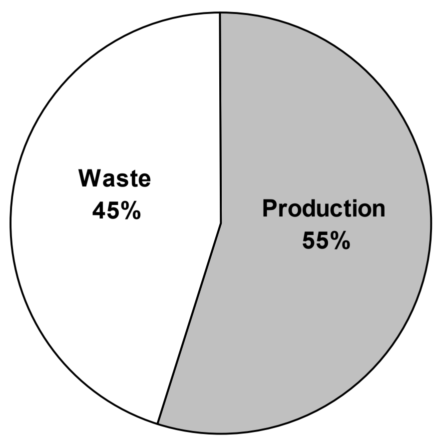


4.3 Energy Requirements

4.3.1 Materials Handled

The term materials handled refer to ore and waste that are generated in the mining and beneficiation processes. Figure 4-2 shows the amount of iron mined in relation to the amount of waste materials produced in iron mining. When looking at energy requirements in mining and beneficiation the tonnage of materials which must be handled drives energy consumption in mining operations. For example, in 2000 the amount of crude iron ore produced was 208 million tons. In addition 158 million tons of waste material was produced for a total of 331 million tons of materials handled in iron mining in 2000. From 1994 to 2000, the average annual ratio of waste to crude ore of iron was 45 percent.

Figure 4-2. Materials Handled for Iron Mining



Source: U.S. Department of the Interior, U.S. Geological Survey, *Minerals Yearbook*, Mining and Quarrying Trends, 1994, 1995, 1996, 1997, 1998, 1999, 2000

4.3.2 Energy Requirements for Iron Extraction

Major energy sources include purchased electric energy and fuel oil. In 1992, iron ore mining consumed 62.3 trillion Btu. Table 4-1 shows the type and quantity of fuels consumed during iron ore preparation.[2]

Table 4-1. Iron Ore Production and Energy Consumed by Type [a]

	Units	1987	1992	1997
Iron Ore Production	*Thousand tons*	-	*61,288.5*	*69,225.1*
Energy Consumption				
Coal	Thousand tons	Withheld	Withheld	Withheld
Fuel oil [b]	Thousand bbl.	542.7	669.6	910.7
Natural Gas	Billion Cubic Feet	21.0	29.7	34.3
Gasoline	Thousand bb.	23.8	26.2	33.3
Electricity Purchased	Million kWh	6,300	7,300	6,200
Electricity Generated Less Sold	Million kWh	0	0	0

a Iron is SIC Code 1011 (1997 NAICS Code 21221)
b Summation of distillate and residual fuel oil
Sources: U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, Census of Mineral Industries, Industry Series, Iron Mining
US Department of the Interior, US Geological Survey, *Minerals Year Book*, Statistical Summary, 1997 & 1994

In 1985, the Bureau of Mines reported that electric power requirements at most taconite operations range between 100 and 150-kilowatt hours per ton of pellets produced. Most pelletizing plants are fueled by natural gas, but some plants use pulverized coal or fuel oil. In the 1970's, thermal energy requirements for pellet induration were about 750,000 Btu per ton of pellets for magnetite concentrates, and upwards of 1 million Btu for hematite concentrates. Installation of heat recuperation systems in most plants has reduced requirements over 40 percent to an estimated 300,000 to 450,000 Btu for magnetite and about 20 percent to 750,000 Btu for hematite.[3]

More recently, the Michigan Technological University, Department of Mining Engineering developed a report in 1982 that estimated that haulage consumes 75 percent of the total energy required in a large hypothetical iron ore mine (with a 5,000,000-ton of iron per year output and a 22-year mine lifetime). Their conclusions are shown in Table 4-2.

Table 4-2. Energy Requirements for Hypothetical Iron Mine	
Process	**Btu/ton of Ore**
Drilling	1,707
Blasting	2,901
Loading	6,315
Haulage	50,859
Miscellaneous	6,485
Total	68,267

Source: U.S Department of Interior, Office of Surface Mining, *The Effects of Increasing Costs on the Future Relation Between Open Pit and Underground Mining*, Michigan Technology University, Department of Mining Engineering, 1982

Due to a lack of current information on the energy requirements of mining and beneficiation, the *SHERPA Mine Cost Estimating Model* along with the *Mine and Mill Equipment Cost, An Estimators Guide* from Western Mine Engineering, Inc. was used to calculate the energy requirements for extraction and beneficiation of iron. The model required some input in order to provide the types and amounts of equipment needed. The Michigan Tech Report provided many of these inputs. The following energy discussion is based on the results of the mine model and equipment cost guide.

Table 4-3 shows the estimated energy requirements for a surface iron mine in the U.S. The iron mine operates over a 22-year lifetime with a 110 million-ton output at the end of its life. The mine runs 364 days per year with two 8.00 hour shifts per day, which gives it a daily production rate of 13,699 tons per day. Both the ore and waste material must be hauled 1,312 feet out of the mine at a gradient of 11 percent.

The front-end loaders require the most energy in the mine and are the most energy intensive piece of equipment. Front-end loaders combined with other transportation equipment such as rear-dump trucks, bulldozers, service and bulk trucks account for 84 percent of the total energy required per ton. All of this equipment is operated by diesel fuel.

Table 4-4 shows the energy requirements for the beneficiation of iron ore. The ball mill requires the most energy and is the most energy intensive equipment in beneficiation. This is due to the ratio of ball-ball hits in the mill versus ball-ore hits. The majority are ball-ball hits, which do not crush ore but instead add to the wear and tear of the balls and liners. The ball mill operates on electric energy, and requires 33 percent of the total beneficiation energy consumed per ton of iron ore produced. It contributes to the crushing and grinding of the iron ore feedstock. Crushing and grinding includes primary, secondary, and tertiary crushing, as well as rod and ball mill. This equipment accounts for 97 percent of the total energy consumed by beneficiation. The total energy required to extract and process iron is 94,400 Btu per ton.

Table 4-3. Energy Requirements for a 13,699 ton/day Surface Iron Mine					
		Energy Consumption			
Equipment (number of Units)	Daily hours/ unit	Single Unit (Btu/ton)	All Units (Btu/hour)	All Units (Btu/day)	All Units (Btu/ton)
Front-end Loaders [b] (3)	16.00	7,560	19,400,000	311,000,000	22,700
Rear Dump Trucks [b] (12)	16.00	1,940	19,900,000	318,000,000	23,200
Bulldozers [b] (7)	16.00	2,730	16,300,000	261,000,000	19,100
Service Trucks [b] (2)	16.00	396	679,000	10,900,000	793
Bulk Trucks [b] (2)	16.00	396	679,000	10,900,000	793
Rotary Drills [b] (2)	16.00	2,900	4,970,000	79,500,000	5,800
Hydraulic Shovels [b] (1)	12.32	5,530	6,150,000	75,800,000	5,530
Pick-up Trucks [b] (10)	16.00	242	2,070,000	33,100,000	2,420
Graders [b] (1)	2.40	213	1,220,000	2,920,000	213
Water Tankers [b] (1)	8.00	1,200	2,050,000	16,400,000	1,200
Pumps [b] (2)	16.00	420	719,000	11,500,000	839
Total			**74,200,000**	**1,130,000,000**	**82,600**

a Calculated at $0.049 per kWH: average for Rocky Mountain Region, 1999

b Calculated at $0.535 per gallon: average prices for sales to end-users in U.S. Petroleum Administration for Defense District No. IV, 1999

Note: Mine operates over a 22-year lifetime with a 110 million-ton output at the end of its life. Assumes mine runs 365 days per year with two 8.00 hour shifts per day, which gives it a daily production rate of 13,699 tons per day. Assumes both ore and waste material must be hauled 1,312 feet out of the mine at a gradient of 11%.

Sources: BCS, Incorporated estimates (September 2002) using the Western Mining Engineering, Inc. *SHERPA Mine Cost Software* and *Mine and Mill Cost, An Estimators Guide*
U.S Department of Interior, Office of Surface Mining, *The Effects of Increasing Costs on the Future Relation Between Open Pit and Underground Mining*, Michigan Technology University, Department of Mining Engineering, 1982

Table 4-4. Energy Requirements for Beneficiation of Iron					
Equipment (number of Units)	**Daily hours/ unit**	**Energy Consumption**			
		Single Unit (Btu/ton)	**All Units (Btu/hour)**	**All Units (Btu/day)**	**All Units (Btu/ton)**
Ball Mill [a] (1)	16.00	3,870	3,310,000	53,000,000	3,870
Primary Crusher [a] (1)	16.00	2,580	2,210,000	35,300,000	2,580
Secondary Crusher [a] (3)	16.00	645	1,660,000	26,500,000	1,940
Tertiary Crusher [a] (4)	16.00	387	1,320,000	21,200,000	1,550
Rod Mill [a] (1)	16.00	1,550	1,330,000	21,200,000	1,550
Screens [a] (4)	16.00	51	176,000	2,810,000	205
Filter [a] (1)	16.00	76	64,800	1,040,000	76
Pelletizer [a] (1)	16.00	38	32,700	524,000	38
Thickener [a] (1)	16.00	19	16,000	256,000	19
Total			**10,100,000**	**162,000,000**	**11,800**

a Calculated at $0.049 per kWh: average for Rocky Mountain Region, 1999

b Calculated at $0.535 per gallon: average prices for sales to end-users in U.S. Petroleum Administration for Defense District No. IV, 1999

Note: Mine operates over a 22-year lifetime with a 110 million-ton output at the end of its life. Assumes mine runs 365 days per year with two 8.00 hour shifts per day, which gives it a daily production rate of 13,699 tons per day. Assumes both ore and waste material must be hauled 1,312 feet out of the mine at a gradient of 11%.

Source: BCS, Incorporated estimates (September 2002) using the Western Mining Engineering, Inc. *SHERPA Mine Cost Software* and *Mine and Mill Cost, An Estimators Guide*
U.S Department of Interior, Office of Surface Mining, *The Effects of Increasing Costs on the Future Relation Between Open Pit and Underground Mining*, Michigan Technology University, Department of Mining Engineering, 1982

4.4 Emissions

After milling the iron ore, concentrates are agglomerated or pelletized to improve blast furnace operations that utilize iron ore. Pelletizing operations produce a moist pellet (often using clay as a binder) that is hardened through heat treatment. Agglomeration generates by-products in the form of particulates and gases, including compounds such as carbon dioxide, sulfur compounds, chlorides, and fluorides. These emissions are usually treated using cyclones, electrostatic precipitators, and scrubbing equipment. These treatment technologies generate iron-containing effluent, which is recycled into the operation. Agglomeration also produces large volumes of sulfur dioxide and nitrogen dioxide.

4.5 Effluents

Mining activities can alter topography and vegetative land cover, consequently effecting the volume and rate of surface water run-off. The run-off increases the variability in stream flows and can dramatically affect aquatic life.

Underground mining generally has less impact on soil and vegetation than surface mining, but can cause greater quantities of acid or alkaline drainage.

4.6 By-products and Solid Waste

The iron ore wastes generated during extraction and beneficiation include:

- Surface mining creates large amounts of waste rock that must be disposed. While underground mines do not create the volume of overburden waste associated with surface mining, some waste rock must still be brought to the surface for disposal. Waste rock may either be returned to the mine as fill or put in a disposal area.

- Before extraction, mobile rigs drill holes in rock. The holes are then filled with explosives for blasting waste rock and ore. Potential pollutants involved in this step in the mining process include the fuel, lubricants, and hydraulic oils consumed by the rigs. Fuels and oils typically contain such constituents as benzene, ethylbenzene, and tuluene. Explosives used to break up the rock usually use a mixture of ammonium nitrate and fuel oil. Other explosives, including trinitrotoluene (TNT) and nitroglycerine, may also be used. Loading and hauling equipment is used to transport ore from the mine to a mill for beneficiation. Depending on the volume of ore, trucks, rail cars, conveyors, and elevators may all be required to haul ore. Equipment involved in this step of the mining process uses hydraulic fluid, batteries, lubricants and fuel. They may contain glycol ethers, sulfuric acid, lead, antimony, arsenic, and petroleum hydrocarbons.

- Wastes from magnetic separation include tailings consisting mostly of silicate rock. The magnetite ore from lower grade deposits is ground, and the concentrate is separated magnetically from the gangue with the ore in a water suspension. These wastes are typically managed in tailing impoundments.

4.7 Hazardous Waste

The commodity iron ore was evaluated from extraction to the first saleable product. There are no RCRA-listed (Resource Conservation and Recovery Act) hazardous wastes associated with iron ore mining up to agglomeration. The material generated from iron ore mining and beneficiation is managed through recycling and impoundment.