

# **Energy and Environmental Profile of the U.S. Iron and Steel Industry**

**August 2000**

*Prepared by*  
Energetics, Incorporated



*Prepared for*  
U.S. Department of Energy  
Office of Industrial Technologies

DOE/EE-0229

## **ACKNOWLEDGMENTS**

This report was written by Nancy Margolis and Ross Brindle of Energetics, Incorporated under the direction of Scott Richlen and Peter Salmon-Cox of the U.S. Department of Energy, Office of Industrial Technologies. Technical review was provided by R. Fillman and R. Bouman of Bethlehem Steel Corporation; J. Stubbles, steel industry consultant, B. Steiner, American Iron and Steel Institute; and Tom Danjczek, Steel Manufacturers Association.

# Table of Contents

<b>1. Overview</b> .....	<b>1</b>
<b>2. Cokemaking</b> .....	<b>27</b>
<b>3. Ironmaking</b> .....	<b>41</b>
<b>4. Steelmaking - Basic Oxygen Furnace</b> .....	<b>53</b>
<b>5. Steelmaking - Electric Arc Furnace</b> .....	<b>61</b>
<b>6. Refining and Casting</b> .....	<b>71</b>
<b>7. Forming and Finishing</b> .....	<b>79</b>
<b>References</b> .....	<b>91</b>



# Tables and Figures

## *Tables*

### **1**

#### **Overview**

Table 1-1.	U.S. and World Production of Raw Steel: 1988 - 1998
Table 1-2.	Total Net Shipments of All Steel Mill Products in the U.S. - 1998
Table 1-3.	Shipments of U.S. Steel Mill Products by Market Classification - 1998
Table 1-4.	U.S. Iron and Steel Industry Energy Consumption - 1998
Table 1-5.	U.S. Blast Furnaces and Steel Mills (SIC 3312) Energy Consumption (MECS Estimate) - 1994
Table 1-6.	U.S. Steel Industry Net Energy Use by Major Process - 1998
Table 1-7.	Typical Energy Intensity of U.S. Integrated and EAF-Based Steelmaking Processes - 1998
Table 1-8.	U.S. Iron and Steel Industry Materials Consumption - 1998
Table 1-9.	U.S. Iron and Steel Industry Consumption of Molten Iron, Scrap, and DRI by Furnace Type - 1998
Table 1-10.	Summary of Source Reduction and Recycling Activity for SIC 331 as Reported within the Toxic Release Inventory - 1996
Table 1-11.	Releases of Select TRI Chemicals for Iron and Steel Facilities - 1995
Table 1-12.	Transfers of Major TRI Chemicals for Iron and Steel Facilities - 1995
Table 1-13.	Estimated Combustion-Related Carbon Intensity of U.S. Integrated and EAF-Based Steelmaking Processes - 1998
Table 1-14.	Estimated Combustion-Related Emissions of Criteria Pollutants for U.S. Integrated Steelmaking Processes - 1998
Table 1-15.	Estimated Combustion-Related Emissions of Criteria Pollutants for U.S. EAF-Based Steelmaking Processes - 1998
Table 1-16.	Total Estimated Combustion-Related Emissions by Major Process in U.S. Steelmaking - 1998
Table 1-17.	Estimated Iron and Steel Industry Major Solid Wastes/Byproducts - 1997

### **2**

#### **Cokemaking**

Table 2-1.	Typical Breakdown of Products and Byproducts from a Ton of Coal Used to Make Coke
Table 2-2.	Cokemaking Energy Use - 1998
Table 2-3.	Cokemaking Byproducts - 1998
Table 2-4.	Estimated Combustion-Related CO <sub>2</sub> Emissions from Cokemaking - 1998
Table 2-5.	Emission Factors for Cokemaking
Table 2-6.	Byproduct Cokemaking Effluent Flows

Table 2-7.	Byproduct Cokemaking Effluent Limitations - Average of Daily Values for 30 Consecutive Days
Table 2-8.	Major Uses of Cokemaking Byproducts
Table 2-9.	Typical Coke Oven Gas Components by Percent Volume
Table 2-10.	Waste Generation Factors for K142 through K145
Table 2-11.	Maximum Allowable Constituent Concentrations in K060 and K087 for Land Disposal
Table 2-12.	Constituents of Concern and Average Measured Concentrations: K141 through K145
Table 2-13.	Maximum Allowable Constituent Concentrations in K141 through K145 Wastewaters for Land Disposal
Table 2-14.	Maximum Allowable Constituent Concentrations in K141 through K145 Non-Wastewaters for Land Disposal

### **3 Ironmaking**

Table 3-1.	Energy Use in Sintering - 1998
Table 3-2.	Energy Use in Blast Furnace Ironmaking - 1998
Table 3-3.	Total Estimated Combustion-Related Emissions for Sintering and Ironmaking - 1998
Table 3-4.	Emission Factors for Sintering
Table 3-5.	Emission Factors for the Blast Furnace
Table 3-6.	Sintering Effluent Limitations - Average of Daily Values for 30 Consecutive Days
Table 3-7.	Blast Furnace Effluent Limitations - Average of Daily Values for 30 Consecutive Days
Table 3-8.	Typical Blast Furnace Gas Components by Percent Volume

### **4 Steelmaking - Basic Oxygen Furnace**

Table 4-1.	Energy Use in BOF Steelmaking - 1998
Table 4-2.	Total Estimated Combustion-Related BOF Steelmaking Emissions - 1998
Table 4-3.	Emission Factors for BOF Steelmaking
Table 4-4.	BOF Steelmaking BPT Effluent Limitations - Average of Daily Values for 30 Consecutive Days

### **5 Steelmaking - Electric Arc Furnace**

Table 5-1.	Energy Use in EAF Steelmaking - 1998
Table 5-2.	Total Estimated Combustion-Related EAF Steelmaking Emissions - 1998
Table 5-3.	Emission Factors for EAF Steelmaking
Table 5-4.	EAF Steelmaking Effluent Limitations - Average of Daily Values for 30 Consecutive Days
Table 5-5.	Comparative Chemical Composition of Dust from Electric Arc Furnaces
Table 5-6.	Concentrations of Fourteen Regulated Elements in Electric Arc Furnace Dust
Table 5-7.	Maximum Allowable Constituent Concentrations in K061 for Land Disposal

### **6 Refining and Casting**

Table 6-1.	Energy Intensities and Consumption of Ingot and Continuous Casting - 1998
Table 6-2.	Total Estimated Combustion-Related Casting Emissions - 1998
Table 6-3.	Emission Factors for Casting
Table 6-4.	Vacuum Degassing and Continuous Casting Effluent Limitations - Average of Daily Values for 30 Consecutive Days

### **7 Forming and Finishing**

Table 7-1.	Average Energy Intensities of Rolling and Finishing Processes
Table 7-2.	Emission Factors for Forming and Finishing
Table 7-3.	Flow Rates for Hot Forming Subcategory
Table 7-4.	Hot Forming Effluent Total Suspended Solids (TSS) Limitations - Average of Daily Values for 30 Consecutive Days
Table 7-5.	Salt Bath Descaling Effluent Limitations - Average of Daily Values for 30 Consecutive Days
Table 7-6.	Acid Pickling Effluent Limitations - Average of Daily Values for 30 Consecutive Days
Table 7-7.	Cold Forming Effluent Limitations - Average of Daily Values for 30 Consecutive Days
Table 7-8.	Average Concentration of Metals in Spent Pickle Liquor
Table 7-9.	Maximum Allowable Constituent Concentrations in K062 for Land Disposal

## ***Figures***

### **1**

- Figure 1-1. Geographic Distribution of SIC 331 Establishments  
Figure 1-2. U.S. Raw Steel Production (1984 - 1999)  
Figure 1-3. 1998 World Production of Raw Steel  
Figure 1-4. U.S. Imports, Exports, and Net Shipments of Steel Products (1979 - 1999)  
Figure 1-5. U.S. Steel Industry Energy Use by Fuel Type (1984 - 1998)  
Figure 1-6. U.S. Steel Industry Average Energy Intensity (1978 - 1998)

### **Overview**

### **2**

- Figure 2-1. Cokemaking Flow Diagram

### **Cokemaking**

### **3**

- Figure 3-1. Sintering Flow Diagram  
Figure 3-2. Blast Furnace Flow Diagram

### **Ironmaking**

### **4**

- Figure 4-1. Basic Oxygen Furnace (BOF) Steelmaking Flow Diagram

### **Steelmaking - Basic Oxygen Furnace**

### **5**

- Figure 5-1. Electric Arc Furnace Steelmaking Flow Diagram

### **Steelmaking - Electric Arc Furnace**

### **6**

- Figure 6-1. Refining and Casting Flow Diagram

### **Refining and Casting**

### **7**

- Figure 7-1. Forming and Finishing Flow Diagram (Sheet Production)

### **Forming and Finishing**





# Overview

# 1

## 1.1 Honing the Competitive Edge

The U.S. iron and steel industry has undergone a major transformation since its recession of the late 1980s and early 1990s. Restructuring, downsizing, and widespread implementation of new technologies have led to major improvements in labor productivity, energy efficiency, and yield. The U.S. steel industry is now one of the most productive in the world, supplying quality products at low cost. Its most recent challenge has been large quantities of low-cost imports stemming from excess global steelmaking capacity and a collapse in Asian demand in late 1998 and 1999.

The industry's current problems come at the end of a relatively healthy decade. The recent crisis

aside, the 1990s have seen the industry benefit from a relatively weak U.S. dollar; strong demand from the automobile, appliance, and construction markets; consolidation of integrated steelmaking capacity, and the application of advanced technology and process controls.

Despite inconsistent profitability, the U.S. steel industry continually improves its technology to help meet market challenges. Huge investments in new process and product technologies, facilities, employee training, and product development have reduced the number of man-hours required to produce a ton of steel by 60% (from 10 to less than 4) in 15 years. In fact, the production of steel at some newer mills requires only one man-hour per ton. New process technologies have increased yields from around 70% in the early 1970s to more than 90% today. Yields may be pushed still higher as even newer technologies come on line.

### ***Industry Focuses on Energy and Environmental Issues***

Over the last 25 years the U.S. iron and steel industry has made great strides in its energy efficiency, productivity, environmental performance, and competitiveness. The industry, which accounts for 2 to 3% of total U.S. energy consumption, is continually improving its energy performance. In part because of the adoption of new technologies, the amount of energy required

### **The U.S. Department of Energy and the Steel Industry of the Future**

The U.S. Department of Energy's (DOE's) Office of Industrial Technologies has formed a partnership with the U.S. iron and steel industry to accelerate development of technologies and processes that will improve the industry's production and energy efficiency and environmental performance. This report is intended to support the DOE/industry partnership.

## Snapshot of the U.S. Iron and Steel Industry - 1999

### Employment

Total Employees: approx. 153,000  
Avg. Employment Cost: \$35.34/hour

### Finances (1998 data)<sup>a</sup>

Sales: \$35.6 billion  
Percent Return on Sales: 2.7%  
Capital Expenditures: \$2.7 billion

### Production (net tons)

Raw Steel Production: 107.2 million  
Total Net Shipments: 105.1 million  
Total Exports: 5.4 million  
Total Imports: 35.9 million

<sup>a</sup> -Financial data are for AISI reporting companies representing 65% of U.S. raw steel production.

Source: American Iron and Steel Institute

to produce a ton of steel has decreased by 45% since the mid 1970s. However, the capital to invest in new technologies is increasingly limited, especially as the costs of environmental control continue to rise.

After foreign competition, the biggest challenge facing the industry today is compliance with environmental regulations. The Clean Air Act and the Resource Conservation and Recovery Act have had significant impacts on the industry. Since 1970, the industry has invested more than \$5 billion in air pollution control systems, much of it for particulate control. In a typical year, 15% of the industry's capital investments go to environmental projects (Darnall 1994).

Over 95% of the water used for steel production and processing is now recycled; in all, the discharge of air and water pollutants has been reduced by more than 90% (AISI 1999). In spite of these achievements, environmental issues will continue to be the focus of policy debates, legislation, and regulation in the future.

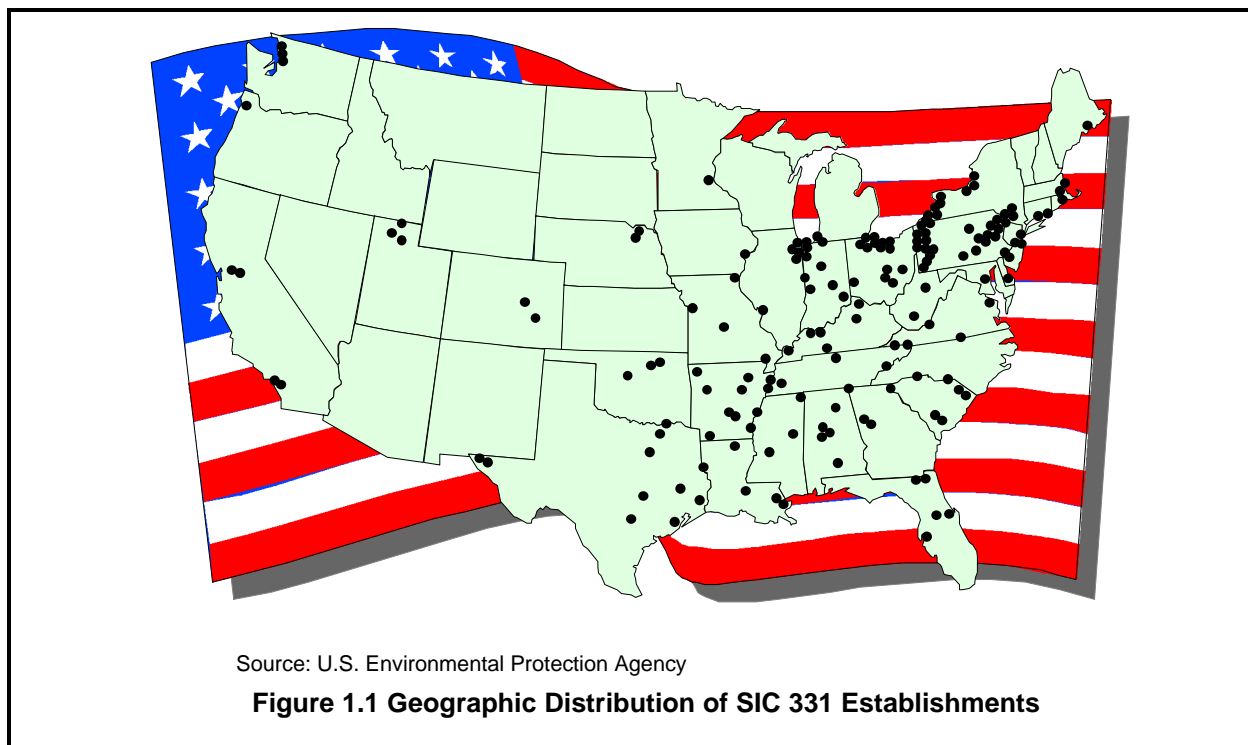
## Fewer Mills, Workers as Industry Consolidates

As a result of industry consolidation, the number of steelmaking facilities has decreased significantly over the last few decades. Large integrated mills have been the hardest hit, largely due to loss of market share to other materials, competition, and the high cost of pension liabilities (EPA 1995). Many of these mills have closed, and those that are still operating have reduced their work forces while making process improvements to remain competitive. Additional closures and an estimated 10,000 layoffs have resulted from the 1998-1999 crisis.

According to the 1997 Census of Manufacturers, the number of establishments under SIC 3312 (blast furnaces and steel mills) dropped from 504 in 1977 to 193 in 1997. The U. S. blast furnace population has declined from about 125 in the mid 1970s to about 40 operating furnaces today. However, the number of integrated mills has always been relatively small (currently 20 mills), and the census reduction is largely due to a drop in the number of small establishments.

The number of employees in the industry decreased by 65% between 1977 (when 442,000 workers were employed) and 1998 (when approximately 153,000 were employed). Although the number of fully integrated mills is small, they employ nearly half of the industry's work force.

The highest geographic concentration of mills is in the Great Lakes region, including Indiana, Illinois, Ohio, Pennsylvania, Michigan, and New York (see Figure 1-1.). Approximately 80% of U.S. steelmaking capacity is in these states. The proximity of these regions to water, iron ore, and coal has been the major attraction for steelmaking operations. The South is the next-largest steel-producing region, and a few mills are sited in the West. Electric arc furnace (EAF) facilities may be built wherever electricity and scrap are reasonably priced and there is a local market for the steel product.



### ***Downsizing Has Led to Greater Capacity Utilization***

Industry downsizing and consolidation has reduced U.S. raw steel production capability by about 30% since 1980. In the early 1980s, U.S. steelmakers were capable of producing raw steel at an annual rate of more than 150 million tons. By 1994 this capability had dropped to 108 million tons. During this same time period, the utilization of U.S. production capability rose from just over 50% to 93% (AISI 1988 and 1995). Since 1994, capability has grown by 10% to 125 million tons in 1998. Utilization of U.S. production capability in 1999 was 83.7%, down from 86.8% in 1998 (AISI 2000).

In 1999 total U.S. raw steel production was 107.2 million net tons. Of this, 57.7 million net tons were produced in Basic Oxygen Furnaces (BOFs) and 49.5 million net tons in Electric Arc Furnaces (EAFs) (see Figure 1-2). Total raw steel production included 97.9 million net tons of carbon steel, 5.1 million net tons of alloy steel, and 2.1 million net tons of stainless steel (AISI 2000).

## **1.2 Market Trends and Statistics**

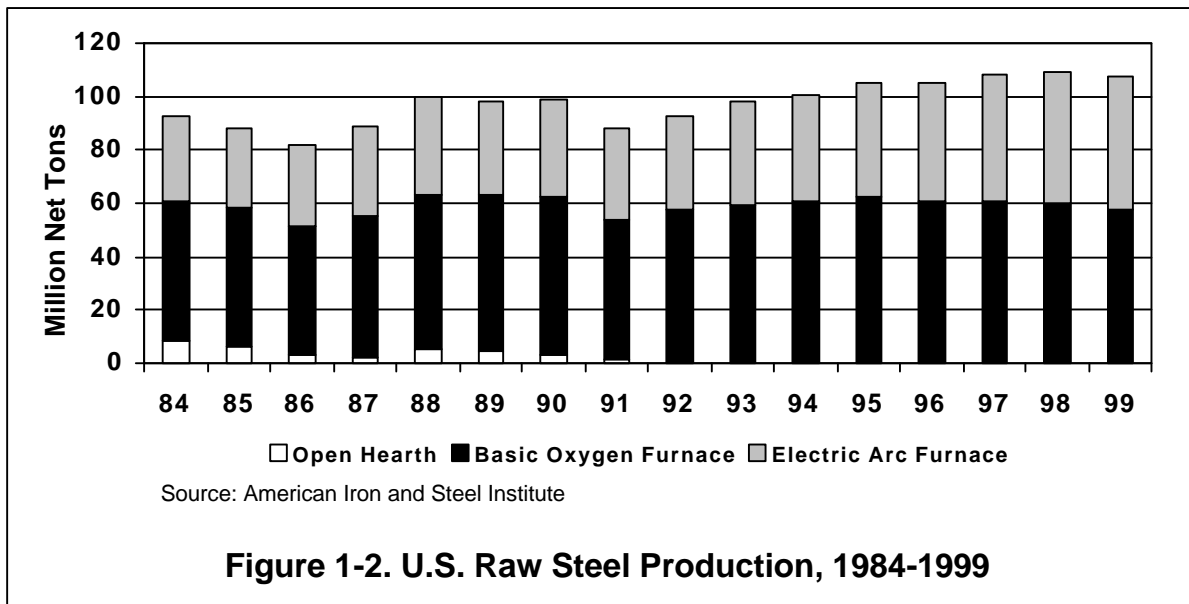
### ***Two Major Steelmaking Routes Used***

Steel is an alloy of iron that contains varying amounts of carbon as well as other elements such as nickel and chromium. Currently there are more than 3,000 catalogued grades of steel available, not counting custom grades for specific users (AISI 2000).

The iron and steel industry (designated as SIC 331 - see box) produces semi-finished steel shapes such as bars, sheets, and strips, as well as

Standard Industrial Code (SIC) 331 includes the following:

- 3312 Steel works, blast furnaces (including coke ovens), rolling mills
- 3313 Electrometallurgical products, except steel
- 3315 Steel wiredrawing and steel nails and spikes
- 3316 Cold-rolled steel sheet, strip, and bars
- 3317 Steel pipe and tubes



**Figure 1-2. U.S. Raw Steel Production, 1984-1999**

finished products such as wires, rods, and pipes. The industry consists of two types of facilities -- integrated (ore-based) and electric arc furnace (mainly scrap-based). Both types produce molten steel that is subsequently cast and formed into steel products, but the methods used to produce this steel differ.

An integrated steel mill produces molten iron (also known as hot metal) in blast furnaces using a form of coal known as coke, which is either produced on site or purchased. This iron is used as a charge to produce steel in a basic oxygen furnace (BOF). An electric arc furnace steel producer, also known as a mini-mill, uses electric arc furnaces (EAFs) to produce steel from steel scrap and other iron-bearing materials.

BOFs are typically used for high-tonnage production of carbon steels. EAFs also produce carbon steels, as well as low-tonnage alloy and specialty steels. EAF steel producers typically have lower capacity than integrated mills and narrower product lines, although some newer mills are producing commercial-quality flat-rolled products, historically a mainstay of integrated mills. The typical output of an EAF facility is about one million tons of steel per year, compared to an average of about three million tons per year for an integrated mill. As of 1999, 46% of U.S. raw steel was produced in electric arc furnaces (AISI 2000).

### ***New Forces Emerge in the World Market***

The steel industry in the 1990s faced a different world than it did in the 1970s. Large numbers of workers held high-paying, secure jobs. Integrated steel production in BOFs and open-hearth furnaces (now obsolete) was the norm, while EAF steelmaking was used mainly for the lowest grades of carbon steel.

In the late 1970s, world raw steel production exceeded 800 million net tons; U.S. production stood at about 137 million tons. The United States, Western Europe and the U.S.S.R. were the industry leaders, with Japan making major strides. Expansions were planned everywhere and global steel output was expected to reach over a billion tons per year by the turn of the century (Szekely 1995a).

These optimistic expectations were not fulfilled. Steelmaking entered a plateau or declined in most developed countries, with most of the growth taking place in the newly industrialized parts of the world.

Although the United States and the European Union are still major players, they are not nearly as dominant as they once were. China and South Korea have greatly increased their world market shares. Even in Japan, which is considered the technology leader in the world, steel production is

not as assured as it once was. Table 1-1 shows world and U.S. production of raw steel for the period 1988 - 1998, and Figure 1-3 shows the percentage of 1998 world production of raw steel by region. Preliminary 1999 data show a jump of nearly 8% in the raw steel production in China and close to 14% in Russia (IISI 2000).

### ***Recession Hurt the Industry from Late 1980s to Early 1990s***

A worldwide recession in the steel industry in 1989 affected practically every major producer except China. In the United States, this recession lasted until about 1993, when the industry experienced a positive turnaround. The recession intensified problems in the international steel trade, prompting a series of trade disputes that reduced both steel imports and exports. The "voluntary restraint arrangements" that limited imports in the 1980s expired in 1992; since then, the U.S. steel industry has discouraged imports by filing complaints that products are being dumped -- sold at less than the cost of production (EPA 1995). Similar cases were also filed against U.S. exporters. To address the problems of unfairly traded steel, most major steel-producing countries participated in multilateral steel agreement negotiations under the General Agreement on Tariffs and Trade (EPA 1995). These talks failed because of other countries' insistence that U.S. trade laws be weakened.

### ***Imports Surge in Late 1990s***

In 1997 and 1998, major structural economic failures -- and corresponding drops in steel demand -- in Asia, the Commonwealth of Independent States (CIS), and elsewhere greatly exacerbated world steel overcapacity. The result was more than 300 million tons (one-third of total world steel capacity) in distress and desperately seeking markets. The United States, as the largest, most open steel market in the world, has seen unprecedented levels of steel imports.

In March of 1999, the House of Representatives passed House Bill 975, which gives relief to the domestic steel industry by calling for limits on steel imports and strong monitoring systems. Although steel imports were down over the first

quarter of 1999 compared with the same period the previous year, imports remain high and rose 30% between April and May 1999. Some trade cases were filed; in June 1999, a coalition of domestic steel companies filed trade cases against 12 countries accused of illegally pricing their cold-rolled steel sold in the U.S. Also in June, the International Trade Administration determined that Korea was selling stainless steel sheet and strip at less than fair value.

Imports surged in recent years, reaching an all-time high of 41.5 million net tons in 1998. U.S. exports of steel products in 1998 were 5.5 million net tons, down 9% from the previous year. In 1999 the United States imported nearly 36 million net tons and exported about the same amount as in 1998 (AISI 2000). Most of the decline in imports from 1998 to 1999 was due to successful cases brought by U.S. producers.

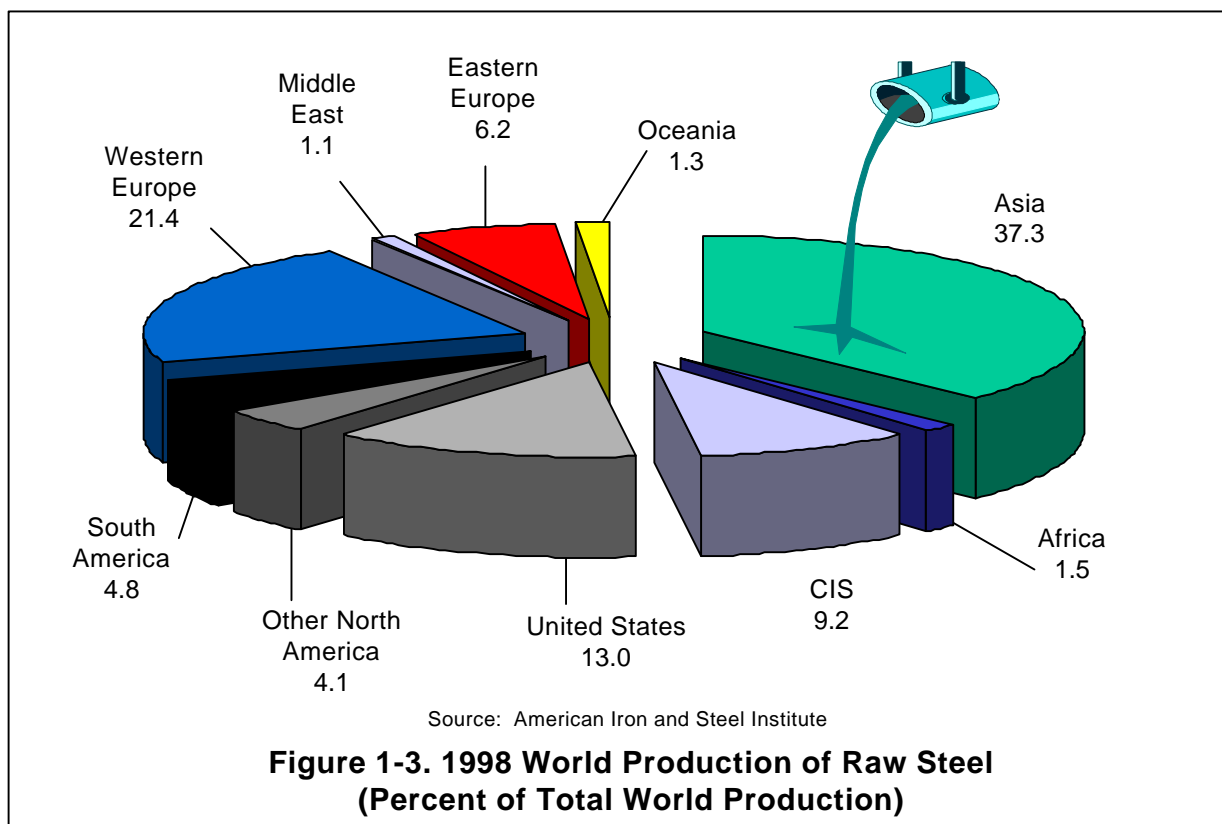
Figure 1-4 shows levels of U.S. imports and exports of steel products from 1978 through 1999, as compared with total U.S. net shipments of these products. Steel imports continued at high levels into 2000; nearly 3.4 million net tons of steel was imported in February of this year, equivalent to an annual rate of 39 million tons. Finished steel imports totaled 2.5 million net tons that month, equivalent to an annual rate of 28 million net tons. (AISI 2000)

### ***Net Shipments Show General Upward Trend***

In 1997, net shipments of steel mill products reached their highest level in almost 15 years. Total net shipments were 105.858 million net tons, up 34% from 1991 shipments. Shipments dropped to 102.42 million net tons in 1998 (see Table 1-2) but rebounded in 1999 to about 105.10 million net tons (see Figure 1-4) (AISI 2000).

Table 1-1. U.S. and World Production of Raw Steel: 1988 - 1998 (10 <sup>6</sup> net tons)							
Country/Region	1988	1991	1993	1995	1998	% of World Product. 1998	% Change 1988 - 1998
United States	100	88	98	105	107	12.7	7
Japan	116	121	110	112	103	12.3	(11)
China	62	78	99	105	126	15.0	103
Western Europe	167	179	174	188	207	24.6	24
Former U.S.S.R.	178	146	108	87	78	9.3	(56)
South Korea	18	29	36	41	44	5.2	144
India	14	19	20	24	26	3.1	86
Other	156	153	157	167	149	17.7	(5)
<b>TOTAL WORLD</b>	<b>811</b>	<b>813</b>	<b>802</b>	<b>829</b>	<b>840</b>	<b>100.0</b>	<b>4</b>

Sources: *Iron & Steelmaker* 1999b.  
 American Iron and Steel Institute 1999.  
 American Iron and Steel Institute 1988.



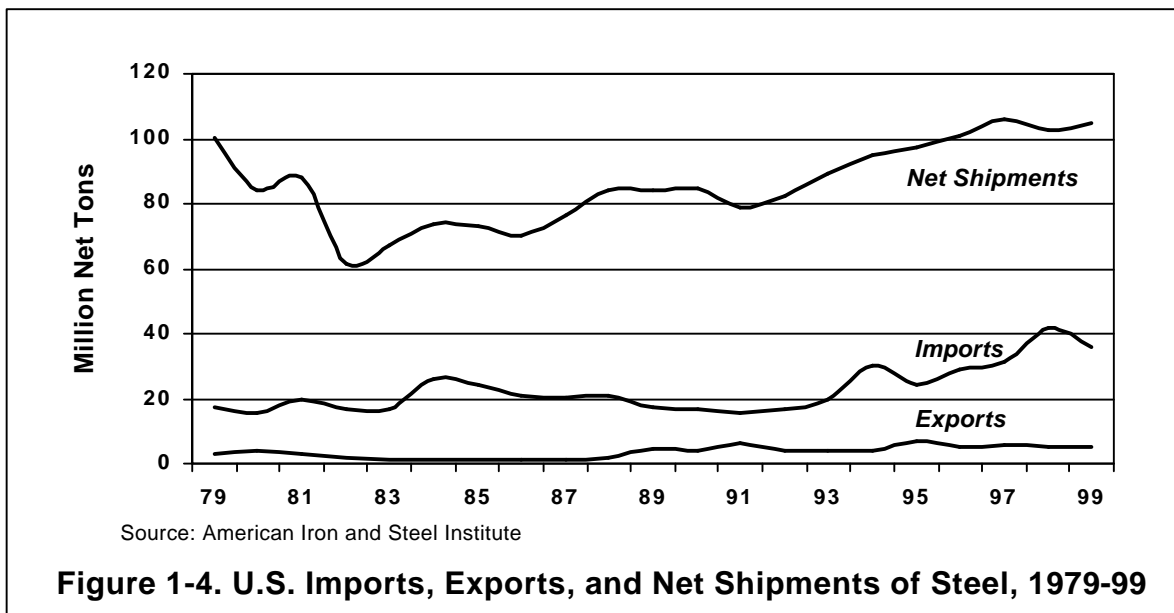


Table 1-2. Total Net Shipments of All Steel Mill Products in the U.S. - 1998 (1,000 net tons)		
Product	Total Net Shipments	Percent of Total
Semi-finished Shapes (blooms, slabs, billets, etc)	7,216.0	7.0
Shapes and Plates	14,458.7	14.1
Rails and Accessories	937.7	0.9
Bars		
Hot rolled	8,189.2	8.0
Reinforcing	5,908.9	5.8
Other	4,257.9	4.1
Tool Steel	51.5	0.1
Pipe and Tubing	5,409.4	5.3
Wire - Drawn and/or Rolled	724.9	0.7
Tin Mill Products	3,714.1	3.6
Sheets		
Hot rolled	15,715.2	15.3
Cold rolled	13,185.3	12.9
Sheets & Strip - Galvanized		
Hot dipped	13,481.4	13.1
Electrolytic	3,742.6	3.7
Sheets & Strip - All Other Metallic Coated/ Electrical	2,747.8	2.7
Strip - Hot and Cold Rolled	2,682.9	2.6
<b>TOTAL</b>	<b>102,419.6</b>	<b>100.0</b>

Source: American Iron and Steel Institute 1999.

This upward trend is attributed to strong demand from the steel industry's two largest customers – the automotive and construction sectors. Table 1-3 shows 1998 shipments of steel mill products by market.

For several years in the mid 1990s, steelmakers were able to raise prices while increasing shipments and have made money each year since 1992's 15% loss. In 1993 the industry enjoyed a 6.4% return on sales; in 1998 that return was 2.7% (includes data for companies making up 65% of total raw steel production) (AISI 1999).

The health of the automotive and construction sectors plays a major role in determining the health of the steel industry. Much of the steel sold to U.S. automakers is covered by long-term

contracts, with the remainder sold on the spot market.

Steel represents about 55% of the material used by weight in the average family car (AISI and SMA 1998). Much of the decline in this value over the past 20 years (it represented closer to 60% of the weight in 1975) has been due to the expanding use of high-strength steels to save weight.

New and expanding applications of steel may also lead to increased demand for steel products. The residential construction sector also represents a major market for steel; increased adoption of steel framing for houses would further boost steel sales.

<b>Table 1-3. Shipments of U.S. Steel Mill Products by Market Classification - 1998 (1,000 net tons)</b>		
<b>Market Classification</b>	<b>Shipments</b>	<b>Percentage of Total</b>
Steel Service Center and Distributors	27,751	27.1
Automotive	15,842	15.5
Construction (including maintenance) and Contractors' Products	15,289	14.9
Steel for Converting and Processing (net shipments)	9,975	9.7
Containers, Packaging, and Shipping Materials	3,829	3.7
Oil and Gas Industry	2,649	2.6
Electrical Equipment	2,255	2.2
Machinery, Industrial Equipment, and Tools	2,147	2.1
Appliances, Utensils, and Cutlery	1,729	1.7
Rail Transportation	1,657	1.6
Forgings (not elsewhere classified)	1,245	1.2
Non-classified Shipments	12,640	12.3
Others (accounting for less than 1.0% of market each)	2,856	2.9
Export (reporting companies only)	2,556	2.5
<b>TOTAL</b>	<b>102,420</b>	<b>100.0</b>

Source: American Iron and Steel Institute 1999.



### 1.3 Energy and Materials Consumption

#### Industry Relies Heavily on Coal

Steel is an energy-intensive industry. According to the most recent manufacturing energy consumption survey conducted by the Energy Information Administration, the U.S. iron and steel industry consumed a gross total of 1.96 quads ( $10^{15}$  Btu) of energy (including electricity generating and transmission losses) in 1994 (EIA

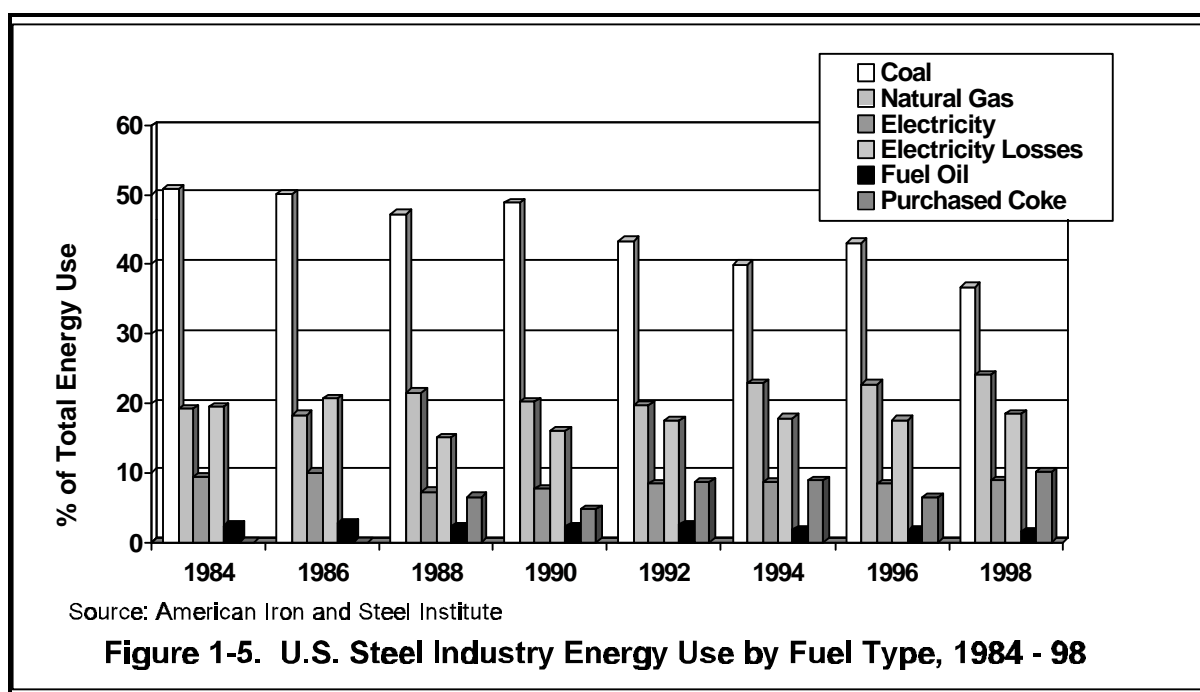
1997). This represented roughly 2.3% of all energy used in this country that year, and approximately 9% of all U.S. manufacturing energy use. Current industry statistics yield a total net energy consumption in 1998 of 1.68 quads.

Energy costs typically account for about 15% to 20% of the manufacturing cost of steel, typically \$60 per ton or more, depending on location (Steiner 1998a and AISI 1999b). Nearly half of the industry's energy is derived from coal, most of which is used to produce coke for use in the blast furnace.

Figure 1-5 illustrates the trends in fuel use by the U.S. steel industry over the past 20 years. Use of natural gas and electricity has increased over the period, while use of coal and petroleum has dropped slightly.

Table 1-4 shows the U.S. iron and steel industry's total energy consumption by fuel type for 1998 according to data compiled by the American Iron and Steel Institute. The total energy consumption for that year was determined to be 1.68 quads with electricity losses included, or about 1.38 quads with losses excluded. The industry's electricity costs are about \$1.5 billion annually (AISI 2000).

Table 1-4 also shows usage levels for coke oven gas and blast furnace gas, the two major byproduct fuels associated with integrated steelmaking. These two fuels are recovered and used throughout the mill. About half of all coke oven gas is used as a fuel for the coke ovens; the rest is used elsewhere in the plant or sold. Blast furnace gas is used to generate steam and to preheat air coming into the blast furnace or to supply heat to other plant processes.



<b>Table 1-4. U.S. Iron and Steel Industry Energy Consumption - 1998</b>		
<b>Fuel</b>	<b>Total Industry Use (units as given)</b>	<b>Total Industry Use (10<sup>12</sup> Btu)<sup>a</sup></b>
Coal	22.01 10 <sup>6</sup> net tons	<b>594.2</b>
Coke (purchased and imported) <sup>b</sup>	6.42 10 <sup>6</sup> net tons	168.8
Electricity (with losses)	42.92 10 <sup>9</sup> kWh	450.7
Natural Gas	395.45 10 <sup>9</sup> ft <sup>3</sup>	395.2
Fuel Oil	172.43 10 <sup>12</sup> gal	24.1
Oxygen	291.06 10 <sup>9</sup> ft <sup>3</sup>	50.9
Blast Furnace Gas	1,197.18 10 <sup>9</sup> ft <sup>3</sup>	179.8
Coke Oven Gas	243.36 10 <sup>9</sup> ft <sup>3</sup>	121.7
<b>SUBTOTAL</b>		<b>1,983.5</b>
<b>LESS RECOVERED ENERGY</b>		
Blast Furnace Gas	1,997.18 10 <sup>9</sup> ft <sup>3</sup>	179.8
Coke Oven Gas	243.36 10 <sup>9</sup> ft <sup>3</sup>	121.7
<b>SUBTOTAL</b>		<b>301.4</b>
<b>EQUALS</b>		
<b>NET TOTAL</b>		<b>1,682.1</b>

a Conversion factors are 27 10<sup>6</sup> Btu/ton of coal, 26 10<sup>6</sup> Btu/ton of coke, 10,500 Btu/kWh, 1,000 Btu/ft<sup>3</sup> of natural gas, 0.140 10<sup>6</sup> Btu/gallon of fuel oil, 175 Btu/ft<sup>3</sup> of oxygen, 90 Btu/ft<sup>3</sup> of blast furnace gas, and 500 Btu/ft<sup>3</sup> of coke oven gas (AISI 1996).

b Taken as the difference between the coke used (22.01 10<sup>6</sup> tons) and the coke produced (15.59 10<sup>6</sup> tons) in the United States in 1998. This represents both imported coke and coke purchased from merchant plants.

Sources: American Iron and Steel Institute 1999 and 1996.

Table 1-5 shows total 1994 energy consumption for SIC 3312 according to the most recently published Manufacturing Consumption of Energy (MECS). The discrepancies between the MECS data and the AISI data shown in Table 1-3 are attributed to the different years and the inclusion of different subsectors of the industry.

Table 1-6 breaks down the total 1998 energy use by major process within the iron and steel industry. Table 1-7 shows typical energy intensities for steelmaking processes. The intensities cannot be accurately used to determine

total energy use for each process but are useful in understanding the relative energy intensities of various process steps along both the integrated and EAF steelmaking routes.

### ***Energy Efficiency Continues to Improve***

The U.S. iron and steel industry has reduced its process energy intensity by about 45% since 1975 through energy conservation measures, process improvements, and consolidation of the industry at the more productive and modern plants (Figure 1-6). In 1994 the average energy intensity of

<b>Table 1-5. U.S. Blast Furnaces and Steel Mills (SIC 3312) Energy Consumption (MECS Estimate) - 1994</b>	
<b>Fuel</b>	<b>Total Industry use (10<sup>12</sup> Btu)</b>
Coal	893
Coke	385
Electricity (with losses)	456
Natural Gas	484
Fuel Oil	Data withheld
Other	26
<b>TOTAL</b>	<b>1,957</b>

Source: Energy Information Administration 1997.

<b>Table 1-6. U.S. Steel Industry Net Energy Use by Major Process - 1998</b>		
<b>Process</b>	<b>Total Industry Use (10<sup>12</sup> Btu)<sup>a</sup></b>	<b>Percentage of Total</b>
Sintering	18	1
Cokemaking	52	3
Ironmaking	641	38
BOF Steelmaking	53	3
EAF Steelmaking	258	15
Casting	44	3
Boilers	194	12
Cogeneration	82	5
<b>SUBTOTAL</b>	<b>1,342</b>	<b>80</b>
All Other Processes (e.g., reheating, rolling, finishing) <sup>b</sup>	340	20
<b>TOTAL</b>	<b>1,682</b>	<b>100</b>

a Including electricity generating and transmission losses.

b Taken as the difference between known total industry use and known subtotal use.

Source: American Iron and Steel Institute 1999 and 1996.

**Table 1-7. Typical Energy Intensity of U.S. Integrated and EAF-Based Steelmaking Processes - 1998<sup>a</sup>**

Process	Integrated Steelmaking			EAF-Based Steelmaking		
	Electric <sup>b</sup>	Other Energy	Total Primary Energy	Electric <sup>b</sup>	Other Energy	Total Primary Energy
	10 <sup>6</sup> Btu/ton steel	10 <sup>6</sup> Btu/ton steel	10 <sup>6</sup> Btu/ton steel	10 <sup>6</sup> Btu/ton steel	10 <sup>6</sup> Btu/ton steel	10 <sup>6</sup> Btu/ton steel
Sintering	0.06	0.24	0.30	N/A	N/A	N/A
Cokemaking <sup>c</sup>	0.35	3.00	3.35	N/A	N/A	N/A
Pulverized Coal Injection <sup>d</sup>	0.01	0.0	0.01	N/A	N/A	N/A
Ironmaking <sup>e</sup>	0.19	10.54	10.73	N/A	N/A	N/A
BOF Steelmaking	0.22	0.67	0.88	N/A	N/A	N/A
EAF Steelmaking	N/A	N/A	N/A	4.58	0.67	5.25
Vacuum Degassing and Ladle Metallurgy	0.32	0.30	0.62	0.97	0.10	1.07
Continuous Casting	0.29	0.00	0.29	0.29	0.0	0.29
Ingot Casting	1.57	1.21	2.78	N/A	N/A	N/A
Slab Mill	0.97	1.75	2.72	N/A	N/A	N/A
Hot Rolling (inc. reheating)	0.80	1.50	2.30	2.88	0.65	3.53
Pickling (Hot Rolling)	0.81	0.40	1.21	0.32	0.36	0.68
Hot Dip Galvanneal	2.25	2.00	4.25	1.91	1.00	2.94
Tempering and Finishing (Hot Rolling)	0.32	0.10	0.42	0.32	0.00	0.32
Cold Rolling (inc. cleaning and annealing)	0.90	0.70	1.60	0.97	0.000	0.97
Tempering and Finishing (Cold Rolling)	1.13	0.20	1.33	0.32	0.00	0.32

a Based on total integrated steel production of 59.686 million tons and total EAF-based steel production of 49.067 million tons in 1998.

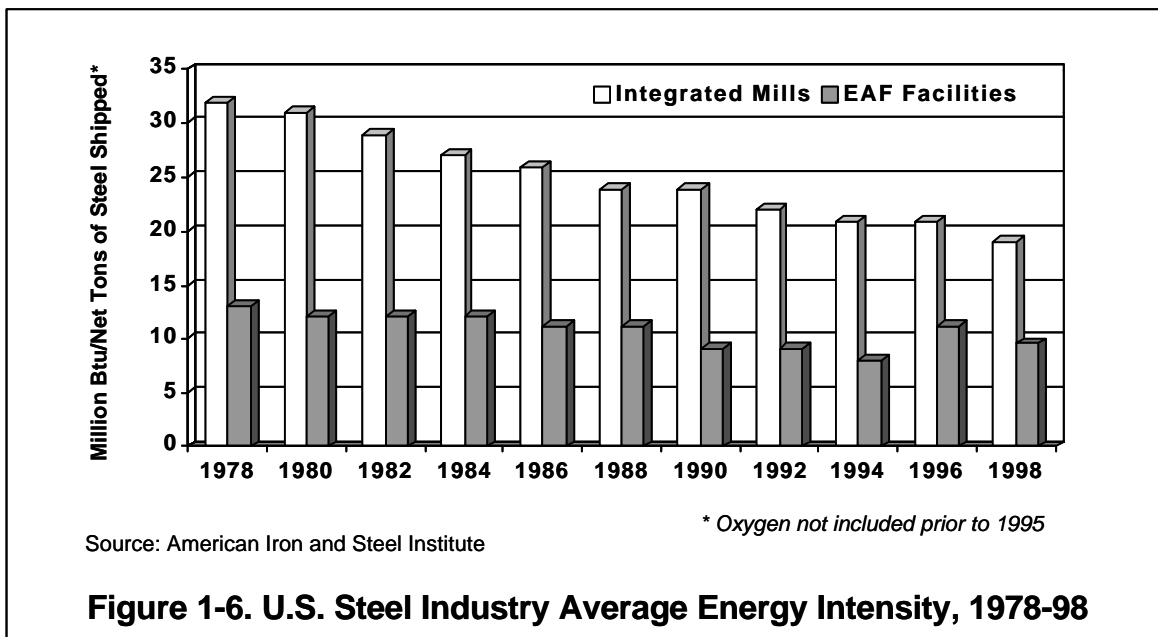
b Using a conversion factor of 10,500 Btu/kWh.

c Values are per ton of coke.

d Based on 1998 total coal consumption of 2.2 million net tons for purposes other than coke production, and assuming 30 kWh/ton of coal for pulverization (Fillman 1999).

e Blast furnace top gas credit taken.

Sources: Stubbles 2000.  
American Iron and Steel Institute 1999 and 1996.  
Barnett 1998.



producing semi-finished steel at integrated mills using BOF steelmaking was 20.76 million Btu/ton. The current energy intensity of integrated steelmaking is estimated at 19 million Btu/ton of steel shipped (AISI 2000). For flat-rolled EAF steel, the current energy intensity is estimated to be around 9.5 million Btu/ton of shipped steel based on the results of a recent SMA survey (Stubbles 2000).

The overall energy intensity of the U.S. steel industry in 1998 is estimated to be 17.4 million Btu/ton (Stubbles 2000). Twenty-six years earlier, in 1974, the average energy intensity for the industry as a whole was 31.71 million Btu per ton of shipped steel (AISI 1995a). This reduction in energy intensity has occurred in spite of the industry's move toward higher value products, which has required additional processing (e.g., refining and finishing steps) that increase energy requirements. Much of the reduction in energy intensity over the past 20 years has been achieved through the following:

- elimination of open hearth furnace steelmaking
- shutdown of older and less efficient mills
- near total conversion to continuous casting
- process improvements that have increased steelmaking yields

- higher capacity utilization
- increased production of steel made in electric arc furnaces

Electric arc furnace steelmaking is only about half as energy intensive as the blast furnace- basic oxygen furnace route because EAFs use a higher percentage of scrap in the charge. Using scrap eliminates the most energy-intensive step of the steelmaking process, the conversion of iron ore to iron in the blast furnace. BOFs are limited in their use of scrap in the charge because of the heat balance in the process.

EAF steelmaking currently accounts for 45% of all U.S. steel production. Some sources believe that this will increase to 50% over the next few years as additional EAF capacity comes on line. When using 100% scrap, EAF steelmaking cannot produce the highest quality sheet products because of the high level of residual elements in scrap. However, alternative iron units from direct reduced iron and other sources can be used to upgrade a charge of lower grade scrap for higher grades of steelmaking (Bechak 1995).

Figure 1-6 shows a relatively flat trend in the industry's average energy intensity during the late 1980s. This trend is believed to be due in part to the industry's depressed operating levels during that period, which caused energy

inefficiencies. Increased energy requirements associated with environmental controls were also a factor in this trend; another is the decline in growth of EAF capacity, which leveled off in about 1986.

Some additional improvements in energy efficiency are anticipated as the industry improves yields even further and produces stronger and lighter steels. The pace of these improvements, however, is dictated by the availability of capital to make the needed investments.

Future reductions in energy intensity are not expected to be as dramatic as those already achieved. Stubbles predicts a decrease in overall industry energy intensity to 15 million Btu/ton by 2010, with an asymptotic trend towards 14 million Btu/ton (Stubbles 2000). These reductions may come from a decrease in the number of process steps (the near net shape concept), more efficient heat transfer to the workpiece, and better conservation of sensible heat (Stubbles 1999). Additional environmental requirements may offset some of the potential gains in industry energy efficiency.

### **Materials Consumed Include Iron, Scrap, Fluxes**

In addition to the fuels shown in Table 1-4, the industry consumed iron ore in the form of pellets and other agglomerated products, fluxes, steel scrap, and direct reduced iron (DRI). DRI and other alternate iron units (e.g., hot briquetted iron) can be used as low-residual alternatives to scrap in the EAF.

Table 1-8 shows the amounts of these materials consumed in the U.S. iron and steel industry in 1998. Total coke consumption included the 6.42 million net tons imported or produced at domestic merchant coke plants (shown in Table 1-4), plus the 15.59 million net tons produced in U.S. iron and steel facilities, for a total of 22.01 million net tons. Table 1-9 breaks down the industry's consumption of scrap, molten (pig) iron, and direct reduced iron (DRI) by furnace type for 1998. About 60% of 1998 U.S. steel production came from ferrous scrap, including home, purchased, and obsolete scrap.

## **1.5 Environmental Overview**

### **Industry Has Made Large Investments in Pollution Control**

Over the past 30 years the U.S. iron and steel industry has invested over \$50 billion in new technologies with \$10 billion of that spent to improve its environmental record. In a typical year, 15% of the industry's capital investments go toward environmental projects.

Costs for operating and maintaining pollution control equipment averaged about \$12/ton of steel (Wrona 1997). In 1994 alone, the iron and steel industry (SIC 331) had capital expenditures of \$231 million for pollution abatement, including \$37 million on water pollution control, \$46 million for solid/contained waste, and \$148 million for air pollution control (DOC 1994). The figure for air pollution control (about 65% of total environmental expenditures) is primarily a result of operating coke ovens in compliance with the Clean Air Act. Environmental factors dominate the design of any new facility, and the trend is toward total utilization of byproducts from various operations, with the exception of gaseous and minor particulate emissions (Stubbles 1999).

*The industry's investment in pollution control technology has contributed substantially to an improved environment. Some of the major accomplishments over the past 25 years are:*

- ! *Over 95% of the water used in producing and processing steel is now being recycled.*
- ! *Discharge of air and water pollutants has been reduced by more than 90% over the past 20 years.*
- ! *Solid waste production (excluding slag) at a typical mill has been reduced by more than 80%.*
- ! *Many hazardous wastes once generated by the industry are now being recycled or recovered for reuse.*
- ! *Steel has an overall recycling rate of about 68%, much higher than other materials.*
- ! *About 70% of all purchased scrap is*

<b>Table 1-8. U.S. Iron and Steel Industry Materials Consumption - 1998<sup>a</sup></b>	
<b>Material</b>	<b>Amount (1,000 net tons)</b>
Iron Ore (total)	82,180
Natural ore	940
Pellets	69,298
Sinter, briquettes, nodules, and other	11,942
Fluxes (total)	5,493
Fluorspar	85
Limestone	880
Lime	3,979
Other fluxes	549
Scrap (total)	60,600
Carbon steel	55,400
Stainless steel	1,100
Alloy steel (excl. stainless)	1,000
Iron scrap	1,000
Other	1,900
Direct Reduced Iron	1,400 <sup>b</sup>

a Excludes alloys.

b Does not include all domestic DRI production.

Source: American Iron and Steel Institute 1999.

<b>Table 1-9. U.S. Iron and Steel Industry Consumption of Scrap, Molten Iron, and DRI by Furnace Type - 1998 (1,000 net tons)</b>				
<b>Furnace Type</b>	<b>Molten (Pig) Iron</b>	<b>Scrap</b>	<b>DRI</b>	<b>Total</b>
Basic Oxygen	51,000	18,000	a (140 in '97)	69,000
Electric Arc	3,500	43,000	a (870 in '97)	46,500
Blast	0	a (1,900 in '97)	4440	440
<b>TOTAL</b>	<b>54,500</b>	<b>61,000</b>	<b>440</b>	<b>115,940</b>

a Data withheld to avoid disclosure.

### ***Steelmakers Manage Large Quantities of Residues, Other Wastes***

In 1997, the U.S. steel industry generated around 39 million tons of solid wastes and residues such as slags, sludges, and dusts. More than 80% of

this total comes from integrated mills. The largest solid byproduct streams included blast furnace slag (about 35% of the total) and BOF slag (about 20%).

In 1996, the industry reported about 0.91 billion pounds of production-related Toxic Release Inventory (TRI) chemical waste. Table 1-10

summarizes the management of this waste. Of the total, about 389 million pounds (42.5%) was managed on-site through recycling, energy recovery, or treatment.

Of the other 526 million pounds (57.5%) of production-related waste, 87.4 million pounds were either released to the environment through direct discharges to air, land, water, and underground injection, or were disposed on-site. The remaining 438.6 million pounds included 326.4 million pounds recycled off-site; the rest (about 85 million pounds) was either treated, discharged, or disposed off-site (EPA 1998).

Table 1-11 presents "release" data on some common iron and steel industry TRI chemicals, showing the percentages of each released to the air, water, and land in 1995. Table 1-12 shows a similar table for "transfers" of TRI chemicals off-site for recycling, treatment, or disposal.

The final column in these tables -- the average release or transfer per facility -- is based on the specific number of facilities reporting that particular pollutant. Although 423 iron and steel facilities in SIC 331 filed TRI reports in 1995, the 155 facilities classified under SIC 3312 (blast furnaces and steel mills) are responsible for over 75% of reported releases and transfers (EPA 1998).

In addition to the pollutants shown in Tables 1-11 and 1-12, numerous others were reported, including many types of solvents and trace metals. The great diversity in the TRI chemical releases/transfers is attributable to a number of factors, including the wide variety of processes used at individual mills.

TRI data for more recent years are not available at the 3-digit SIC level; all primary metal industries are combined in the 1997 and 1998 estimates.

<b>Table 1-10. Summary of Source Reduction and Recycling Activity for SIC 331 as Reported within the Toxic Release Inventory - 1996</b>		
<b>Activity</b>	<b>Pounds</b>	<b>% of Total</b>
<b>RELEASES</b>		
<b>On-Site Releases and Land Disposal - Subtotal</b>	<b>87,362,396</b>	<b>9.6</b>
Air Emissions	22,922,759	2.5
Water discharges	25,433,888	2.8
Underground injection	613,450	0.1
RCRA Subtitle C Landfills	9,241,029	1.0
Other On-Site Land Releases	29,151,270	3.2
<b>ON-SITE MANAGEMENT AND TRANSFERS</b>		
<b>On-Site Management - Subtotal</b>	<b>388,750,619</b>	<b>42.5</b>
Recycling	229,090,200	25.0
Energy Recovery	4,248,280	0.5
Treatment	155,412,139	17.0
<b>Transfers - Subtotal</b>	<b>438,563,131</b>	<b>47.9</b>
POTW discharge	3,075,268	0.3
Disposal	63,725,678	7.0
Recycling	326,364,306	35.7
Treatment	45,015,538	4.9
Energy recovery	121,665	0.0
Other Off-Site Transfers	260,676	0.0
<b>TOTAL</b>	<b>914,676,146</b>	<b>100.0</b>

Source: U.S. Environmental Protection Agency 1998.



**Table 1-11. Releases of Select TRI Chemicals for Iron and Steel Facilities - 1995  
(lbs/year)**

<b>Chemical</b>	<b>Fugitive Air</b>	<b>Point Air</b>	<b>Water Discharges</b>	<b>Undergrnd Injection</b>	<b>Land Disposal</b>	<b>Total Releases</b>	<b>Avg. Release Per Facility</b>
Manganese compounds	374,353	1,803,613	392,851	3,000	27,900,531	30,474,348	256,087
Zinc compounds	815,939	1,040,835	234,021	250	20,582,148	22,673,193	182,848
Hydrochloric acid	481,418	1,656,840	5	0	5	2,138,268	23,759
Ammonia	8,596,982	1,276,314	818,748	0	152,984	10,845,028	180,750
Zinc (fume or dust)	246,418	199,446	7,340	0	2,100	455,268	11,674
Copper compounds	4,663	5,655	5,797	0	53,800	69,915	1,165
Lead compounds	70,337	180,618	26,175	0	1,207,312	1,484,442	21,514
Ethylene	322,401	1,118,097	0	0	0	1,440,498	57,620
Manganese	36,050	40,086	11,814	0	790,523	878,473	8,698
Sulfuric acid	204,099	104,260	0	0	0	308,359	5,930
Nickel compounds	10,117	25,156	17,457	0	262,937	315,667	3,469
Chromium	25,381	55,931	6,666	0	508,968	596,946	5,016
Cyanide compounds	130,941	151,159	61,124	0	13,527	356,751	15,511

Source: U.S. Environmental Protection Agency 1998a and 1995.

The releases and transfers in 1995 were dominated by large volumes of metal-bearing wastes, which account for approximately 80% of the industry's transfers and more than 50% of the releases. Of the 90.7 million pounds of iron and steel industry TRI chemical releases in 1995, more than half (54.7 million pounds) was land-disposed on site. More than one quarter of the releases (28.4 million pounds) were fugitive or point source air emissions.

The industry's air releases are associated with volatilization, fume, or aerosol formation in the high-temperature furnaces and in byproduct processing. Ammonia, lighter weight organics

(e.g., methanol), acids, and metal contaminants found in the iron ore are the principal types of chemicals released to the air (EPA 1995).

Of the 513.9 million pounds of TRI chemicals transferred by the industry in 1995, about 80% (404 million pounds) were sent off-site for recycling.

***Pollutant Emissions Continue to Decrease***

According to EPA data, releases and transfers from the industry continued to decrease from 1993 to 1995. A key factor influencing an overall

Table 1-12. Transfers of Major TRI Chemicals for Iron and Steel Facilities - 1995 (lbs/year)							
Chemical	POTW <sup>a</sup> Discharge	Disposal	Recycling	Treatment	Energy Recovery	Total Transfers	Avg. Transfer Per Facility
Zinc compounds	23,768	45,043,648	161,076,355	1,947,577	0	208,090,348	1,678,148
Zinc (fume or dust)	3,017	810,586	66,851,862	5,411,809	5,594	73,082,868	1,873,920
Hydrochloric acid	1,358,466	2,397,609	20,556,576	2,918,806	0	27,231,457	302,572
Aluminum (fume/dust)	5	81,840	761,149	253,742	1,000	1,097,736	45,739
Manganese	3,340	1,268,224	17,562,708	1,061,194	0	19,896,216	196,992
Sulfuric Acid	1,760	559,017	649,631	3,357,561	0	4,728,252	90,928
Chromium	3,597	1,111,505	26,689,081	1,887,120	0	29,691,303	249,507
Manganese compounds	8,836	5,013,032	35,123,503	1,520,361	0	42,185,802	354,503
Chromium compounds	2,844	5,264,939	12,648,224	1,711,870	4,593	19,665,420	161,192
Lead compounds	2,005	1,746,567	19,811,212	228,350	0	23,045,894	333,998
Nickel	3,610	600,523	14,674,853	58,207	0	15,337,193	147,473

a Publicly Owned Treatment Works.

Source: U.S. Environmental Protection Agency 1998a and 1995.

downward trend since 1988 in releases and transfers is the decrease in steel production during the 1988 to 1995 period. In addition, pollution control equipment and a shift to new technologies such as continuous casting are believed to be responsible for significant changes in the amount and type of pollutants released during steelmaking.

The industry's efforts in pollution prevention also have been a factor (EPA 1995) in releases and transfers. For example, many steel companies participated in EPA's 33/50 Program, a voluntary program that lead to significant reductions in TRI releases from 1990 to 1995.

Table 1-13 shows the combustion-related carbon intensities of both integrated and EAF-based steelmaking processes. Blast furnace ironmaking in blast furnaces is the most carbon-intensive process among those considered, accounting for about 2,000 lbs CO<sub>2</sub>/ton steel.

Environmental regulations affect the industry throughout all stages of the manufacturing and forming processes (EPA 1995). The following subsections briefly discuss air pollution, water pollution, and solid/hazardous waste in iron and steelmaking and describe the major environmental regulations that apply to the industry.

Table 1-13. Estimated Combustion-Related Carbon Intensity of U.S. Integrated and EAF-Based Steelmaking Processes - 1998 <sup>a,b</sup>				
Process	Integrated Steelmaking		EAF-Based Steelmaking	
	lbs CO <sub>2</sub> /ton steel	metric ton CE/ metric ton steel	lbs CO <sub>2</sub> /ton steel	metric ton CE/ metric ton steel
Sintering	69	0.009	N/A	N/A
Cokemaking	102	0.014	N/A	N/A
Pulverized Coal Injection	1	0.000	N/A	N/A
Ironmaking <sup>c</sup>	2,000	0.273	N/A	N/A
BOF Steelmaking	490	0.067	N/A	N/A
EAF Steelmaking	N/A	N/A	1,012	0.138
Vacuum Degassing and Ladle Metallurgy	78	0.011	141	0.019
Continuous Casting	39	0.006	39	0.006
Ingot Casting <sup>d</sup>	351	0.047	N/A	N/A
Slab Mill	334	0.045	N/A	N/A
Hot Rolling (includes reheating)	376	0.051	282	0.038
Pickling (Hot Rolling)	155	0.021	85	0.012
Hot Dip Galvanneal	534	0.073	376	0.051
Tempering and Finishing (Hot Rolling)	55	0.008	43	0.006
Cold Rolling (includes cleaning and annealing)	229	0.031	129	0.018
Tempering and Finishing (Cold Rolling)	175	0.024	43	0.006

a Emission factors (in lbs/10<sup>6</sup> Btu) are as follows: Coal (56); Coke (69); Residual Fuel Oil (47); Distillate Fuel Oil (43); Gasoline (42); LPG (37); Tar (61); Light Oil (50); Natural Gas (32); Blast Furnace Gas (135); Coke Oven Gas (26); Electricity (110 for primary electricity; 36 for delivered electricity that includes losses); Oxygen (114) (AISI 1996).

b Using conversion factor of 10,500 Btu/kWh.

c Credit taken for top gas used elsewhere in the plant.

d Values are per ton of steel ingot cast rather than per ton of steel.

Source: American Iron and Steel Institute 1998 and 1996.  
Barnett 1998.  
LBNL 1998.

### **Industry's Emissions of Air Pollutants Must Comply with the Clean Air Act**

In addition to air releases of chemicals reported in the TRI database, the iron and steel industry is a significant source of combustion-related particulates, carbon monoxide, nitrogen oxides, and sulfur compounds. Air pollutant emissions

have dropped significantly since the 1970s as a result of increased pollution control as well as improved energy efficiency. A typical integrated steel mill in the U.S. currently emits about 4 million tons of CO<sub>2</sub> and about 10,000 tons of SO<sub>x</sub> annually, reductions of 28 and 95%, respectively, from their values in the mid 1970s (Szekely 1995a).

The Clean Air Act and its amendments, including the Clean Air Act Amendments of 1990 (CAAA), have established national ambient air quality standards (NAAQS) to limit levels of six criteria pollutants. The NAAQS that affect the iron and steel industry the most include those for particulate matter, nitrogen dioxide, and lead. Under the Act, each state must develop an implementation plan to identify sources of air pollution and determine what reductions are required to meet Federal air quality standards.

Tables 1-14 and 1-15 show estimated emissions of combustion-related criteria pollutants (pounds of pollutant per ton of steel) of various process stages for integrated and EAF-based steelmaking, respectively. These tables do not include emissions resulting from coke oven and blast furnace gas because reliable emission factors do not exist for these fuels.

Table 1-16 shows estimated total U.S. iron and steel industry combustion-related emissions of criteria pollutants and CO<sub>2</sub> for steelmaking processes through casting. Ironmaking accounts for over half of the total emissions for each criteria pollutant (with the exception of VOCs), as well as about a third of the total CO<sub>2</sub> emissions for the entire industry. Total CO<sub>2</sub> emissions are estimated to be approximately 147 million tons in 1998. This equates to approximately 40 million tons of carbon equivalent, or 36 million metric tons of carbon equivalent (MMTce, a unit used in international discussions on greenhouse gas emissions).

Also under the Act, the U.S. Environmental Protection Agency (EPA) has established New Source Performance Standards for new stationary sources within particular industrial categories, including such iron and steel industry categories as cokemaking, blast furnace ironmaking, both types of steelmaking, and various refining and finishing processes.

New facilities, as well as expansions of existing facilities or process modifications, must also comply with the 1990 CAAA New Source Review (NSR) requirements. For non-attainment areas that do meet NAAQS for a given pollutant, permits require the new source to meet the lowest achievable emission rate (LAER) standards, and the new source must procure reductions in emissions of the same pollutants from other sources in the area in equal or greater amounts to the new source. For areas meeting the NAAQS, permits require the best available control technology (BACT), and continuous air quality testing is required for one year.

As part of the Clean Air Act, EPA has established and enforces National Emission Standards for Hazardous Air Pollutants (NESHAPs), uniform national standards oriented towards controlling particular hazardous air pollutants (HAPS). NESHAPs currently in effect for the industry include standards for coke oven batteries, benzene emissions from coke byproduct recovery plants, halogenated solvent cleaning, and chromium from industrial process cooling tower.

EPA has developed a list of sources that emit any of 189 HAPS. To date, EPA has listed about 170 categories of sources of these HAPS and has developed a schedule for the establishment of emission standards. These standards will be developed for both new and existing sources based on maximum achievable control technology (MACT). The MACT is defined as the control technology achieving the maximum degree of reduction in the emission of the HAPS, taking into account cost and other factors.

Included on the list of 189 HAPS to be regulated are compounds of chromium, nickel, manganese, cadmium, and other heavy metals. Because many of these metals are routinely found in iron ore, scrap, and alloying materials, most steelmaking processes will be affected in some way. MACTs for air emissions of these metals are expected to be established in 2000.

<b>Table 1-14. Estimated Combustion-Related Emissions of Criteria Pollutants for U.S. Integrated Steelmaking Processes - 1998<sup>a,b,c</sup></b>					
<b>Process</b>	<b>Pollutant (lbs/ton steel)</b>				
	<b>SOx</b>	<b>NOx</b>	<b>CO</b>	<b>Particulate</b>	<b>VOCs</b>
Sintering	0.676	0.258	0.083	0.194	0.001
Cokemaking <sup>d</sup>	--	--	--	--	--
Pulverized Coal Injection	0.015	0.006	0.002	0.004	0.000
Ironmaking <sup>e</sup>	26.470	10.270	3.267	7.624	0.062
BOF Steelmaking	0.320	0.165	0.050	0.089	0.003
Vacuum Degassing and Ladle Metallurgy	0.469	0.220	0.067	0.130	0.003
Continuous Casting	0.421	0.160	0.051	0.116	0.001
Ingot Casting	2.277	1.033	0.319	0.632	0.014
Slab Mill	1.407	0.779	0.232	0.393	0.014
Hot Rolling (includes reheating)	1.160	0.650	0.193	0.325	0.012
Pickling (Hot Rolling)	1.175	0.502	0.157	0.325	0.006
Hot Dip Galvanneal	3.260	1.517	0.466	0.905	0.021
Tempering and Finishing (Hot Rolling)	0.469	0.192	0.060	0.130	0.002
Cold Rolling (includes cleaning and annealing)	1.305	0.593	0.183	0.362	0.006
Tempering and Finishing (Cold Rolling)	1.643	0.651	0.207	0.454	0.006

a These tables do not account for emissions generated by the use of coke oven gas and blast furnace gas.

b In all process steps except cokemaking, ironmaking, and BOF steelmaking, fuel use is assumed to be entirely natural gas.

c Combustion emissions factors used (in lbs/million Btu) were as follows: Natural Gas/Propane/LPG (SOx - 0.000, NOx - 0.140, CO - 0.0351, Particulate - 0.003, VOCs - 0.006); Residual Oil (SOx - 1.700, NOx - 0.370, CO - 0.0334, Particulate - 0.080, VOCs - 0.009); Gasoline (SOx - 0.000, NOx - 0.140, CO - N/A, Particulate - 0.0000, VOCs - 0.090); Coal (SOx - 2.500, NOx - 0.950, CO - 0.3044, Particulate - 0.720, VOCs - 0.005); Electricity (SOx - 1.450, NOx - 0.550, CO - 0.176, Particulate - 0.400, VOCs - 0.004).

d Values have not been calculated because of a lack of emission factors for coke oven gas, the main fuel used in cokemaking.

e Does not include emissions from combustion of coke oven gas and blast furnace gas, which represent approximately 10% of total ironmaking fuel use.

Sources: American Iron and Steel Institute 1999 and 1996.  
Barnett 1998.  
LBNL 1998.

<b>Table 1-15. Estimated Combustion-Related Emissions of Criteria Pollutants for U.S. EAF Steelmaking Processes - 1998<sup>a,b,c</sup></b>					
<b>Process</b>	<b>Pollutant (lbs/ton steel)</b>				
	<b>SOx</b>	<b>NOx</b>	<b>CO</b>	<b>Particulate</b>	<b>VOCs</b>
EAF Steelmaking	6.638	2.546	0.813	1.832	0.020
Vacuum Degassing and Ladle Metallurgy	1.407	0.548	0.174	0.388	0.004
Continuous Casting	0.421	0.160	0.051	0.116	0.001
Hot Rolling	1.160	0.650	0.193	0.325	0.012
Pickling (Hot Rolling)	0.469	0.228	0.070	0.130	0.033
Hot Dip Galvanneal	2.815	1.207	0.377	0.779	0.014
Tempering and Finishing (Hot Rolling)	0.469	0.178	0.057	0.129	0.001
Cold Rolling (includes cleaning and annealing)	1.305	0.593	0.183	0.362	0.006
Tempering and Finishing (Cold Rolling)	0.469	0.178	0.057	0.129	0.001

a These tables do not account for emissions generated by the use of coke oven gas and blast furnace gas.

b In all processes except EAF Steelmaking, fuel use is assumed to be entirely natural gas.

c Combustion emission factors used are given in Table 1-14.

Sources: American Iron and Steel Institute 1999 and 1996.  
Barnett 1998.  
LBNL 1998.

### **Industry Complying with Tighter Air Standards**

The NESHAPs have already had a significant effect on the iron and steel industry's coke ovens. In late 1991, representatives of the iron and steel industry participated in formal regulatory negotiations with EPA, state and local regulatory agencies, and environmental groups to develop a mutually acceptable rule to implement the terms of the Act's coke oven provisions. NESHAPs for coke oven charging, top side and door leaks were finalized in October 1993. In 2000, MACTs will be established for air toxic emissions from coke pushing, quenching, and battery stacks. In addition, coke oven operators will still face unknown but likely tighter technology-based standards in 2010 and risk-based standards in 2020.

The final rule establishing the MACT standard for air emissions from hydrochloric acid steel pickling operations was promulgated in June 1999. These new requirements are expected to cost the industry in excess of \$20 million in new equipment costs and over \$7 million in additional operating and maintenance costs (Glanders 1999). The proposed rule for MACT standards for integrated iron and steel manufacturing is forthcoming. The source categories for nonstainless and stainless steel manufacturing by electric arc furnace were delisted as NESHAPs in 1996.

The industry may also be affected by possible revisions to the National Ambient Air Quality Standard for PM-10 (particulate matter less than 10.0 microns in diameter). New national health standards for ozone and particulate matter were adopted by EPA in July 1997. Subsequently, several states and associations petitioned the U.S.

**Table 1-16. Total Estimated Combustion-Related Emissions by Major Process in U.S. Steelmaking - 1998<sup>a,b</sup>**

Process	Pollutant (1,000 tons)					
	SOx	NOx	CO	Particulate	VOCs	CO <sub>2</sub>
Cokemaking <sup>c</sup>	--	--	--	--	--	3,029
Sintering	20.2	7.7	2.5	5.8	0.1	2,050
Ironmaking <sup>d</sup>	834.0	320.8	101.5	236.1	2.0	59,800
BOF Steelmaking <sup>e</sup>	9.5	4.9	1.5	2.7	0.1	14,720
EAF Steelmaking <sup>e</sup>	162.9	62.5	19.9	44.9	0.5	24,820
Casting	27.3	10.8	3.4	7.5	0.09	2,813.8
Ingot Casting	5.5	2.5	0.8	1.5	0.03	841.0
Continuous Casting	21.8	8.3	2.6	6.0	0.06	1,972.8
<b>SUBTOTAL</b>	<b>1,181.4</b>	<b>454.3</b>	<b>142.8</b>	<b>328.7</b>	<b>3.2</b>	<b>107,233</b>
Other Processes (reheating, rolling, finishing) <sup>e</sup>	117.2	63.3	20.0	37.0	0.9	40,253
<b>TOTAL</b>	<b>1,298.6</b>	<b>517.6</b>	<b>162.8</b>	<b>365.7</b>	<b>4.1</b>	<b>147,486</b>

a Estimates based on energy consumption reported in Table 1-6 (breakdown by fuel types not shown in that table but taken from AISI) and emission factors as stated in Table 1-14. Also based on integrated steel production of 59.686 million net tons and EAF-based steel production of 49.067 million net tons in 1998.

b Criteria pollutant emissions do not account for coke oven gas or blast furnace gas due to the lack of reliable emission factors for these gases. Carbon dioxide emissions do account for coke oven gas and blast furnace gas.

c Values have not been calculated because of a lack of emission factors for coke oven gas, the main fuel used in cokemaking.

d Criteria pollutant estimates do not include emissions from combustion of coke oven gas and blast furnace gas, which represent approximately 10% of total ironmaking fuel use. The CO<sub>2</sub> estimate *does* account for combustion of these fuels.

e Includes emissions associated with production of oxygen by electric-based processes.

f Industry-wide estimates for all other processes cannot reliably be made because of lack of data on the amount of metal undergoing each process.

Sources: American Iron and Steel Institute 1999 and 1996.  
Barnett 1998.  
LBNL 1998.

Circuit Court of Appeals for the District of Columbia to review the standards. In May of 1999, the Court ruled that EPA could not use a PM10 standard in combination with a fine particulate standard. New standards will not be in effect until EPA satisfies the Court's requirement for criteria in setting the level of the standards. The Court found that any control requirements under the new ozone standard were unenforceable because of the specific classifications, dates, and controls set forth by congress for the old ozone standards in the 1990 Clean Air Act Amendments.

### ***Industry's Effluents Are Regulated Under the Clean Water Act***

Water is an important commodity because it is an integral part of the steelmaking process. It takes approximate 75,000 gallons of water to produce one ton of steel (AISI 1999 Policy). Water is used

- to cool equipment, furnaces, and intermediate steel shapes;
- to remove scale from steel products;
- as a source of steam;
- as a medium for lubricating oils and cleaning solutions; and
- in wet scrubbers for air pollution control.

Much of the water used at steel plants is not consumed but is reused and recycled.

The Clean Water Act (CWA) regulates both direct and indirect discharges of toxic pollutants, total suspended solids, oil, grease, and other pollutants. Effluent limitation guidelines and standards for the iron and steel industry have been established by the Environmental Protection Agency in 40 CFR 420. These standards are implemented through the permit program of the National Pollutant Discharge Elimination System (NPDES) of the Clean Water Act, and through state and local pretreatment programs. The regulated pollutants include the following:

- Conventional Pollutants - Total suspended solids, oil, grease, and pH
- Nonconventional Pollutants - Ammonia-nitrogen and phenols
- Priority or Toxic Pollutants - Total cyanide, total chromium, hexavalent chromium, total lead, total nickel, total zinc, benzene, benzo(a)pyrene, naphthalene, and tetrachloroethylene

A facility that intends to discharge into the nation's waters must obtain a permit prior to initiating its discharge. The iron and steel industry often recycles its wastewater both "in-plant" and "end-of-pipe" to reduce the volume of discharge. Process wastewater is usually filtered and/or clarified on-site before being directly or indirectly discharged. Oil and greases are removed from the process wastewater by oil skimming, filtration, and air flotation; these oils can then be reused. The remaining sludge contains waste metals and organic chemicals. Iron in the sludges can be recovered and reclaimed.

Many steel mills discharge industrial wastewater through sewers to publicly owned treatment works (EPA 1995). Currently, over 95% of the water used for steel production and processing is recycled.

EPA is currently in the process of setting new effluent limitation guidelines for the iron and steel industry. Under a recent extension, the agency must issue a proposal by October 2000 and take

final action by April 2002. Many changes have occurred in steel manufacturing processes over the more than 15 years since the current guidelines were issued.

A recent regulatory development that significantly affects the iron and steel industry has been the development of uniform water quality standards under the Great Lakes Water Quality Initiative. In April of 1995, the Great Lakes states (including Illinois, Indiana, Michigan, Minnesota, New York, Pennsylvania, Ohio, and Wisconsin) were given two years to adopt rules and procedures consistent with the Water Quality Guidance for the Great Lakes System (40 CFR 132; also amendments 122, 123, and 131). The Guidance places particular emphasis on decreasing bioaccumulative toxics and also provides a process for addressing both point and non-point source pollution. As of April of 1998, only Indiana has met the requirements; several other states are in the process of finalizing rules.

This Initiative has widely varying cost implications, ranging from an EPA estimate of annual compliance costs of \$80 to \$505 million to an estimate from the Council of Great Lakes Governors that ranges from \$710 million to \$2.3 billion (Whitaker 1998). Because Federal and State regulations are likely to incorporate many of the GLI concepts, the controversial Initiative has strong implications for the future of environmental limits.

### ***RCRA Establishes Regulations on Handling, Disposal of Solid and Hazardous Waste***

In 1997, the U.S. steel industry generated approximately 39 million tons of solid wastes and residues such as slags, sludges, and dusts. Some of these materials are produced during an ironmaking or steelmaking process, such as the formation of blast furnace slag during ironmaking. Other of these materials result from pollution control measures, such as the air pollution control dusts captured during the cleaning of gaseous furnace waste streams.



The cost of disposing of these wastes is estimated to be as high as half a billion dollars each year. In addition, the value of the potentially recoverable iron units is believed to be in the \$500-million range (Szekely 1995).

Table 1-17 lists the major solid wastes and, where available, an estimate of the amount of each produced annually. In addition to those processes shown in the Table, there are other processes, such as secondary slags, grinding wastes, fines, and fly ashes, which produce solid wastes. However, the quantities of these wastes is not very significant to the overall total.

The Resource Conservation and Recovery Act (RCRA) of 1976, which amended the Solid Waste Disposal Act, addresses solid (Subtitle D) and hazardous (Subtitle C) waste management activities. The Hazardous and Solid Waste Amendments of 1984 strengthened RCRA's waste management provisions. Regulations promulgated pursuant to Subtitle C of RCRA establish a cradle-to-grave system governing hazardous waste from the point of generation to disposal.

<b>Table 1-17. Estimated Iron and Steel Industry Major Solid Wastes/Byproducts - 1997 (1,000 tons)</b>	
<b>Solid Waste/Byproduct</b>	<b>Estimated Annual Production</b>
Blast Furnace Slag	13,100
Blast Furnace Dust	410
Blast Furnace Sludge	690
Basic Oxygen Furnace Slag	7,760
Basic Oxygen Furnace Dust and Sludge	1,100
Electric Arc Furnace Slag	4,600
Electric Arc Furnace Dust	600
Mill Scale	3,670
Rolling Sludge	1,000
Spent pickle liquor	6,000

Sources: U.S. Department of the Interior 1998.  
 Association of Iron and Steel Engineers 1998.  
 Environmental Law Institute 1997.  
 Hamling 1996.  
 Kolarik 1996.  
 U.S. Environmental Protection Agency 1995.  
 Szekely 1995.  
 Electric Power Research Institute Center for Materials Production 1995.

Hazardous wastes specific to the iron and steel industry are designated with the code "K", which is used for wastes from specific industries or sources. In addition, the industry generates some wastes from the "D" series, which designates materials that exhibit a hazardous waste characteristic. The RCRA requirements for the industry also apply to any company that transports, treats, stores, or disposes of the waste. The specific RCRA-listed wastes associated with the iron and steel industry include:

#### Cokemaking

- Tar residues (K035, K087, K141, K142, and K147)
- Oil (K143 and K144)
- Naphthalene residues (K145)
- Lime sludge (K060)
- Wastewater sump residues containing benzene and polynuclear aromatic hydrocarbons (K144)

#### Iron and Steel Manufacturing

- EAF emission control dust and sludge (K061)

#### Finishing

- Wastewater sludge from cooling, descaling, and rinsing (D006, D007, D008, D009, D010, and D011)
- Spent pickle liquor (K062)

The handling of EAF dust (K061) is one of the industry's most pressing concerns. Disposal costs remain high relative to other landfilled solid wastes. The potential for radioactive scrap to get into the charge is another serious issue because of the huge cleanup costs associated with landfilling contaminated material.

# 2

# Cokemaking

## 2.1 Process Overview

In cokemaking, coal is heated to high temperatures (1,650-2,200°F) in an oxygen-deficient atmosphere to remove the volatile components. The remaining residue is coke, an efficient reductant for blast furnace ironmaking, whose permeability allows the free flow of gases within the furnace shaft. Coke is generally produced from bituminous (coking) coals. Approximately 1.30 to 1.35 tons of coal are needed to produce one net ton of coke. While some cokemaking facilities are owned by or affiliated with iron and steelmaking companies, there are also merchant plants who produce coke for sale on the open market.

Between 1979 and 1996, the number of active coke batteries declined from 179 to 78, and annual capacity dropped 60% from 57.1 million net tons to 22.7 million net tons (Hogan and Koelble 1996). In 1996, 50 of the active batteries were operated by iron and steel companies, with the other 28 run by merchant companies.

Almost all coke for the U.S. integrated iron and steel industry is manufactured using the byproduct process. Byproduct coke ovens permit collection of the volatile material evolved from

coal during the coking process. Coking is carried out in narrow, rectangular refractory brick ovens arranged in groups of up to 100 ovens known as batteries. The ovens consist of coking chambers, heating flues, and regenerative chambers. The coking chambers in a battery alternate with heating chambers; regenerative chambers are located underneath.

Pulverized coal is charged into the ovens through openings in the top. The necessary heat for distillation of the volatile components is supplied by external combustion of recovered coke oven gas, blast furnace gas, and natural gas through flues located between ovens.

When the coking cycle is completed, doors on both ends of the oven are removed and the coke is pushed out into a quenching car and transported to a quenching tower, where approximately 270 gallons of water per ton of coke are sprayed onto the coke mass to cool it. The coke is subsequently sized (crushed and screened) and sent to the blast furnace or to storage. The unpurified "foul" gas from byproduct coking is processed to recover byproducts such as tar, light oils, ammonia, and naphthalene, leaving purified coke oven gas that is used in the mill as a fuel.

A few operating coke ovens use the non-recovery process, where all of the byproduct gas is burned within the process rather than recovered as byproduct. The only energy recovered from the process is the sensible heat of the waste gases. The 1,830°F flue gas is put through a waste heat boiler and used to generate steam for electricity production or process use.

Naphthalene residues generated in the final cooling tower  
 Sulfur and sulfur compounds recovered from coke oven gas  
 Wastewater from cleaning and cooling (contains zinc, ammonia still lime, or decanter tank tar, or tar distillation residues)  
 Air pollution control (APC) dust

## 2.2 Summary of Inputs/Outputs

Inputs: Coal  
 Heat (from coke oven gas, blast furnace gas, natural gas)  
 Electricity  
 Water

Outputs: Coke  
 Coke oven gas and byproducts including coal tar, light oil, and ammonia liquor  
 Ammonia, phenol, cyanide, and hydrogen sulfide  
 Charging, pushing, and quenching emissions  
 Products of combustion (SO<sub>2</sub>, NO<sub>x</sub>, CO, particulate)  
 Oil (K143 and K144)  
 Ammonia still lime sludge (K060)  
 Decanter tank tar sludge (K087)  
 Tar residues (K141, K142)  
 Benzene releases in byproduct recovery operations

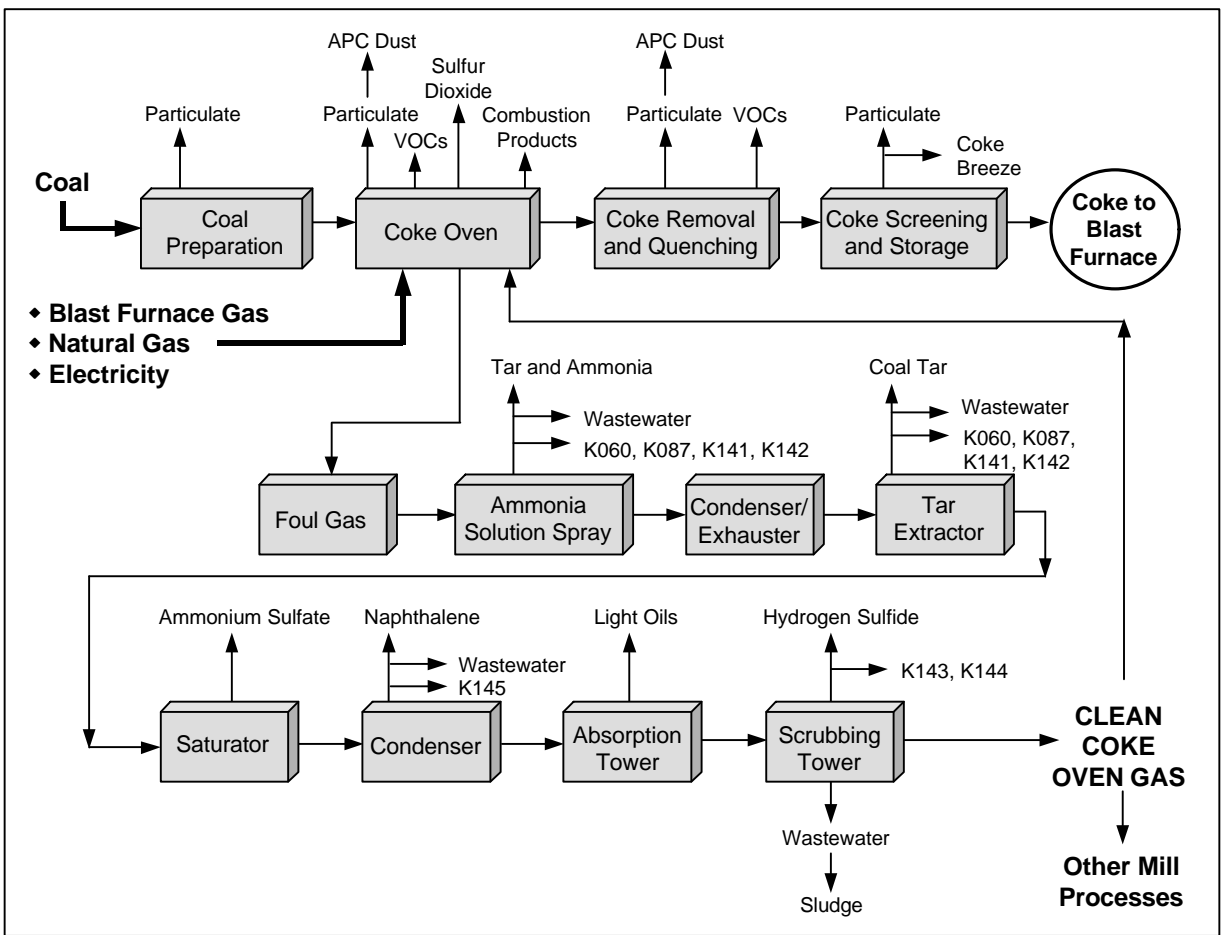
Table 2-1 shows the typical breakdown of products from a ton of coal. Figure 2-1 illustrates the cokemaking process with its major inputs and outputs.

## 2.3 Energy Requirements

Coal is the primary raw material used in cokemaking. In 1998, 20.174 million net tons of metallurgical coal was used to produce 15.567 million net tons of coke in iron and steel plants (AISI 1999). Table 2-2 shows that the industry used a total of 52.2 trillion Btu of fuel and electricity (the energy content of the coal is excluded) to produce the 1998 coke total. The specific energy consumption of cokemaking was calculated to be 3.4 million Btu/ton of coke. This equals the average reported by IISI in its 1998 report.

<b>Table 2-1. Typical Breakdown of Products and Byproducts from a Ton of Coal Used to Make Coke</b>	
<b>Product/Byproduct</b>	<b>Amount</b>
Blast furnace coke	1,200 -1,600 lb
Coke breeze (fine particle coke)	100 -200 lb
Coke oven gas	9,500 - 11,500 ft <sup>3</sup>
Tar	8 -12 gal
Ammonia sulfatate	20 -28 lb
Ammonia liquor	15 -35 gal
Light oil	2.5 - 4.0 gal

Sources: AISE 1999.  
 Nelson, Scheff, and Keil 1991.



<b>Key Energy and Environmental Facts - Cokemaking</b>			
<b>Energy</b>	<b>Emissions</b>	<b>Effluents</b>	<b>Byproducts/Hazardous Wastes</b>
3.4 10 <sup>6</sup> Btu per ton of coke produced	<p>Major Pollutants - particulate, VOCs, CO</p> <p>Largest Sources - coke handling, charging, pushing, quenching</p>	<p>Largest Sources - waste ammonia liquor, ammonia distillation, crude light oil recovery</p> <p>Typical Wastewater Volume - 100 gallons per ton of coke</p>	<p>Major Byproducts - tar, light oils, ammonia, naphthalene</p> <p>Hazardous Wastes - 7 RCRA-listed wastes (K060, K087, K141 through K145)</p> <p>Largest Source - coke oven gas cleaning</p>

Figure 2-1. Cokemaking Flow Diagram

<b>Table 2-2. Cokemaking Energy Use - 1998</b>			
<b>Fuel</b>	<b>Total Industry Use (units as given)</b>	<b>Total Industry Use (10<sup>12</sup> Btu)<sup>a</sup></b>	<b>Specific Energy Use (10<sup>6</sup> Btu/ton of coke)<sup>b</sup></b>
Coke Oven Gas	88,386 10 <sup>6</sup> ft <sup>3</sup>	44.2	2.8
Blast Furnace Gas	23,115 10 <sup>6</sup> ft <sup>3</sup>	2.2	0.2
Natural Gas	275 10 <sup>6</sup> ft <sup>3</sup>	0.3	0.0
Electricity <sup>c</sup>	544.85 10 <sup>6</sup> kWh	5.5	0.4
<b>TOTAL</b>		<b>52.2</b>	<b>3.4</b>

a Conversion factors are 500 Btu/ft<sup>3</sup> of coke oven gas, 90 Btu/ft<sup>3</sup> of blast furnace gas, 1,000 Btu/ft<sup>3</sup> of natural gas, 10,500 Btu/kWh (AISI 1998).

b Based on total U.S. metallurgical coke production of 15.567 10<sup>6</sup> tons in 1998 (AISI 1999).

c Assuming 35 kWh/net ton of coke produced (IISI 1998).

Sources: American Iron and Steel Institute 1999, 1998, and 1996.

International Iron and Steel Institute 1998.

Energy Information Administration 1995.

Bouman 1983.

The energy content of the byproducts of cokemaking, including the heating value of the coke oven gas and the energy content of the other byproducts that are used or sold (i.e., tar, light oil, and coke breeze), is shown in Table 2-3. The heating value of the coke itself is accounted for in Section 3, Ironmaking.

Aside from the use of coal feedstock, the major energy-consuming steps in cokemaking are:

- underfiring on the coke battery (fuel)
- exhauster operation and byproduct treatments (steam from fuel-fired boilers)
- pumps, motors, blowers, etc. (electricity)

<b>Table 2-3. Cokemaking Byproducts - 1998</b>			
<b>Fuel</b>	<b>Total Industry Production (units as given)</b>	<b>Total Industry Production (10<sup>12</sup> Btu)<sup>a</sup></b>	<b>Specific Energy Use (10<sup>6</sup> Btu/ton of coke)<sup>b</sup></b>
Coke Oven Gas	251,942 10 <sup>6</sup> ft <sup>3</sup>	126.0	7.8
Tar <sup>c</sup>	191.79 10 <sup>6</sup> gal	30.7	1.9
Light Oil <sup>c</sup>	61.80 10 <sup>6</sup> gal	8.6	0.5
Coke Breeze <sup>c</sup>	1.60 10 <sup>6</sup> tons	41.6	2.6

a Conversion factors are 500 Btu/ft<sup>3</sup> of coke oven gas, 160,000 Btu/gal of tar, 140,000 Btu/gal of light oil, 26 10<sup>6</sup> Btu/ton of coke breeze (AISI 1999).

b Based on total U.S. metallurgical coke production of 16.144 10<sup>6</sup> tons in 1997 (AISI 1998).

c Based on coal use of 20.17 10<sup>6</sup> tons and using the mid-point of the range shown for tar, light oil, and coke breeze given in Table 2-1.

Sources: American Iron and Steel Institute 1999, 1998, and 1996.

International Iron and Steel Institute 1998.

Energy Information Administration 1995.

Bouman 1983.

## 2.4 Emissions

### ***Cokemaking Emits Particulates, VOCs, Other Pollutants***

Particulate, VOCs, carbon monoxide, and other emissions originate from coal preparation (materials handling), preheating (if used), charging, oven leakage during coking, coke removal (pushing), hot coke quenching, underfire combustion stacks, and the purification of coke oven gas.

Specific emissions include:

- Handling - Fugitive particulate emissions are associated with material handling operations.
- Charging - Oven charging can produce significant emissions of particulate matter and VOCs if not properly controlled.
- Oven leaks - During the coking cycle, VOC emissions from the distillation occurring in the oven can occur through leaks in the doors, charge lids, and offtake caps.
- Pushing - Pushing the coke from the oven into the quench car is a major source of particulate emissions.
- Quenching - Coke quenching entrains particulate from the coke mass; in addition, dissolved solids from the quench water may become entrained in the steam plume rising from the tower. Trace organic compounds may also be present.
- Combustion - Combustion of gas in the coke oven flues produces emissions from the underfire or combustion stack.
- Purifying - The processing steps used to separate ammonia, coke oven gas, tar, phenol, light oils, and pyridine from the foul gas are all potential sources of VOC emissions.

Table 2-4 shows total estimated combustion-related emissions of CO<sub>2</sub> from cokemaking operations.

<b>lbs/ton of coke</b>	<b>1,000 tons</b>
389.17	3,029.1

a Includes emissions associated with the generation of electricity used in cokemaking.

Sources: American Iron and Steel Institute 1999.

The coking operation emission factors available from the U.S. EPA for total particulate, PM<sub>10</sub> (particulate matter less than 10.0 microns in diameter), sulfur oxides, carbon monoxide, VOCs, and nitrogen oxides are given in Table 2-5. It should be noted that steel industry representatives have raised questions about the validity of some of these emission factors which, because of their very nature, are continually being revised (as are those of processes discussed in later sections).

### ***Industry, EPA Have Worked Together on Defining Compliance Options***

A variety of pollution control equipment is used to capture the fine particles of coke generated during charging, pushing, loading, and transporting operations. This solid waste, which is primarily fine particles, is generally landfilled. Effective control of charging emissions requires that goosenecks and the collecting main passages be cleaned frequently to prevent obstructions. Leaks are controlled by effective maintenance or by rebuilding doors.

Most facilities control pushing and quenching emissions by using mobile scrubber cars with hoods, shed enclosures evacuated to a gas cleaning device, or traveling hoods with a fixed duct leading to a stationary gas cleaner.

Table 2-5. Emission Factors For Cokemaking (lb/ton of coke produced)						
Type of Operation	Particulate	PM <sub>10</sub> <sup>a</sup>	SOx	CO	VOC	NOx
Coal Crushing With cyclone	0.11	0.05	0.0	N/A	0.0	N/A
Coal Preheating Uncontrolled	3.50	3.40		0.3		
With scrubber	0.25	ND	ND	ND	ND	ND
With wet ESP	0.012	ND		ND		
Oven Charging Uncontrolled	0.48	0.01	0.02	0.6	2.5	0.03
With sequential charging	0.016	ND	ND	ND	ND	ND
With scrubber	0.014	ND	ND	ND	ND	ND
Oven Door Leaks Uncontrolled	0.51	0.48	0.1	0.6	1.5	0.01
Oven Pushing Uncontrolled	1.15	0.5	3.3	0.07	0.2	0.3
With ESP	0.45	ND	ND	0.07	0.2	ND
With venturi	0.18	ND	ND	0.07	0.2	ND
With baghouse	0.09	ND	ND	0.07	0.2	ND
With mobile scrubber car	0.072	ND	ND	0.07	0.2	ND
Quenching Uncontrolled						
dirty water	5.24	1.2	0.4	ND	0.02	0.6
clean water	1.13	ND	N/A	ND	ND	N/A
With baffles dirty water	1.30	ND	N/A	ND	ND	N/A
clean water	0.54	ND	N/A	ND	ND	N/A
Combustion Stack Uncontrolled (raw COG)	0.47	0.45	4.0	ND	2.0	0.04
Uncontrolled (desulf. COG)	0.47	0.45	0.28	ND	ND	ND
Uncontrolled (BFG)	0.17	ND	1.08	ND	ND	ND
With ESP (BFG)	ND	ND	0.64	ND	ND	ND
With ESP (COG)	0.091	ND	ND	ND	ND	ND
With baghouse (COG)	0.11	ND	ND	ND	ND	ND
Coke Handling With cyclone	0.006	--	N/A	N/A	N/A	N/A

Key: ND - No data available; N/A - Not applicable

a Particulate matter less than 10.0 microns in diameter.

Sources: U.S. Environmental Protection Agency 1995b and 1990.

Emissions from combustion of gas in the coke oven battery flues are controlled by conventional gas cleaning equipment such as electrostatic precipitators and fabric filters.

The Clean Air Act, with its 1990 amendment, regulates the pollutants that steel mills (including coke ovens) can emit. Title I of the Act addresses

requirements for the attainment and maintenance of the National Ambient Air Quality Standards (40 CFR Part 50).

The National Emission Standards for Hazardous Air Pollutants (NESHAPs) associated with the Clean Air Act as amended in 1990 have had a significant effect on cokemaking. As a result of a



formal regulatory negotiation between the industry, EPA, and state and local agencies, the industry agreed to daily monitoring, installation of flare systems to control upset events, and the development of work practice plans to minimize emissions in exchange for some flexibility in how the industry demonstrates compliance. NESHAPs currently in effect for cokemaking include Coke Oven Batteries (40 CFR Part 63 Subpart L) and Benzene Emissions from Coke Byproduct Recovery Plants (40 CFR Part 61 Subpart L).

In fulfillment of requirements under the benzene NESHAP rule, existing coke ovens have recently equipped coke byproduct plants with inert gas blanketing systems that eliminate 95% to 98% of benzene emissions, in addition to preventing emissions of other VOCs (including volatile organic hazardous air pollutants). In this process, an inert blanket is placed over various process vessels and storage tanks for reduced emissions (Marsosudiro 1994).

## 2.5 Effluents

### ***Wastewaters Contain Numerous Inorganic and Organic Compounds, Toxic Metals***

The largest volume of water used in coke plants is for non-contact cooling in a variety of cooling and condensing operations. Consumption of water for the coke quenching can range from 120 to 900 gallons per ton (AISE 1998).

Moisture from the coal being coked and from process steam condensation make byproduct coking a net generator of process water. Process wastewater sources include (AISE 1998):

- excess ammonia liquor from the primary cooler tar decanter
- barometric condenser wastewater from the crystallizer, the final coolers, light oil recovery operations, desulfurization processes, and air pollution control operations

The typical volume of process wastewaters generated at a well controlled coke plant is approximately 100 gallons per ton of coke produced, excluding dilution water to optimize bio-oxidation (AISE 1999 and EPA 1995a). About 25 to 35 gallons per ton are generated from water contained in the coal charge form of waste ammonia liquor. Table 2-6 gives typical effluent amounts from byproduct cokemaking by source.

Cokemaking wastewaters contain high levels of oil and grease, ammonia-nitrogen, sulfides, cyanides, thiocyanates, phenolics, benzenes, toluene, xylene, other aromatic volatile components, and polynuclear aromatic compounds. They may also contain the toxic metals antimony, arsenic, selenium, and zinc. The exact amount of each of these pollutants generated depends on the equipment and practices being used at a given facility. However, an idea of the amounts can be obtained from the effluent limitations given by the U.S. EPA in 40 CFR Part 420.

Table 2-7 shows the limitations for average daily values for 30 consecutive days using the best practicable control technology currently available (BPT) and the best available technology economically achievable (BAT). The BPT limitations assume the following model steps are taken: recycle of final cooler water, dissolved gas flotation for benzol plant wastewaters, free- and fixed-ammonia stripping, equalization, and single-stage activated sludge. The BAT limitations assume that, in addition to the BPT, ammonium crystallizer water is recycled and single-stage activated sludge is modified to two-stage activated sludge with nitrification. The pH for the BPT case is required to be between 6.0 and 9.0.

### ***Most Residuals Are Recovered or Sold***

The conventional wastewater treatment approach consists of physical/chemical treatments, including oil separation, dissolved gas flotation, and ammonia distillation (for removal of free cyanides, free sulfides, and ammonia) followed by biological treatment (for organics removal) and

<b>Table 2-6. Byproduct Cokemaking Effluent Flows<sup>a</sup> (gallons/ton of coke)</b>		
<b>Wastewater Source</b>	<b>Integrated Producers</b>	<b>Merchant Producers</b>
Waste ammonia liquor	32	36
Final cooler blowdown	10	12
Barometric condenser blowdown	3	5
Benzol plant wastewater	25	28
Steam & lime slurry	13	15
Miscellaneous sources	20	24
<b>SUBTOTAL - PROCESS WASTEWATERS</b>	<b>103</b>	<b>120</b>
Dilution to optimize bio-oxidation	50	50
<b>BASIC TOTAL FLOW</b>	<b>153</b>	<b>170</b>

a Assumptions for BAT (Best Available Technology Economically Achievable) case.

Source: AISE 1999

<b>Table 2-7. Byproduct Cokemaking Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lbs of coke)</b>		
<b>Pollutant</b>	<b>BPT Limitation</b>	<b>BAT Limitation</b>
Total Suspended Solids	0.131	--
Oil & Grease	0.0109	--
Ammonia-Nitrogen	0.0912	0.0160
Cyanide	0.0219	0.00351
Phenols	0.00150	0.0000319

Source: Bureau of National Affairs 1992.

residual ammonia nitrification. Virtually all residuals from cokemaking operations are either recovered as crude byproducts (e.g., as crude coal tar, crude light oil, ammonium sulfate, or other sulfur compounds) and sold, or recycled to the coke ovens for recovery of carbon values (e.g., coal tar decanter sludge, coke plant wastewater treatment sludge) (EPA 1995a).

Water-to-air transfers may result from loss of volatile pollutants from open coke plant wastewater equalization and storage tanks and wastewater treatment systems.

## 2.6 Byproducts

### ***Many Byproducts Are Generated During Coke Oven Gas Cleaning***

In the byproduct coking process, the volatile components distilled off are collected as unpurified "foul" gas containing water vapor, tar, light oils, solid particulate of coal dust, heavy hydrocarbons, and complex carbon compounds. The condensable materials (tar, light oils, ammonia, naphthalene) are removed, recovered and processed as gas and coal chemical byproducts, leaving purified coke oven gas. Table 2-8 lists major uses of cokemaking byproducts.

<b>Table 2-8. Major Uses of Cokemaking Byproducts</b>	
<b>Byproduct</b>	<b>Major Uses</b>
Metallurgical coke	Iron production
Coke oven gas	Fuel for steelmaking operations
Ammonium sulfate	Agricultural fertilizers
Anhydrous ammonia	Agricultural fertilizers
Phenol	Manufacture of resinous condensation products
Ortho cresol	Production of synthetic resins
Meta-para cresol	Production of synthetic resins
Naphthalene	Production of phthalic anhydride for plasticizers
Creosote	Pressure impregnation of wood
Pitch	Binder for carbon electrodes; roofing pitch
Benzene	Manufacture of styrene
Toluene	Manufacture of synthetic organic chemicals
Sulfur	Production of sulfuric acid
Sulfuric acid	Agricultural fertilizers

Sources: AISE 1999.

Foul gas cleaning involves a number of steps. First, the gas is cleaned with a weak ammonia spray, which condenses some tar and ammonia from the gas. The remaining gas is cooled as it passes through a condenser and then compressed by an exhauster. Any remaining coal tar is removed by a tar extractor, either by impingement against a metal surface or collection by an electrostatic precipitator.

The gas still contains 75% of original ammonia and 95% of the original light oils. Ammonia is removed by passing the gas through a saturator, where ammonia reacts with sulfuric acid to form ammonium sulfate, which is crystallized and removed. The gas is further cooled to condense naphthalene. The light oils are removed in an absorption tower and subsequently refined. The last cleaning step is the removal of hydrogen sulfide in a scrubbing tower. The purified gas is then ready for use as fuel for the coke ovens, in other plant combustion processes, or sold.

Approximately 11,000 scf of coke gas is produced per ton of coal charged in conventional high-temperature coking processes (AISE 1998). About 40% of the gas is used to heat the coke ovens; the

rest is used in other production processes or sold. Coke oven gas is sometimes combined with blast furnace gas in soaking pits, reheat furnaces, and other applications. The composition of coke oven gas varies according to the grade and density of coal and operating practices. Typical percentage ranges for constituents of dry coke oven gas by volume are shown in Table 2-9.

## 2.7 Hazardous Wastes

### ***Cokemaking Processes Generate Seven RCRA-Listed Hazardous Wastes***

There are currently seven RCRA-listed hazardous wastes associated with cokemaking. These wastes are:

- K060 - Ammonia still lime sludge
- K087 - Decanter tank tar sludge K141-  
Process residues from coal tar  
recovery operations
- K142 - Tar storage tank residues
- K143 - Process residues from the  
recovery of light oil

<b>Table 2-9. Typical Coke Oven Gas Components by Percent Volume</b>	
<b>Major Component</b>	<b>Percent Volume</b>
Hydrogen	46.5 - 57.9
Methane	26.7 - 32.1
Carbon monoxide	4.5 - 6.9
Carbon dioxide (including H <sub>2</sub> S)	1.3 - 2.4
Nitrogen	2.0 - 9.6
Oxygen	0.2 - 0.9
Non-methane hydrocarbons	0.5 - 5.2
Hydrogen sulfide	0.5 - 4.5
Ammonia	1.3 - 9.0
<b>Minor Components</b>	<b>Concentration (g/m<sup>3</sup>)</b>
Hydrogen cyanide	0.1 - 4.0
Dust	1.8 - 36.0
Benzo(a)pyrene	0.2 - 0.6
Benzene	21.4 - 35.8
Toluene	1.5 - 3.0

Sources: AISE 1998.  
Nelson, Scheff, and Keil 1991.  
U.S. EPA 1988.

- K144 - Wastewater sump residues from light oil refining
- K145 - Residues from naphthalene collection and recovery operations

The first two wastes have been listed since 1988; the last five were listed in 1992. Generation factors for K142 - K145 are given in Table 2-10.

Table 2-11 lists the constituents of concern for K060 and K087 and their maximum allowable concentration for land disposal. The constituents of concern and their average measured concentrations for K141 through K145 are presented in Table 2-12. Tables 2-13 and 2-14 show the maximum allowable concentration of these constituents for land disposal of the wastes in wastewaters and non-wastewaters, respectively.

Process residues from coal tar recovery (K141) are generated when the uncondensed gas that leaves the

coke oven collecting main enters the primary cooler. The condensates from the primary cooler flow into the tar collecting sump and are discharged to the flushing liquor decanter. Tar collection sump residue or sludge accumulates at the bottom of the collecting sump and must be disposed periodically, either as an individual stream or by recycling it through the flushing liquor decanter or back to the coke oven. Tar storage tank residues (K142) are produced when residuals settle out of the crude coal tar collected as a coking byproduct. The residues are periodically removed from the storage tanks and are recycled to the oven or landfilled.

Residues from light oil processing units (K143) include material that builds up in the light oil scrubber over time and material that accumulates in the light oil stripping still. A related waste is the resin that accumulates as a result of cleaning up the wash oil used in the light oil recovery process. The residue from either a wash oil purifier or a wash oil decanter is called wash oil

Table 2-10. Waste Generation Factors for K142 through K145	
Waste	Generation Factor (lb/ton of coke)
K142 (Tar storage tank residues)	0.723
K143 (Process residues from the recovery of light oil)	
Benzol plant scrubber residue	0.048
Wash oil purifier residue	0.174
Wash oil decanter muck	0.323
K144 (Wastewater sump residues from light oil refining)	0.100
K145 (Residues from naphthalene collection/recovery)	
Final cooler sump residue	0.040
Naphthalene skimmer residue	0.020

Source: DPRA Inc. 1992.

Table 2-11. Maximum Allowable Constituent Concentrations in K060 and K087 for Land Disposal				
Regulated Hazardous Constituent	Concentration in Wastewaters (mg/l)		Concentration in Non-Wastewaters (mg/kg)	
	K060	K087	K060	K087
Acenaphthalene	--	0.059	--	3.4
Benzene	0.14	0.14	10	10
Benzo(a)pyrene	0.061	--	3.4	--
Chrysene	--	0.059	--	3.4
Cyanides (total)	1.2	--	590	--
Fluoranthene	--	0.068	--	3.4
Indeno(1,2,3-cd)pyrene	--	0.0055	--	3.4
Naphthalene	0.059	0.059	5.6	5.6
Phenanthrene	--	0.059	--	5.6
Phenol	0.039	--	6.2	--
Toluene	--	0.080	--	10
Xylenes (mixed isomers)	--	0.32	--	30
Lead	--	0.69	--	0.37 <sup>a</sup>

a In mg/l based on the Toxicity Characteristic Leaching Procedure (TCLP).

Source: Bureau of National Affairs 1995.

muck and is periodically removed and recycled to the coke oven, reclaimed off site, or used as blast furnace or boiler fuel.

Wastewater sump residues (K144) accumulate in the bottom of a sump used to provide sufficient quiescent residence time for oil and water to separate during light oil recovery. These settled

**Table 2-12. Constituents of Concern and Average Measured Concentrations: K141 through K145 (ppm)**

<b>Constituent</b>	<b>K141 (Process Residues from Coal Tar Recovery)</b>	<b>K142 (Tar Storage Tank Residues)</b>	<b>K143 (Residues from Light Oil Processing)</b>	<b>K144 (Wastewater Treatment Sludges from Light Oil Refining)</b>	<b>K145 (Residues from Naphthalene Collection and Recovery)</b>
Benzene	3,850	260	1,600	3,000	1,000
Benz(a)anthracene	7,850	6,600	69	68	22
Benzo(a)pyrene	8,450	6,500	34	65	7
Benzo(b)fluoranthene	5,450	7,500	59	75	26
Chrysene	7,950	6,000	59	66	22
Dibenz(a,h)anthracene	1,750	1,000	38	15	1
Indeno(1,2,3-cd)- pyrene	6,140	2,900	40	37	4
Naphthalene	95,000	55,000	52,000	27,000	140,000

Source: U.S. Environmental Protection Agency 1992.

**Table 2-13. Maximum Allowable Constituent Concentrations in K141 through K145 Wastewaters for Land Disposal (mg/l)**

<b>Constituent</b>	<b>K141</b>	<b>K142</b>	<b>K143</b>	<b>K144</b>	<b>K145</b>
Benzene	0.14	0.14	0.14	0.14	0.14
Benz(a)anthracene	0.059	0.059	0.059	0.059	0.059
Benzo(a)pyrene	0.061	0.061	0.061	0.061	0.061
Benzo(b)fluoranthene	0.11	0.11	0.11	0.11	--
Benzo(k)fluoranthene	0.11	0.11	0.11	0.11	--
Chrysene	0.059	0.059	0.059	0.059	0.059
Dibenz(a,h)anthracene	0.055	0.055	--	0.055	0.055
Indeno(1,2,3-cd)- pyrene	0.0055	0.0055	--	--	--
Naphthalene	--	--	--	--	0.059

Source: Bureau of National Affairs 1995.

solids are removed periodically and either recycled to the oven or landfilled off-site.

Residues from naphthalene collection and recovery (K145) accumulate at the bottom of a skimmer sump where naphthalene is mechanically skimmed

off the surface. Residues also accumulate in the hot and cold sumps, which are used as collection or surge vessels, and on the surfaces of the cooling tower. K145 is currently recycled to the decanter or sometimes to the oven.

<b>Table 2-14. Maximum Allowable Constituent Concentrations in K141 through K145 Non-Wastewaters for Land Disposal (mg/kg)</b>					
<b>Constituent</b>	<b>K141</b>	<b>K142</b>	<b>K143</b>	<b>K144</b>	<b>K145</b>
Benzene	10	10	10	10	10
Benz(a)anthracene	3.4	3.4	3.4	3.4	3.4
Benzo(a)pyrene	3.4	3.4	3.4	3.4	3.4
Benzo(b)fluoranthene	6.8	6.8	6.8	6.8	--
Benzo(k)fluoranthene	6.8	6.8	6.8	6.8	--
Chrysene	3.4	3.4	3.4	3.4	3.4
Dibenz(a,h)anthracene	8.2	8.2	--	8.2	8.2
Indeno(1,2,3-cd)- pyrene	3.4	3.4	--	--	--
Naphthalene	--	--	--	--	5.6

Source: Bureau of National Affairs 1995.





# 3

# Ironmaking

## 3.1 Process Overview

In blast furnace ironmaking, the iron ore is reduced by removal of the oxygen, and the resulting iron is melted. In 1998, the U.S. iron and steel industry produced 53.164 million net tons of pig iron in blast furnaces. In the process, 21.874 million net tons of coke, 0.866 million net tons of natural ore, 69.278 million net tons of pellets, and 11.731 million net tons of sinter, briquettes, nodules and other agglomerated products were consumed (AISI 1999).

### ***Pelletizing Is Most Common Method of Preparing Ore for the Blast Furnace***

Agglomeration processes such as pelletizing produce coarse particles of suitable size for charging into the blast furnace. In pelletizing, an unbaked ball or "green" pellet is formed from iron ore concentrate combined with a binder. The green pellets are then hardened by heat treatment in an oxidizing furnace. The major pelletizing systems are the traveling grate, the shaft furnace, the grate kiln, and the circular grate. Pelletizing is almost always done at the mine site rather than at the mill. From the mine, the pellets are transported by boat or railroad to the mill, where they are fed into the blast furnace along with coke, fluxes, and often sinter.

### ***Sintering Permits Recycling of Iron-Rich Byproducts***

In addition to pelletizing, the other major agglomeration process for preparing ore for charging into the blast furnace is sintering. Sintering converts natural fine ores, ore fines from screening operations, water treatment plant sludges, air pollution control dusts, and other iron-bearing materials of small particle size into a clinker-like agglomerated product. Sintering enables a mill to recycle iron-rich material such as mill scale and processed slag back into the ironmaking process.

The raw materials, which are mixed with about 5% of a fuel (such as coke breeze or anthracite) and sometimes with water, are placed on a continuous, traveling grate called the sinter strand. At the beginning of the strand, the coke breeze in the mixture is ignited by gas burners, which leads to surface melting and agglomeration of the bed. On the underside of the strand are windboxes that pull combustion gases down through the material bed into a duct leading to gas cleaning equipment. The bed temperature reaches 1,300°C - 1,480°C (2,370°F - 2,700°F), hot enough to sinter the fine ore particles together into porous clinkers. The fused sinter mass is cooled, crushed, screened, and

sent to be charged along with ore to the blast furnace. Approximately 2.5 tons of raw materials, including water and fuel, are required to produce one ton of sinter product (EPA 1995b).

### ***Blast Furnace Makes Pig Iron for the Steelmaking Furnaces***

Blast furnaces are used to produce pig iron, which represents about three-quarters of the charge to basic oxygen steelmaking furnaces. In the liquid form the pig iron is generally referred to hot metal. The chemical composition of pig iron can vary substantially, but it typically contains the following (AISE 1998):

- 4.0 - 4.5% carbon
- 0.3 - 1.5% silicon
- 0.25 - 2.2% manganese
- 0.04 - 0.20% phosphorus
- 0.03 - 0.8% sulfur (before desulfurization)
- >90% iron

The blast furnace is a tall, shaft-type furnace with a vertical stack superimposed over a crucible-like hearth. Iron ore, coke, flux (limestone and dolomite), and sinter are fed into the top of the blast furnace; heated air, typically augmented with gaseous, liquid, or powdered fuel, is injected into its base. As the charge materials descend through the furnace, reducing gas (containing carbon monoxide) generated by the burning coke flows upward, converting the iron oxide (FeO) in the ore to iron (Fe). The coke also provides the structural support for the unmelted burden materials.

The combustion of the coke generates sufficient heat to melt the iron, which accumulates in the bottom of the furnace (hearth). The major function of the flux is to combine with unwanted impurities such as ash in the coke and gangue in the ores to make a drainable fluid slag. Unreacted reducing gas (blast furnace gas) is collected at the top, cleaned, and used as a fuel (see Section 3.6).

The operation of a blast furnace is a continuous process, and the furnace continues to produce liquid iron and slag as long as it is in operation. The iron and slag that accumulate in the hearth

are removed at regular intervals through tapholes located slightly above the floor of the hearth.

Essentially every blast furnace in the United States uses some form of auxiliary fuel injection to displace coke. The primary drivers for injectants are the rising costs associated with the coke supply coupled with the low cost of coal (Stubbles 2000). Coal injection rates are in the range of 200 to 450 lbs/net ton of hot metal (NTHM), with an average of about 220 lbs/NTHM; rates for natural gas injection range from 40 to 200 lbs/NTHM, with an average of about 80 lbs/NTHM (Fillman 1999 and Stubbles 2000). All of the largest U.S. blast furnaces inject coal (Stubbles 1999). The higher the injection rates, the greater the need for oxygen enrichment of the blast.

The molten iron, which has a temperature as high as 2,850°F, is tapped into refractory-lined cars for transport to the basic oxygen furnace. The iron may be processed at desulfurization stations to minimize sulfur compounds prior to charging in the basic oxygen furnace. Molten slag, which floats on top of the molten iron, is also tapped and processed for sale as a byproduct.

Blast furnace air is preheated in blast stoves fueled by clean blast furnace gas at temperatures of about 2,000°F. There are typically several hot blast stoves per blast furnace. Because the blast furnace gas is not high enough in Btu value to achieve the needed flame temperature, the gas is enriched with natural gas or coke oven gas.

The production of one net ton of iron requires approximately 1.5 to 1.7 tons of ore or other iron-bearing material, 0.35 to 0.55 tons of coke, 0.25 tons of limestone or dolomite, and 1.6 to 2.0 tons of air (AISE 1999 and EPA 1995b). In 1998, the industry used 1.30 tons of iron ore pellets and 0.22 tons of sinter per ton of molten iron produced (AISI 1999).

## **3.2 Summary of Inputs/Outputs**

Inputs: Iron ore (primarily as pellets)  
Coke (coal)  
Sinter

Limestone  
 Heated air (from coke oven gas,  
 blast furnace gas, natural gas, fuel  
 oil)  
 Electricity  
 Natural Gas  
 Coal  
 Oxygen  
 Water

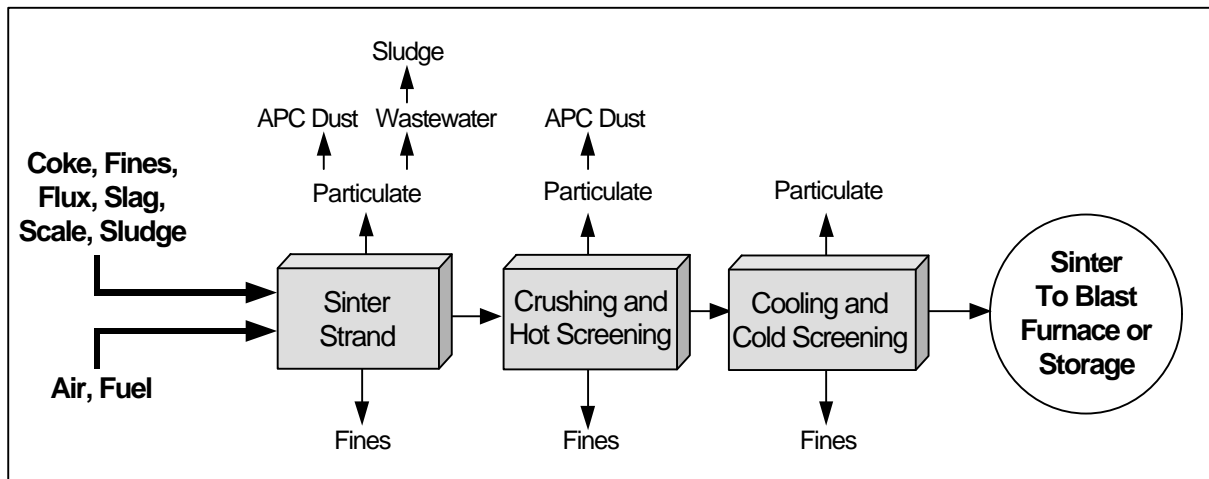
Outputs: Molten iron  
 Slag  
 Blast furnace gas  
 Residual sulfur dioxide or  
 hydrogen sulfide  
 Air pollution control (APC) dust  
 and/or waste treatment plant sludge  
 Process wastewater  
 Kish

### 3.3 Energy Requirements

Because pelletizing occurs mainly at the mine site, not at the steel mill, it is considered outside the scope of steelmaking, and thus not included in this analysis. However, it is estimated that 129 trillion Btu were used to produce 69.3 million tons of pellets in 1998.

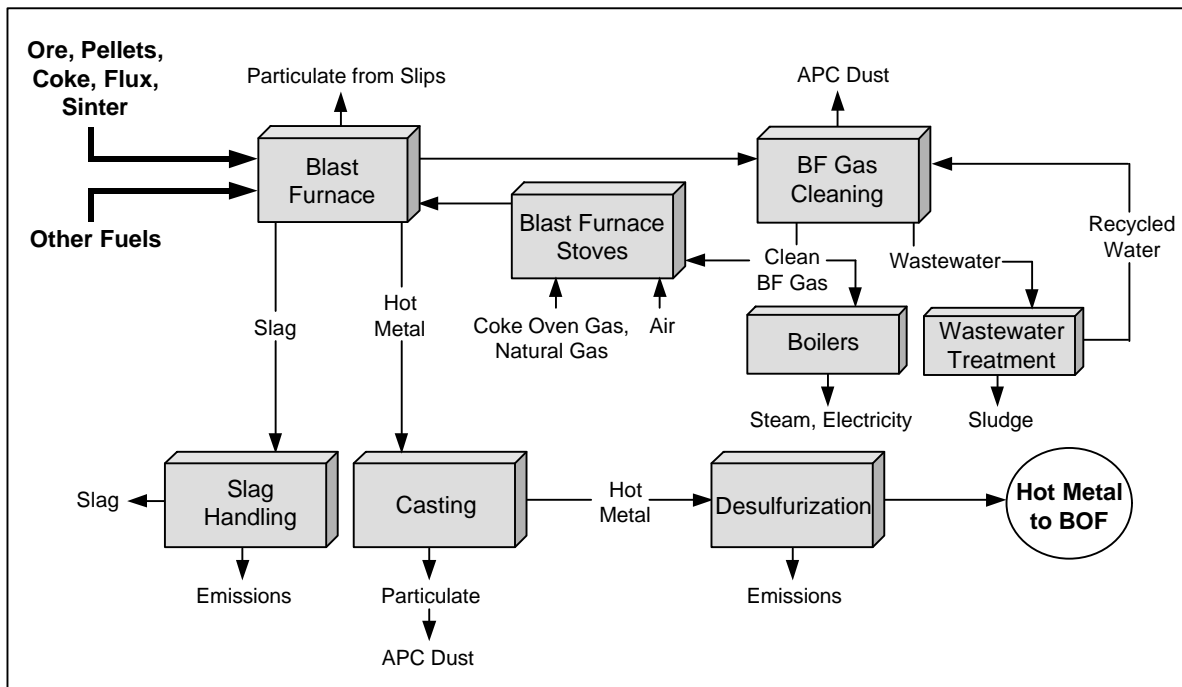
Table 3-1 shows the estimated energy used to produce sinter, by fuel type. In 1998, about 18.2 trillion Btu were used to produce 11.7 million tons of sinter, yielding a specific energy consumption of 1.6 million Btu/ton sinter. Over 75% of this energy is in the form of coke breeze, a byproduct created during the cokemaking process, and small quantities of other fuels used as sinter feed. Other energy requirements are natural gas for the ignition furnace and electricity for waste fans. Energy for limestone calcination has not been included.

Figures 3-1 and 3-2 illustrate the sintering and blast furnace ironmaking processes, respectively, with their major inputs and outputs.



<b>Key Energy and Environmental Facts - Sintering</b>			
<b>Energy</b>	<b>Emissions</b>	<b>Effluents</b>	<b>Byproducts</b>
1.55 10 <sup>6</sup> Btu per ton of sinter	Largest Source - windbox  Particulate - iron and sulfur oxides, carbonaceous compounds, aliphatic hydrocarbons, chlorides	Largest Source - wet air pollution control devices  Typical Wastewater Volume - 120 gallons per ton of sinter	Dust/sludge data rolled into blast furnace data below

Figure 3-1. Sintering Flow Diagram



<b>Key Energy and Environmental Facts - Blast Furnace Ironmaking</b>			
<b>Energy</b>	<b>Emissions</b>	<b>Effluents</b>	<b>Byproducts</b>
16.1 10 <sup>6</sup> Btu per ton of iron (gross)	Largest Source - removal of iron and slag from furnace (casting)	Largest Source - gas cooling water and scrubber water for gas cleaning	Total Generation (ton/yr) Slag - 14 10 <sup>6</sup> Dust/Sludge - ~1.1 10 <sup>6</sup>
12.1 10 <sup>6</sup> Btu per ton of iron (net)	Particulate - iron oxides, MgO, carbonaceous compounds	Typical Water Flows - 6,000 gallons/ton of iron	Reuse - near 100% (slag); approx. 40% (dust/sludge)

**Figure 3-2. Blast Furnace Flow Diagram**

The energy used to produce molten iron in the blast furnace is shown in Table 3-2 by fuel type. The majority of the energy input is in the form of coke, although natural gas, oil, or coal are injected as supplemental fuels. The use of these fuels does not reduce the energy intensity of the blast furnace process. Blast furnace gas, coke oven gas, and natural gas are used to preheat the furnace air blast.

The coke burns with great intensity when it reaches the lower portion of the furnace. Because of the very high temperature (1,650°C, or about 3,000°F) and the large quantity of carbon present as coke, the CO<sub>2</sub> formed as a product of combustion is not stable and reacts immediately

with additional carbon to form CO. This reaction provides the main source of heat for the smelting operation. The best U.S. blast furnaces are operating at coke rates around 650 lbs/NTHM, with coal/gas/oil injection rates of 300 lbs/NTHM, yielding total fuel rates of 950 lbs/NTHM. Since these fuels contain only 90% carbon, the carbon rate is close to 900 lbs/NTHM (Stubbles 2000).

Both total energy use for 1998 and specific energy consumption (based on the 1998 production level of 53.164 million net tons of hot metal) are shown in Table 3-2. The net specific energy consumption, after accounting for the top gas credit (the blast furnace gas used elsewhere in the

<b>Table 3-1. Energy Use in Sintering - 1998</b>			
<b>Fuel</b>	<b>Total Industry Use (units as given)</b>	<b>Total Industry Use (10<sup>12</sup> Btu)<sup>a</sup></b>	<b>Specific Energy Use (10<sup>6</sup> Btu/ton of sinter)<sup>b</sup></b>
Coke Breeze & Other Solid Fuels	0.54 10 <sup>6</sup> tons	14.1	1.2
Gas <sup>c</sup>	1,200 10 <sup>6</sup> ft <sup>3</sup>	0.6	0.05
Electricity	330 10 <sup>6</sup> kWh	3.5	0.3
<b>TOTAL</b>		<b>18.2</b>	<b>1.55</b>

a Conversion factors are 26 10<sup>6</sup> Btu/ton of coke breeze, 500 Btu/ft<sup>3</sup>, 1,000 Btu/ft<sup>3</sup> of natural gas, 10,500 Btu/kWh of electricity.

b Based on total U.S. industry sinter production of 11.731 10<sup>6</sup> tons of sinter.

c Mainly coke oven gas but also blast furnace gas and natural gas.

Sources: American Iron and Steel Institute 1999 and 1996.  
IISI 1999.  
Bouman 1983.

mill as fuel), is 12.1 million Btu/ton of molten iron. Approximately 10% to 12% of this (1.2 to 1.5 million Btu/ton) is consumed in the blast stoves. The average total fuel rate from Table 3-2 is calculated to be about 1,025 lbs/NTHM, compared to 950 lbs/NTHM estimated by Stubbles for the best U.S. blast furnaces.

### 3.4 Emissions

#### ***Sinter Plant Emissions Include Particulates, Hazardous Air Pollutants***

Emissions from sinter plants are generated from raw material handling, windbox exhaust, sinter discharge (associated sinter crushers and hot screens), and from the cooler and cold screen.

The windbox exhaust is the primary source of particulate emissions, mainly iron oxides, sulfur oxides, carbonaceous compounds, aliphatic hydrocarbons, and chlorides. Contaminants such as fluorides, ammonia, and arsenic may also be present. At the discharge end, emissions are mainly iron and calcium oxides.

A wide variety of organic and heavy metal hazardous air pollutants (or HAPS, as defined in the Clean Air Act and its amendments) may be released during sinter operations. Organic HAPS

can be released from coal and coke on the sinter grate. Heavy metal HAPs may be released (as particulate) from the iron. Total HAPs releases from individual sinter manufacturing operations may exceed 10 tons per year (Marsosudiro 1994). VOC emissions may be generated when oil-bearing material such as mill scale is used as a revert material. The VOCs are evaporated off of the sinter strand into the windbox prior to incineration (Carmichael and Carson 1998).

Sinter strand windbox emissions commonly are controlled by cyclone cleaners followed by a dry or wet electrostatic precipitator, high-pressure drop wet scrubber, or baghouse. Crusher and hot screen emissions, usually controlled by hooding and a baghouse or scrubber, are the next largest emission source.

Emissions are also generated from other material handling operations. Baghouses are used to capture particulates generated during conveyor transport and loading/unloading of sinter plant feedstocks and product. The air pollution control dust that is collected by the baghouses is either recycled as feedstock to the sinter plant or landfilled as solid waste (EPA 1995 and Baker Environmental 1992).

<b>Table 3-2. Energy Use in Blast Furnace Ironmaking - 1998</b>			
<b>Fuel</b>	<b>Total Industry Use (units as given)</b>	<b>Total Industry Use (10<sup>12</sup> Btu)<sup>a</sup></b>	<b>Specific Energy Use (10<sup>6</sup> Btu/ton of iron)<sup>b</sup></b>
Coke	21.874 10 <sup>6</sup> net tons	568.7	10.7
Coke Oven Gas	17,336 10 <sup>6</sup> ft <sup>3</sup>	8.7	0.2
Blast Furnace Gas	596,329 10 <sup>6</sup> ft <sup>3</sup>	53.7	1.0
Natural Gas	95,265 10 <sup>6</sup> ft <sup>3</sup>	95.3	1.8
Fuel Oil	144,479 10 <sup>3</sup> gallons	20.2	0.4
Coal <sup>c</sup>	2.9 10 <sup>6</sup> net tons	78.3	1.5
Electricity <sup>d</sup>	1,063 10 <sup>6</sup> kWh	11.2	0.2
Oxygen	98,472 10 <sup>6</sup> ft <sup>3</sup>	17.2	0.3
<b>SUBTOTAL</b>	--	<b>853.3</b>	<b>16.1</b>
<b>LESS</b>			
Top Gas Credit <sup>e</sup>	--	212.7	4.0
<b>EQUALS</b>			
<b>NET TOTAL</b>	--	<b>640.6</b>	<b>12.1</b>

- a Conversion factors are 26 10<sup>6</sup> Btu/ton of coke, 500 Btu/ft<sup>3</sup> of coke oven gas, 90 Btu/ft<sup>3</sup> of blast furnace gas, 1,000 Btu/ft<sup>3</sup> of natural gas, 0.140 10<sup>6</sup> Btu/gal of fuel oil, 27 10<sup>6</sup> Btu/ton of coal, 10,500 Btu/kWh of electricity, 175 Btu/ft<sup>3</sup> of oxygen (AISI 1996).
- b Based on total 1998 U.S. industry blast furnace production of 53.164 10<sup>6</sup> tons of iron.
- c Based on coal injectant data reported in "1999 Blast Furnace Roundup," *Iron and Steelmaker*, August 1999.
- d Assuming 20 kWh/net ton of metal produced (Bouman 1983).
- e Based on top gas credits from IISI (IISI 1998) and data estimated by Stubbles, 2000.

Sources: Stubbles 2000.  
*Iron and Steelmaker* 1999.  
 American Iron and Steel Institute 1999 and 1996.  
 IISI 1998.  
 Energy Information Administration 1995.  
 Bouman 1983.

Although the chemical composition of the dust is highly dependent upon the sintering practice, typical components include iron, carbon, sulfur, Fe<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, and MgO.

Table 3-3 shows total combustion-related emissions for 1998 for sintering and ironmaking. In that year, sintering operations emitted 2 million tons of CO<sub>2</sub> and ironmaking about 60 million tons.

Table 3-4 lists emission factors for major air pollutants for various sintering process operations. EPA is currently gathering data to update some of the factors in Table 3-4; its unreleased data shows some venturi scrubber emission factors may be significantly lower (in the range of 0.18 to 0.20) than 0.47 lb/ton of sinter shown in Table 3-4 (Mulrine 1995).

Table 3-3. Total Estimated Combustion-Related Emissions for Sintering and Ironmaking - 1998 <sup>a</sup>				
Pollutant <sup>b</sup>	Sintering <sup>c</sup>		Ironmaking <sup>d,e</sup>	
	Intensity (lbs/ton steel)	Total (1,000 tons)	Intensity (lbs/ton steel)	Total (1,000 tons)
SOx	3.2	20.2	31.4	834.0
NOx	1.2	7.7	12.1	320.8
CO	0.4	2.5	3.8	101.5
Particulate	0.9	5.8	8.9	236.1
VOCs	<0.01	0.04	0.08	2.0
CO <sub>2</sub>	69	2,050	2,000	59,800

- a Includes emissions associated with generation of electricity used in sintering and ironmaking.
- b All estimates but CO<sub>2</sub> exclude emissions associated with combustion of coke oven gas and blast furnace gas, which represent approximately 10% of total fuel use in ironmaking.
- c Based on 11.731 10<sup>6</sup> net tons of sinter and 59.686 10<sup>6</sup> net tons of integrated steel production in 1998.
- d Based on 53.164 10<sup>6</sup> net tons of pig iron and 59.686 10<sup>6</sup> net tons of integrated steel production in 1998.
- e Emissions associated with blast furnace top gas used elsewhere in the plant are not included here.

Sources: American Iron and Steel Institute 1999 and 1996.

Table 3-4. Emission Factors for Sintering (lbs/ton of finished sinter)						
Source	Particulate	PM <sub>10</sub> <sup>a</sup>	SOx	CO	VOC	NOx
Windbox						
Uncontrolled						
Leaving grate	11.1	1.67	2.5	44.0	1.4	0.3
After coarse particulate removal	8.7	--	--	--	--	--
Controlled by dry ESP	1.6	--	--	--	--	--
Controlled by wet ESP	0.17	--	--	--	--	--
Controlled by venturi scrubber	0.47	--	--	--	--	--
Controlled by cyclone	1.0	--	--	--	--	--
Sinter Discharge						
Uncontrolled	6.8	1.02	0.0	--	0.0	0.0
Controlled by baghouse	0.1	--	0.0	--	0.0	0.0
Controlled by venturi scrubber	0.59	--	0.0	--	0.0	0.0
Windbox and Discharge						
Controlled by baghouse	0.3	--	--	--	--	--
Sinter Conveyor - Transfer Station	0.17	0.013	0.0	--	0.0	0.0

- a Particulate matter less than 10.0 microns in diameter.

Sources: U.S. Environmental Protection Agency 1995b and 1990.

### Most Blast Furnace Emissions Generated During Removal of Molten Iron, Slag

Large carbon monoxide releases occur during the burning of coke to produce iron. Sulfur dioxide and particulate are also emitted during ironmaking. The primary source of blast furnace particulate emissions is the removal of molten iron and slag from the furnace, known as casting. During casting, molten iron and slag flow out of a taphole at the base of the furnace into runners that lead to transport ladles. Particulate emissions are generated when the molten iron and slag contact air above their surface. Emissions also are generated by drilling and plugging the taphole. Heavy emissions result from the use of an oxygen lance to open a clogged taphole.

During the blast furnace casting operations, iron oxides, magnesium oxide, and carbonaceous compounds are generated as particulate. Casting emissions at existing blast furnaces are controlled by evacuation through retrofitted capture hoods to a gas cleaner, or by flame suppression techniques. Emissions controlled by hoods and an evacuation system are usually vented to a baghouse. Newer furnaces have been constructed with evacuated runner cover systems and local hooding ducted to a baghouse.

The quantities of dust that are captured from casting emissions are typically negligible compared to that collected by the blast furnace gas cleaning system described under Ironmaking Byproducts, Section 3.6 (EPA 1995 and Baker Environmental 1992).

Another potential source of emissions is the blast furnace top. Charging through a sealed system creates no serious emission problem if the seals are adequately maintained. Minor emissions may occur during charging from imperfect bell seals in the double bell system. Occasionally a cavity may form in the blast furnace charge, causing a collapse of part of the charge above it. The resulting pressure surge in the furnace opens a relief valve to the atmosphere to prevent damage to the furnace by the high pressure created and is referred to as a "slip" (EPA 1995).

Total combustion-related ironmaking emissions in 1998 were shown in Table 3-3. The ironmaking process step by far the highest-emitting process among those considered, responsible for approximately 40% of total emissions for both criteria pollutants and CO<sub>2</sub>. Particulate emission factors for the blast furnace are shown in Table 3-5, together with emission factors of other pollutants.

Source	Particulate	PM <sub>10</sub> <sup>a</sup>	SOx	CO	VOC	NOx
Blast Heating Stoves	--	--	--	--	0.01	--
Slip	87.0 <sup>b</sup>	33.0	--	--	0.0	--
Uncontrolled Casthouse Roof monitor <sup>c</sup>	0.6	--	--	--	--	--
Furnace with Local Evacuation <sup>d</sup>	1.3	--	--	--	--	--
Taphole and trough (not runners)	0.3	--	--	--	--	--
Hot Metal Desulfurization	--	0.22	--	--	--	--

- a Particulate matter less than 10.0 microns in diameter.
- b lb/ton of slip.
- c Typical for canopy hoods or total casthouse evacuation.
- d Typical of large, new furnaces with local hoods and covered evacuated runners.

Sources: U.S. Environmental Protection Agency 1995b and 1990.



If hot metal desulfurization is used to remove or alter the sulfur compounds in the hot metal, the exhaust gases are discharged through a series of baghouses to control airborne particulate matter. Emissions may also result from slag handling; when the slag is removed from the furnace, sulfur dioxide is formed when the sulfur in the slag is exposed to air. The presence of moisture can result in the formation of hydrogen sulfide. Most sulfur emissions associated with slag handling result from quenching operations.

Most of the HAPs generated in the blast furnace are heavy metals, including cadmium, chromium, lead, manganese, and nickel. Emissions from the blast furnace are controlled by a wet venturi scrubber or another control device (see Ironmaking Byproducts) and may total several tons per year per blast furnace (Marsosudiro 1994).

Blast furnace gas, a byproduct of the blast furnace, is discussed in Section 3.6.

### 3.5 Effluents

#### ***Sintering Wastewaters Derived Mainly from Emissions Control Equipment***

The main uses of water in a sintering plant are for controlling the moisture content of the pre-sinter mix, for dust control, and for sinter product

cooling. Wastewaters are generated from the wet air pollution control devices on the windbox and discharge ends of the sinter machines. Either electrostatic precipitator or wet venturi-type scrubber technology is typically used for dust control (AISE 1999). Applied flows for wet air pollution control devices are typically 1,000 gallons per ton, with discharge rates of 50 to 100 gallons per ton for the better controlled plants (AISE 1999).

Wastewater treatment comprises sedimentation for removal of heavy solids, recycle of clarifiers or thickener overflows, and metals precipitation treatment for blowdowns. Some sinter plants are operated with once-through treatment.

The principal pollutants include total suspended solids, oil and grease, ammonia-nitrogen, cyanide, phenolic compounds, and metals (principally lead and zinc, but also arsenic, cadmium, copper, chromium, and selenium) (EPA 1995a). An estimate of the amounts of these pollutants generated can be obtained from the effluent limitations given by the U.S. EPA in 40 CFR Part 420.

Table 3-6 shows the limitations for average daily values for 30 consecutive days using the best practicable control technology currently available (BPT) and the best available technology economically achievable (BAT).

<b>Table 3-6. Sintering Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lbs of sinter)</b>		
<b>Pollutant</b>	<b>BPT Limitation</b>	<b>BAT Limitation</b>
Total Suspended Solids	0.0250	--
Oil and Grease	0.00501	--
Ammonia-Nitrogen	--	0.00501
Cyanide	--	0.00150
Phenols (4AAP)	--	0.0000501
Lead	--	0.000150
Zinc	--	0.000225

Source: Bureau of National Affairs 1992.

The BPT guidelines (which also require pH of 6.0 to 9.0) are based on the use of clarification and recycle (92%) of air emission control scrubber water, followed by sludge dewatering. The BAT guidelines assume recycle system blowdown treatment comprising metals precipitation, two-stage alkaline chlorination, and dechlorination.

### ***Blast Furnace Has High Process Water Requirements***

The blast furnace is one of the largest water users in an integrated mill. The main water use is for non-contact cooling of various parts of the furnace and auxiliaries. Additional water is used for furnace moisture control, dust control, and slag granulation (AISE 1998). Contact water use is primarily associated with blast furnace gas cleaning operations necessary to recover the fuel value of the off gas. Nearly all of the wastewater generated from blast furnace operations is direct contact water used in the gas coolers and high-energy scrubbers used to clean the blast furnace gas. Typical water requirements are 6,000 gallons per ton of iron (EPA 1995a).

The principal pollutants include total suspended solids, ammonia-nitrogen, cyanides, phenolic compounds, copper, lead, nickel, zinc, chromium, and cadmium. Standard treatment includes sedimentation in thickeners or clarifiers, cooling with mechanical draft cooling towers, and

high-rate recycle. Low-volume blowdowns (<70 gallons per ton) are either consumed in slag cooling at furnaces with adjacent slag pits, or treated in conventional metals precipitation systems. A few mills practice alkaline chlorination to treat ammonia-nitrogen, cyanides, and phenolic compounds (EPA 1995a).

Table 3-7 presents the EPA blast furnace BPT and BAT effluent limitations for average daily values for 30 consecutive days. The BPT technology is assumed to be clarification, cooling, and recycle (96%) for blast furnace gas cleaning and gas cooling waters, and subsequent sludge dewatering. The BAT technology is assumed to be increased recycle (98%) and recycle system blowdown treatment comprising metals precipitation, two-stage alkaline chlorination, and dechlorination. BPT pH is also required to fall between 6.0 and 9.0.

## **3.6 Byproducts**

### ***Cleaning the Blast Furnace Gas Generates Dust, Sludge***

The primary byproducts generated during the production of molten iron include blast furnace gas, slag, air pollution control dust (flue dust), and waste treatment plant sludge (blast furnace filter cake).

<b>Pollutant</b>	<b>BPT Limitation</b>	<b>BAT Limitation</b>
Total Suspended Solids	0.0260	--
Ammonia-Nitrogen	0.0537	0.00292
Cyanide	0.00782	0.000876
Phenols (4AAP)	0.00210	0.0000292
Lead	--	0.0000876
Zinc	--	0.000131

Source: Bureau of National Affairs 1992.

The gas leaving the top of the blast furnace, known as blast furnace gas or top gas, is a heated, dust-laden, combustible gas that can be used as a fuel throughout the plant. Between 2.0 and 3.0 net tons of this gas are generated for each ton of pig iron produced (AISE 1999). Blast furnace gas contains up to 40% carbon monoxide and carbon dioxide combined.

When producing ordinary grades of iron, the ratio of CO to CO<sub>2</sub> varies from 1.25:1 to 2.5:1 (AISE 1998). The gas contains a small amount of hydrogen; the remainder is mainly nitrogen. Typical blast furnace gas components are shown in Table 3-8.

<b>Component</b>	<b>Percent Volume</b>
Nitrogen	55 - 57
Carbon Monoxide and Carbon Dioxide	40
Hydrogen	3 - 5

Source: AISE 1998.

Blast furnace gas is almost always cleaned prior to its use to prevent plugging and damage to combustion equipment, and to prevent the dust from being discharged into the atmosphere with the products of combustion.

Blast furnace gas may be used without preheat in the following applications:

- blast furnace stoves
- soaking pits
- normalizing and annealing furnaces
- gas turbines and gas engines
- boilers

Preheated blast furnace gas burned with preheated air can be used in coke oven heating and in reheating furnaces.

When blast furnace gas leaves the top of the furnace, it contains dust particles (known as flue dust) varying in size from about 6 mm (1/4 inch)

to only a few microns (~0.00004 inch). About 60% of the particulate is removed from the blast furnace gas stream by dry cyclonic vortex separation (i.e., dust catcher) of the heavy particles (flue dust). Fine particulates are subsequently removed in a two-stage cleaning operation consisting of a wet scrubber (primary cleaner), which removes about 90% of the remaining particulate, and a high-energy venturi impact scrubber or electrostatic precipitator (secondary cleaner), which removes up to 90% of the particulate eluding the primary cleaner.

This two-stage cleaning process produces a gas containing less than 0.05 grams/m<sup>3</sup> (0.64 lb/ft<sup>3</sup>) of particulate (EPA 1995b). The fine particles removed by the gas washer become entrained in a liquid-solid stream that continues on to the treatment plant for settling and solids separation. The concentrated sludge can be dewatered further by mechanical filtration (Baker Environmental 1992).

About 50 to 100 pounds of flue dust are produced by the blast furnace for every net ton of iron (AISE 1999). Blast furnace dust captured by the dry gas cleaning system and sludge generated by the wet gas cleaning system are produced at a rate that is one to four percent the rate of molten iron production. In 1994, approximately 410,000 tons of blast furnace dust and 690,000 tons of blast furnace sludge were generated in the U.S. (Hamling 1996).

The dust and sludge are composed primarily of oxides of iron, calcium, silicon, magnesium, manganese, and aluminum. The blast furnace dust at some plants is recycled as feedstock to the sinter plant. At plants without sintering operations, blast furnace dust is sometimes mixed with other byproduct residues, briquetted, and recycled back to the blast furnace. In other plants, the dust is landfilled and/or stockpiled.

Water treatment plant sludges generated as a result of wet scrubbing systems contain relatively high levels of zinc and lead; if the sludge is continually recycled without treatment, unacceptably high levels of zinc and lead would build up in the furnace (Weidner 1993). Several techniques are available for removing the zinc and

lead, enabling the beneficiated sludge solids to be recycled as feedstock to the sinter plant or blast furnace. However, the majority of blast furnace sludge is land disposed as solid waste and/or stockpiled. Because of the similarity between wastewater sludges generated by sinter plants and blast furnaces, it is not uncommon for these streams to be commingled and co-treated (Baker Environmental 1992).

### ***Blast Furnace Slag Is Treated, Reused in a Variety of Applications***

Production of iron in a blast furnace yields a slag that contains oxides of calcium, silicon, magnesium, aluminum, and manganese along with other trace elements. The average slag compositions in mass percent are in the following ranges (AISE 1999):

- CaO - 38 - 42%
- SiO<sub>2</sub> - 34 - 38%
- Al<sub>2</sub>O<sub>3</sub> - 10 - 12%
- MgO - 8 - 10%
- MnO - 0.5 - 1.0%

Slag output depends on the blast furnace feed chemistry, but typically amounts to 20% to 40% (400 to 800 pounds) of molten iron production by weight (AISE 1999). Lower grade ores yield higher slag fractions, sometimes as high as 500 to 1,000 pounds of slag for each ton of pig iron produced.

Molten blast furnace slag is cooled prior to subsequent processing, including magnetic separation of the metal in the slag, crushing, and

sizing. Depending upon the cooling process used, one of three types of slag is produced: air-cooled slag, granulated slag, or expanded slag.

Air-cooled slag tends to be hard and dense, granulated slag is granular and glassy, and expanded slag is a lightweight aggregate. Blast furnace slags are used extensively on-site in land reclamation and landfill construction, and in the following applications (Baker Environmental 1992):

- concrete and concrete block aggregate
- railroad ballast
- bituminous pavements
- mineral wool
- roofing cover material
- sewage trickling filters
- highway and airport pavement base/sub-base construction aggregate
- agricultural uses (e.g., conditioning soil)

In 1997, about 14 million tons of blast furnace slag were produced (U.S. Dept. of Interior 1998). That same year, about 13 million tons of blast furnace slag were sold and/or used in the U.S. at an average price of about \$9 per ton. Air-cooled slag, 85% of the total slag sold, averaged around \$6 per ton, while the remainder (expanded and granular) sold for an average of \$28 per ton (U.S. Dept. of Interior 1998).

## **3.7 Hazardous Wastes**

There are no RCRA-listed hazardous wastes associated with sintering and blast furnace operations.

# 4

# Steelmaking - Basic Oxygen Furnace

## 4.1 Process Overview

The oxygen steelmaking process rapidly refines a charge of molten pig iron and ambient scrap into steel of a desired carbon and temperature using very high purity oxygen (AISE 1998). The basic oxygen furnace (BOF) process produces steel with a carbon content of less than 1% from hot metal containing about 4% carbon. Other elements in the hot metal such as silicon, phosphorus, sulfur and manganese, are transferred to a slag phase. The production of a 250-ton batch, or heat, of steel in the BOF takes approximately 30 to 60 minutes.

The basic raw materials required to make steel in the oxygen steelmaking process include:

- hot metal (pig iron) from the blast furnace
- steel scrap
- other metallic iron sources (e.g., DRI, ore, oxides)
- fluxes (e.g., lime)

The charge consists primarily of molten iron, but 20% to 35% scrap is also typically used. DRI and iron ore can be used as a substitute coolant

(in place of scrap) as well as a source of iron units. Waste iron oxides are also beginning to be used in the BOF.

After the hot metal and scrap are charged, oxygen is injected into the BOF. Soon after oxygen injection begins, fluxes are added to control sulfur and phosphorus and to control erosion of the furnace refractory lining. The principle active ingredients from the fluxes are CaO (from burnt lime) and MgO (from dolomitic lime). Burnt lime consumption ranges from 40 to 100 pounds per net ton of steel produced, while dolomitic lime requirements range from 30 to 80 pounds per ton.

The energy required to raise the fluxes, scrap, and hot metal to steelmaking temperatures is provided by oxidation of various elements in the charge materials, particularly iron, silicon, carbon, and manganese. No external heat source is needed; - the temperature increase caused by the oxidation reactions is countered by the addition of scrap and other coolants. During processing, the carbon in the iron is oxidized and released as CO (about 90%) and CO<sub>2</sub> (about 10%). These gaseous oxides exit the furnace carrying small amounts of iron oxide and lime dust.

BOFs can be classified according to the location of oxygen injection:

- *top blown* – oxygen is injected above the hot metal bath by means of a retractable, water-cooled lance
- *bottom blown (OBM or Q-BOP)* – oxygen is injected under the molten metal bath, usually carrying pulverized additives
- *combination blown* – oxygen is injected both above and below the bath

Bottom stirring is accomplished by the introduction of inert gas under the bath. The BOF vessel is tilted for charging and tapping.

Silicon, manganese, iron, and phosphorus form oxides that, in combination with the fluxes, create a liquid slag that is able to remove sulfur and phosphorus from the metal. At the end of the cycle the slag floats on top of the steel bath.

Upon completion of the cycle, the raw steel is tapped into a ladle where it is deoxidized and alloying elements are added to adjust the composition to final levels, or to concentrations suitable for further ladle treatment processes (see Section 6).

## 4.2 Summary of Inputs/Outputs

Inputs:	<p>Molten iron  Metal scrap  Other metallic iron sources  Ore  Iron oxide materials and waste oxides  Oxygen  Alloy materials (e.g., aluminum, manganese, chromium, nickel)  Fluxes (e.g., lime)  Electricity and natural gas for auxiliary processes  Nitrogen  Argon  Water</p>
Outputs:	<p>Molten steel  Air pollution control (APC) dust and sludge  Metal dusts (consisting of iron</p>

particulate, zinc, and other metals associated with the scrap, and flux)  
Slag  
Kish  
Carbon monoxide and carbon dioxide  
Nitrogen oxides and ozone

Figure 4-1 illustrates BOF steelmaking with its major inputs and outputs.

## 4.3 Energy Requirements

The BOF steelmaking process is autogenous and does not require fuel for melting and refining. However, the process does require oxygen, as shown in Table 4-1. In addition, relatively small amounts of natural gas and electricity are required for auxiliary processes, including oxygen generation. The specific energy intensity for BOF steelmaking is calculated in Table 4-1 to be 0.9 million Btu per net ton of raw steel. The electricity requirements of oxygen generation are estimated to be about 0.01 kWh per cubic foot of oxygen (Goodwill 1998).

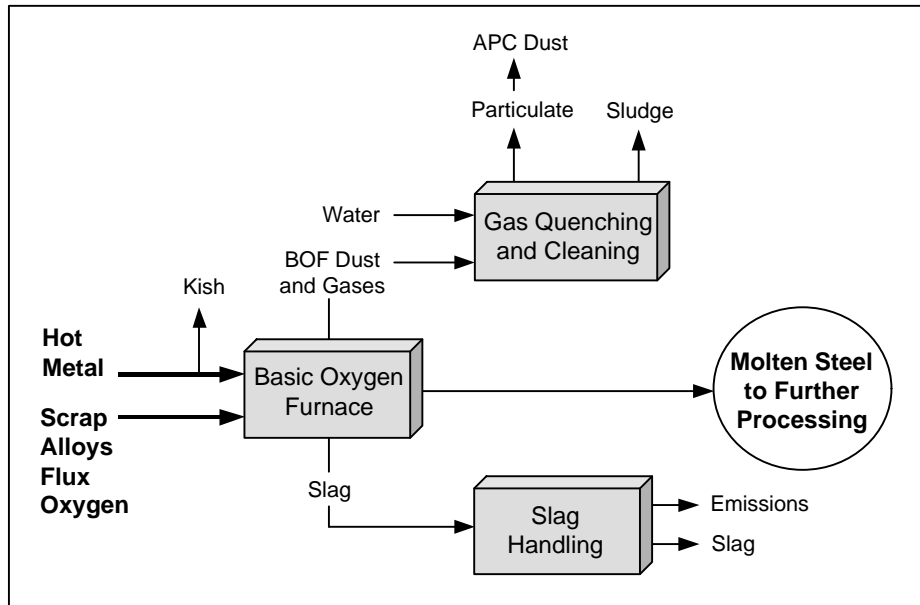
Some BOFs employ post-combustion, which involved the injection of auxiliary oxygen to react with the CO coming off of the bath. This highly exothermic reaction creates additional thermal energy for the process (AISE 1998).

## 4.4 Emissions

### ***Particulate Emissions Primarily Contain Iron Oxides***

The most significant emissions from BOF steelmaking occur during the oxygen blow period. The predominant compounds emitted are iron oxides (including FeO and Fe<sub>2</sub>O<sub>3</sub>), although heavy metals are usually present.

Charging emissions vary with the quality and quantity of scrap metal charged to the furnace and with the pour rate. Tapping emissions include iron oxides, sulfur oxides, and other metallic oxides, depending on the grade of scrap used. Hot metal transfer emissions are mostly iron oxides (EPA 1995 and Marsosudiro 1994).



<b>Key Energy and Environmental Facts - BOF Steelmaking</b>			
<b>Energy</b>	<b>Emissions</b>	<b>Effluents</b>	<b>Byproducts</b>
0.9 10 <sup>6</sup> Btu per net ton of raw steel	Largest Source - oxygen blow  Particulate - iron oxides, heavy metals, fluorides	Largest Source - BOF off-gas control systems  Typical Water Flows - 1,000 gallons/ton	Total Generation (ton/yr) Slag - 6.0 10 <sup>6</sup> Dust - 0.3 10 <sup>6</sup> Sludge - 1.3 10 <sup>6</sup>  Reuse - less than 50%

**Figure 4-1. Basic Oxygen Furnace (BOF) Steelmaking Flow Diagram**

### **BOFs Use Three Main Types of Air Pollution Control Systems**

The particulate-laden combustion gases and fume (a very fine iron oxide containing high and variable amounts of zinc) released during oxygen blow periods are removed from the furnace by evacuation through a large collection main. The BOF gas, consisting mainly of CO, leaves the BOF at a temperature of 1,600 - 1,800°C.

The hot gases are typically treated by one of three air pollution control methods:

- *Semi-Wet.* Water is added solely for the purpose of conditioning furnace off-gas temperature and humidity prior to processing the gas in electrostatic precipitators or baghouses.

- *Wet - Open Combustion.* Excess air is admitted to the off-gas collection system, allowing carbon monoxide to combust prior to high-energy wet scrubbing for air pollution control.
- *Wet - Suppressed Combustion.* Excess air is not admitted to the off-gas collection system prior to high-energy wet scrubbing for air pollution control, thus suppressing combustion of carbon monoxide (EPA 1995a).

Charging and tapping emissions are controlled by a variety of evacuation systems and operating practices. Charging hoods, tapside enclosures, and full furnace enclosures are used in the industry to capture these emissions and send

<b>Fuel</b>	<b>Total Industry Use (units as given)</b>	<b>Total Industry Use (10<sup>12</sup> Btu)<sup>a</sup></b>	<b>Specific Energy Use (10<sup>6</sup> Btu/net ton of raw steel)<sup>b</sup></b>
Oxygen	115,595 10 <sup>6</sup> ft <sup>3</sup>	20.2	0.3
Natural Gas <sup>c</sup>	18,819 10 <sup>6</sup> ft <sup>3</sup>	18.8	0.3
Electricity <sup>d</sup>	1,253 10 <sup>6</sup> kWh	13.2	0.2
Coke Oven Gas	847 10 <sup>6</sup> ft <sup>3</sup>	0.4	0.1
<b>TOTAL</b>		<b>52.6</b>	<b>0.9</b>

- a Conversion factors are 175 Btu/ft<sup>3</sup> of oxygen, 1,000 Btu/ft<sup>3</sup> of natural gas, 10,500 Btu/kWh of electricity, and 500 Btu/ft<sup>3</sup> of coke oven gas (AISI 1996).
- b Based on total U.S. BOF raw steel production of 59.686 10<sup>6</sup> net tons.
- c Based on total steelmaking furnace (including EAF) natural gas use of 28,819 10<sup>6</sup> ft<sup>3</sup> (AISI 1999) and assuming EAF natural gas use of approximately 10,000 10<sup>6</sup> ft<sup>3</sup> (Stubbles 1999).
- d Assumes 21 kWh/net ton of steel (Worrell 1994).

Sources: Stubbles 1999.  
American Iron and Steel Institute 1999 and 1996.  
Steiner 1995.  
Worrell 1994.

them to either the primary hood gas cleaner or a second gas cleaner (EPA 1995).

Table 4-2 shows estimated total emissions of criteria pollutants and CO<sub>2</sub> from BOF steelmaking in 1998. In that year, BOF steelmaking generated about 14.7 million tons of CO<sub>2</sub>. Emissions of CO<sub>2</sub>, about 490 pounds per ton of steel produced, amounted to approximately 10% of the total steel industry CO<sub>2</sub> emissions.

Table 4-3 lists emission factors for major air pollutants for various sources within the BOF process. In addition to these emission factors, EPA reported a total of 617,000 tons of CO emitted from basic oxygen furnaces in 1992 (EPA 1993).

As in the case of the blast furnace, most of the hazardous air pollutants (HAPs) generated in the BOF are heavy metals, including cadmium, chromium, lead, manganese, and nickel.

Emissions from the BOF are approximately 31 pounds per ton of steel, 90% of which is from the oxygen blow and reblow. Fugitive emissions are

<b>Pollutant<sup>b</sup></b>	<b>Intensity (lbs/ton steel)</b>	<b>Total (1,000 tons)</b>
SOx	0.32	9.5
NOx	0.17	4.9
CO	0.05	1.5
Particulates	0.09	2.7
VOCs	0.003	0.1
CO <sub>2</sub>	490	14,720

- a Includes emissions associated with the generation of electricity used in BOF steelmaking, including oxygen production in electric-based processes.
- b With the exception of CO<sub>2</sub>, estimates do not include emissions associated with the combustion of coke oven gas.

Sources: American Iron and Steel Institute 1999 and 1996.

0.2 pounds per ton of steel and may exceed 10 tons per year per furnace (Marsosudiro 1994). Factors affecting HAPs emissions from the BOF include the degree of oxidation of the molten steel and the amount of time required to process the melt.



Table 4-3. Emission Factors for BOF Steelmaking (lbs/ton of raw steel)						
Source	Particulate	PM <sub>10</sub> <sup>a</sup>	SOx	CO	VOC	NOx
Top Blown Furnace Melting						
Uncontrolled	28.5	13.1	--	139.0	0.001	0.08
Controlled by open hood venter to:						
ESP	0.13	--	--	--	--	--
Scrubber	0.09	--	--	--	--	--
Controlled by closed hood vented to scrubber	0.0068	--	--	--	--	--
BOF Charging <sup>b</sup>						
At source	0.6	0.3	--	--	0.001	--
At building monitor	0.142	--	--	--	--	--
Controlled by baghouse	0.0006	--	--	--	--	--
BOF Tapping						
At source	0.92	0.4	--	--	0.002	0.02
At building monitor	0.29	--	--	--	--	--
Controlled by baghouse	0.0026	--	--	--	--	--
Hot Metal Transfer <sup>b</sup>						
At source	0.19	0.09	--	--	0.001	--
At building monitor	0.056	--	--	--	--	--
BOF Monitor (All Sources)	0.5	--	--	--	--	--
Quelle BOF Melting and Refining Controlled by scrubber	0.056	--	--	--	--	--

a Particulate matter less than 10.0 microns in diameter.

b Emission factor is lbs/ton of hot metal.

Sources: U.S. Environmental Protection Agency 1995b and 1990.

Pollution prevention opportunities for the reduction of heavy metals at the BOF are somewhat limited because heavy metals are an inherent part of the iron ore material stream and because iron production is directly proportional to the amount of ore used.

## 4.5 Effluents

The BOF uses large quantities of water. Non-contact cooling is used for the vessel hood, ductwork, trunnion, and oxygen lance. Both closed-loop and evaporative systems are used for component cooling.

The gases and sub-micron fumes that are released during BOF steelmaking are quenched with water to reduce their temperature and volume prior to being treated in air pollution control systems. The

three major off-gas control systems (listed in Section 4.4) result in the generation of wastewater streams containing total suspended solids and metals (primarily lead and zinc, but also arsenic, cadmium, copper, chromium, and selenium).

In the open combustion and suppressed combustion systems, about 1,100 and 1,000 gallons of water per ton of steel are used, respectively (EPA 1995a). Standard treatment consists of sedimentation in clarifiers or thickeners and recycle of at least 90% of the applied water. Blowdown treatment consists of metals precipitation.

Table 4-4 presents the EPA basic oxygen furnace steelmaking effluent limitations for average daily values for 30 days using the best practicable control technology currently available (BPT) and

Table 4-4. BOF Steelmaking BPT Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lbs of steel)				
Pollutant	Limitation for Semi-Wet and Wet-Suppressed Combustion		Limitation for Wet-Open Combustion	
	BPT	BAT	BPT	BAT
Total Suspended Solids	0.0104	--	0.0229	--
Lead	--	0.0000626	--	0.000138
Zinc	--	0.0000939	--	0.000207

Source: Bureau of National Affairs 1992.

the best available technology economically achievable (BAT). The BAT technology is assumed to be clarification and recycle (90% recycle in the case of open combustion; 95% recycle in the case of suppressed combustion) of steelmaking wet air emission control scrubber water, and subsequent sludge dewatering.

For the case of semi-wet air emission control systems, the BPT guidelines assume that gas conditioning water is recycled to extinction. The BAT technology is assumed to be recycle system blowdown treatment comprising metals precipitation and pH control for steelmaking furnaces with wet air emission control systems. In addition to the limitations shown, the BPT case requires the effluent pH to fall between 6.0 and 9.0.

## 4.6 Byproducts

### ***BOF Slag Has Fewer Uses Than Blast Furnace Slag***

BOF steelmaking byproducts include BOF slag, air pollution control (APC) dust, and water treatment plant (WTP) sludge. BOF slag is composed of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium, and magnesium. After the molten BOF slag is removed from the furnace, it is cooled and processed to recover the high metallic portions (iron and manganese) for use in the sinter plant or blast furnaces. The

remaining non-ferrous fraction is then crushed and sized for reuse either within the steel works or externally.

BOF slag is a hard, dense material somewhat similar to air-cooled blast furnace slag. Because BOF slag differs from blast furnace slag in composition -- the oxides present in BOF slag can result in volume expansion of up to 10% when hydrated -- its use is more limited than blast furnace slag. The lower metallic aggregate is typically used in construction applications such as railroad ballast or unconfined highway base or shoulders, where its expansion will not create a problem. It is also used as an addition to cement kilns.

BOF slag outputs are approximately 20% by weight of the steel output. Entrained steel in the slag is typically recovered and returned to the furnace. A typical BOF slag composition is as follows:

- CaO - 48%
- FeO - 26%
- SiO<sub>2</sub> - 12%
- MgO - 6-7%
- MnO - 5%
- Al<sub>2</sub>O<sub>3</sub> - 1-2%
- P<sub>2</sub>O<sub>5</sub> - 1%

After removal of the entrained steel, the marketable slag makes up about 10 to 15% of the steel output, or 210 to 300 pounds per ton of steel (U.S. Dept. of Interior 1998).

The U.S. Department of the Interior estimates that a total of about 17 million tons of steelmaking slag was produced in the United States from BOF and EAF furnaces. Of this, approximately 9 million tons was from BOF operations. In 1997 approximately 7.7 million tons of steelmaking (BOF and EAF) slag were sold by the U.S. steel industry at an average price of about \$3 per ton (U.S. Dept. of Interior 1998).

A higher percentage of BOF slag used to be recycled internally; this recycling has been reduced over the last decade because of increasing quality demands. At present, less than 50% of the BOF slag produced worldwide is being utilized. The U.S. steel industry is currently stockpiling BOF slag at a rate of approximately 4 million tons annually. It is believed that for many applications more BOF slag could be used as aggregate to replace naturally occurring stone, with an overall reduction in environmental impact. The use of BOF slag for agricultural purposes has also been assessed.

### ***Dust, Sludge Are Generated During the Cleaning of BOF Gas***

BOF dust and sludge generated during the cleaning of gases emitted from the BOF represent two of the three largest-volume wastes typically land disposed by the iron and steel industry. Together with central water treatment plant sludge, these wastes represent more than 93% of the total industry wastes generally disposed (Baker Environmental 1992).

Particulate matter can be separated from the combustion gases generated during BOF steelmaking by one of the three means described in Section 4.4. Cleaned gases from suppressed combustion systems are ignited before release to the atmosphere to prevent emissions of CO in the uncombusted gas. These gases can also be recovered for heating value.

Typically, for the wet process, the mixture of gas and particulate mixture first is quenched with water in the collection main to reduce the temperature. This quenching process removes the

larger particles from the gas stream and entrains them in the water system. After settling in the classifier, these coarse solids can be easily dewatered via a long sloping screw conveyor or reciprocating rake and deposited in bins or hoppers. These solids are referred to as classifier sludge.

The fine particulate matter remaining in the gas stream is forced through venturi scrubbers where it is entrained in a wastewater stream and sent to thickener/flocculation tanks for settling and solids removal. This underflow slurry can be dewatered using mechanical filtration. In dry cleaning systems, the particulate matter collected in the electrostatic precipitator or baghouse is managed as a dust (Baker Environmental 1992).

The actual production rate of BOF steelmaking dust and sludge varies but typically falls in the range of 8 to 62 pounds per ton of raw steel, with an average value of about 36 pounds per ton (Szekely 1995). In 1988, approximately 1.54 million tons of APC dust/sludge were generated industry-wide, with an average waste-to-product ratio of 0.028 (EPA 1990). During 1997, approximately 1.1 million tons of steelmaking dust and sludge were produced (AISE 1998).

Steelmaking dust and sludge have been used in the production of Portland cement and as coloring agents for concrete. At present, however, much less than half of BOF dust and sludge is being reused. A small amount is recycled through the sinter plant or, in a very recent development, as charge to the BOF following cold agglomeration (Edgar 1996).

The rising cost of scrap and waste disposal, scarce on-site landfill space, and potential future environmental liabilities provide economic incentive to recover iron units from dust and sludge. Unfortunately, recycling to the blast furnace may raise the hot metal phosphorus content to undesirable levels. In addition, the increasing use of galvanized scrap could increase dust and sludge zinc content.

### ***Zinc Content of BOF Dust, Sludge Affects Their Recyclability***

The main problem associated with recycling BOF dust directly to the blast furnace or the steelmaking furnace is its zinc content, which has an adverse effect on the blast furnace.

Because of zinc's detrimental effect on blast furnace refractories and operations, the quantity of zinc that can be charged to the blast furnace lies between 0.2 and 0.9 pounds per ton of hot metal.

Dust and sludge from the blast furnace alone are currently recycled in sufficient quantities so that

the maximum allowable input level is approached but not exceeded. Consequently, there is little opportunity for internal recycling of BOF dust and sludge (IISI 1994). Only a very small fraction of dust and sludge is being used externally (Szekely 1995). BOF dust and sludge that is not recycled is landfilled.

## **4.7 Hazardous Wastes**

There are no RCRA-listed hazardous wastes associated with BOF steelmaking, but dusts can sometimes be characteristically hazardous because of constituents such as lead and chrome.

# 5

# Steelmaking - Electric Arc Furnace

## 5.1 Process Overview

Electric arc steelmaking furnaces produce carbon and alloy steels from scrap metal along with variable quantities of direct reduced iron (DRI), hot briquetted iron, and cold pig iron. Hot metal may also be added if available. The feed or charge is melted in cylindrical, refractory-lined electric arc furnaces (EAFs) equipped with carbon electrodes (one for DC furnaces, three for AC furnaces) that are lowered through the furnace roof.

During charging, the roof is removed and the scrap metal and other iron-bearing materials are placed into the furnace. Alloying agents and fluxes are added through doors on the side of the furnace. The electrodes are lowered into the furnace to about an inch above the metal and current is applied, generating heat to melt the scrap.

Modern electric arc furnaces use an increasing amount of chemical energy to supplement the melting process. The chemical energy contribution is derived by burning elements or compounds in an exothermic manner.

Sources that provide chemical energy include (Heard 1998):

- oxy-fuel burners and oxygen lancing
- charge carbon
- foaming carbon
- exothermic constituents in scrap
- exothermic constituents in alternate iron sources

Oxy-fuel burners are used to introduce combinations of natural gas, oil, or even coal into the furnace to displace electricity use. Oxy-fuel burners aid in scrap melting by transferring heat to the scrap primarily via forced convection and radiation from the combustion products. As higher oxygen utilization has developed as a standard EAF practice, more carbon is required in EAF operations as a fuel (Jones 1998). The reaction of carbon with oxygen within the bath to produce CO results in a significant energy input to the process.

The injection of a carbon source also promotes the formation of a foamy slag, which retains energy that is transferred to the bath. The generation of the CO within the bath is key to flushing out dissolved gases (nitrogen and hydrogen) in the

steel, as well as flushing oxide inclusions from the steel into the slag (Jones 1998).

Some EAFs use ferromanganese as a catalyst in the melt to add energy and help stabilize the melt. The efficiency of manganese combustion can be between 90% and 100% (Heard 1998).

Residence time in the furnace for a 100%-scrap charge ranges from about 45 minutes to several hours. The best operations have average heat times in the range of 40 to 45 minutes, with power-on times of 30 to 35 minutes and power-off times of 5 to 10 minutes (Stubbles 2000). When the charge is fully molten it is refined to remove unwanted materials (e.g., phosphorus, sulfur, aluminum, silicon, manganese, and carbon), tapped from the tilted furnace, and sent for secondary treatment prior to casting. Because scrap metal rather than molten iron is the primary material charged, EAF steel producers avoid the cokemaking and ironmaking process steps.

## 5.2 Summary of Inputs/Outputs

Inputs: Scrap metal  
Direct reduced iron  
Hot briquetted iron  
Cold pig iron  
Hot metal  
Alloy materials (e.g., aluminum, manganese, chromium, nickel)  
Fluxes (e.g., lime)  
Electricity  
Oxygen  
Nitrogen  
Natural gas  
Oil  
Coal or other carbon source  
Water

Outputs: Molten steel  
Slag  
Carbon monoxide  
Nitrogen oxides and ozone  
EAF emission control dust and sludge (K061)

Figure 5-1 illustrates electric arc furnace steelmaking with its major inputs and outputs.

## 5.3 Energy Requirements

### *EAF Steelmaking Is Electricity-Intensive*

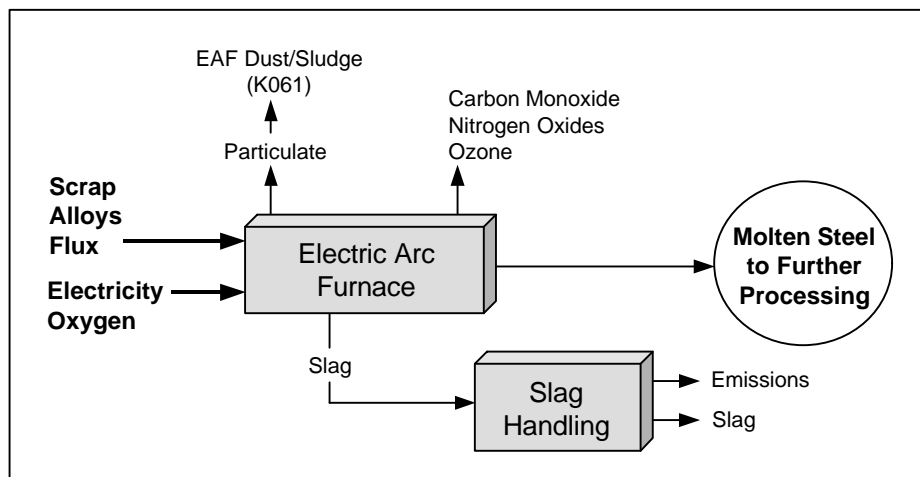
As shown in Table 5-1, electric arc steelmaking is very electricity-intensive, consuming an average of 436 kWh (4.58 million Btu) per ton of raw steel produced. Some modern furnaces have reported electricity consumption as low as 300 kWh/ton (I&SM 1999a). As electricity requirements have dropped, however, consumption of natural gas, carbon, and oxygen has been on the rise. Stubbles reports an average carbon consumption of 0.6 million Btu/ton of steel, significantly higher than the 0.2 value shown in Table 5-1 (Stubbles 2000). Using the higher value would give an average energy requirement of 5.6 million Btu/ton of steel tapped from the EAF.

In addition to the fuels shown in Table 5-1, approximately 0.1 million Btu/ton of steel is attributable to electrode consumption (Fruehan 1999). The energy associated with the lime flux would contribute about another 0.3 million Btu/ton of steel (Stubbles 2000).

A recent survey of EAF energy use conducted by the Steel Manufacturers' Association yielded typical EAF energy consumption under 500 kWh/cast ton, but an average consumption of 770 kWh/shipped ton (Stubbles 2000). This indicates the considerable energy used in auxiliary equipment in the melt shop, in rolling, in oxygen production, and in general utilities.

### *Scrap Preheating, Oxygen Injection Improve EAF Energy Efficiency*

Higher electrical input rates and increased oxygen and natural gas consumption have led to shorter residence times, higher throughputs, and lower energy losses. Up to 60% of the total power input to the EAF ends up in the steel. Typically 8% to 10% of the power input is lost to the cooling water, and offgas temperatures are very high, with losses of approximately 20% of the power input to the offgas (AISE 1998).



<b>Key Energy and Environmental Facts - Electric Arc Furnace Steelmaking</b>			
<b>Energy</b>	<b>Emissions</b>	<b>Effluents</b>	<b>Byproducts/Hazardous Wastes</b>
5.2 to 5.6 10 <sup>6</sup> Btu per net ton of raw steel	Largest Sources - melting and refining  Particulate - iron oxide (melting); calcium oxide (refining)	Largest Source - wet/semi-wet air cleaning systems (few used)	EAF Slag - 50-75% reused  K061 - EAF dust/sludge Major Components - Fe, Zn, Cr and their oxides Total Generation - about 900,000 tons/yr

**Figure 5-1. Electric Arc Furnace Steelmaking Flow Diagram**

<b>Table 5-1. Energy Use in EAF Steelmaking - 1998</b>			
<b>Fuel</b>	<b>Total Industry Use (units as given)</b>	<b>Total Industry Use (10<sup>12</sup> Btu)<sup>a</sup></b>	<b>Specific Energy Use (10<sup>6</sup> Btu/net ton of raw steel)<sup>b</sup></b>
Electricity <sup>c</sup>	21,393 10 <sup>6</sup> kWh	224.6	4.6
Oxygen	62,042 10 <sup>6</sup> ft <sup>3</sup>	10.9	0.2
Natural Gas <sup>d</sup>	10,000 10 <sup>6</sup> ft <sup>3</sup>	10.0	0.2
Carbon <sup>e</sup>	--	~ 12 to 30	0.2 - 0.6
<b>TOTAL</b>	--	<b>257.5</b>	<b>5.2 - 5.6</b>

- a Conversion factors are 10,500 Btu/kWh of electricity, 175 Btu/ft<sup>3</sup> of oxygen, and 1,000 Btu/ft<sup>3</sup> of natural gas (AISI 1996).
- b Based on total U.S. EAF raw steel production of 49.067 10<sup>6</sup> net tons in 1998 (AISI 1999).
- c Based on EAF energy intensity of 436 kWh/ton of raw steel (LBNL 1997 and I&SM 1999a).
- d Assuming total EAF natural gas use of approximately 10,000 10<sup>6</sup> ft<sup>3</sup> (Stubbles 1999).
- e Lower value estimated from AISI data; higher value estimated by Stubbles (Stubbles 2000).

Sources: Stubbles 2000 and 1999.  
AISI 1999 and 1996.  
Fruehan 1999.  
Iron and Steelmaker 1999a  
Steiner 1995.

One way to recapture the heat contained in the offgas is through scrap preheating. It has been estimated that scrap preheating can save 5% to 10% of total EAF energy requirements (Fruehan 1999).

The use of oxy-fuel burners can reduce tap-to-tap times by as much as 20% and electricity requirements by more than 10% (Natural Gas Applications in Industry 1993). Oxy-fuel burners have evolved from simple heating units to multi-functional units that can inject gas and oxygen at different ratios as well as solid carbon (Stubbles 2000). Approximately 40% of EAFs in the United States reported use of oxy-fuel burners in 1998 (I&SM 1999a).

Post combustion can reduce energy requirements by another 5% to 10%. In post combustion, oxygen is injected into the EAF in order to achieve more complete combustion and capture additional process energy.

The use of liquid hot metal in the charge can reduce EAF energy requirements by 3 kWh for each percentage point of hot metal in the charge, although more oxygen is required and the burden on the baghouse is increased (Stubbles 2000).

## 5.4 Emissions

### ***Melting Process Generates Particulate Emissions, Gases***

Essentially all phases of normal EAF operation result in either primary or secondary emissions. Primary emissions are those produced during EAF melting and refining operations. Secondary emissions result from charging, tapping, and also from escape of fume from the EAF (AISE 1998).

During the EAF process, oxide and other metal forms are volatilized in the presence of intense heat and turbulence inside the furnace. Also, carbon from the scrap and graphite electrodes reacts with injected air or oxygen. Consequently, major constituents in EAF emissions are particulate matter and gases (particularly carbon monoxide, SO<sub>x</sub>, and NO<sub>x</sub>) that evolve together.

As oxygen use has increased in the EAF, so have the quantities of CO and CO<sub>2</sub> emitted from furnace operations. CO gas is produced in large quantities in the EAF both from oxygen lancing and slag foaming activities, and from the use of pig iron or DRI in the charge. Large amounts of CO and hydrogen are generated at the start of meltdown as oil, grease, and other combustible materials evolve from the surface of the scrap. If there is sufficient oxygen present, these compounds will burn to completion, increasing emissions of CO<sub>2</sub> (AISE 1998).

NO<sub>x</sub> is formed in furnace operations when nitrogen passes through the arc between electrodes. Some thermal NO<sub>x</sub> is also generated from burner use in EAFs. Typical levels of NO<sub>x</sub> reported are in the range of 36 to 90 grams per ton of steel (AISE 1998).

Most scrap mixes contain organic compounds to some extent. When scrap is charged to the furnace, some of these organic compounds (VOCs) burn off. If there is insufficient oxygen available for combustion, these hydrocarbon compounds will be sent to the offgas system. Total emissions of hydrocarbons appear to be related to the amount of chlorine in the EAF.

Scrap preheating tends to produce greater emissions of hydrocarbons (AISE 1998). VOCs can be burned off in the furnace or may be destroyed by preheating followed by afterburning.

Iron oxide and zinc oxide are the predominant constituents of the particulate emitted during melting. In addition, minor amounts of nitrogen oxides and ozone are generated during melting. During refining, small amounts of calcium oxide may be emitted from the slag. Melting emissions account for about 90% of total EAF emissions. The remaining 10% of emissions are generated during charging and tapping.

Emissions from charging scrap are difficult to quantify because they depend on the grade of scrap utilized. Scrap emissions usually contain iron and other metallic oxides from alloys in the scrap metal. Iron oxides and oxides from the



fluxes are the primary constituents of the slag handling emissions. During tapping, iron oxide is the major particulate compound emitted (EPA 1995 and Baker Environmental 1992).

Estimates for combustion-related emissions from EAF-based steelmaking (including the generation of electricity used in the EAF) in 1998 are shown in Table 5-2. In that year, EAF-based steelmaking emitted an estimated 25 million tons of CO<sub>2</sub>. Table 5-3 lists emission factors for major air pollutants for various sources within the EAF steelmaking process.

<b>Table 5-2. Total Estimated Combustion-Related EAF Steelmaking Emissions - 1998<sup>a</sup></b>		
<b>Pollutant</b>	<b>Intensity (lbs/ton steel)</b>	<b>Total (1,000 tons)</b>
SO <sub>x</sub>	6.6	162.9
NO <sub>x</sub>	2.5	62.5
CO	0.8	19.9
Particulates	1.8	44.9
VOCs	0.02	0.5
CO <sub>2</sub>	1,012	24,820

a Includes emissions associated with the generation of electricity used in EAF steelmaking, including production of oxygen in electric-based processes.

Sources: American Iron and Steel Institute 1999 and 1996.

### **Control of EAF Emissions Involves Evacuation Systems**

Primary emissions are generally controlled using a direct evacuation system. Secondary emissions are captured using canopy hoods and in some cases auxiliary tapping hoods (AISE 1998). A direct evacuation system (DES) consists of ductwork attached to a separate hole in the furnace roof that draws emissions to a gas cleaner. A modern DES controls CO, NO<sub>x</sub>, and VOC emissions in addition to capturing particulate.

The canopy hood is most useful for capturing emissions during charging and tapping. The building evacuation system consists of an

enclosure that completely surrounds the furnace and evacuates furnace emissions through hooding in the top of the enclosure. Most newer furnaces incorporate the canopy hood with one of the evacuation systems.

Particulate collection is typically achieved with a baghouse, although scrubbers and electrostatic precipitators are also used in some cases. Particulate matter removed from EAF emissions using these cleaning methods is the hazardous waste known as EAF dust, which is discussed in Section 5.7 (EPA 1995 and Baker Environmental 1992).

## **5.5 Effluents**

### **Few EAFs Generate Wastewater**

Although EAFs can have significant non-contact cooling water requirements, few furnaces have significant process wastewater discharges. Most electric arc furnaces are operated with dry air cleaning systems with no process wastewater discharges. Other non-contact water applications include water-cooled ductwork, roof, sidewalls, doors, lances, panels, cables, and arms. These systems usually incorporate evaporative cooling towers or closed cooling loops (AISE 1999). A small number of wet and semi-wet air cleaning systems also exist. The water flows for those systems with wet and semi-wet air cleaning systems are about 2,100 gallons/ton. Pollutants of concern are similar to those for the wet basic oxygen furnaces, but the levels of metals (primarily lead and zinc, but also arsenic, cadmium, copper, chromium, and selenium) are higher because of the higher percentage of scrap charged. Wastewater treatment operations are similar to those for the wet basic oxygen furnaces, including sedimentation in clarifiers or thickeners and recycle of the water (EPA 1995a).

Table 5-4 presents the EPA electric arc furnace steelmaking effluent limitations for average daily values for 30 days using the best practicable control technology currently available (BPT) and the best available technology economically achiev-

Table 5-3. Emission Factors for EAF Steelmaking (lbs/ton of raw steel)						
Source	Particulate	PM <sub>10</sub> <sup>a</sup>	SOx	CO	VOC	NOx
Melting and Refining Uncontrolled carbon steel	38.0	--	--	--	--	--
Charging, Tapping, and Slagging Uncontrolled emissions escaping monitor	1.4	--	--	--	0.003	--
Melting, Refining, Charging, Tap- ping, and Slagging Uncontrolled						
Alloy steel	11.3	6.55	0.7	18.0	0.35	0.1
Carbon steel	50.0	29.0	0.7	18.0	0.35	0.1
Controlled by:						
Building evacuation to baghouse for alloy steel	0.3	--	--	--	--	--
Direct evacuation (plus charging hood) vented to common baghouse for carbon steel	0.043	--	--	--	--	--

a Particulate matter less than 10.0 microns in diameter.

Sources: U.S. Environmental Protection Agency 1995b and 1990.

Table 5-4. EAF Steelmaking Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lbs of steel)				
Pollutant	Limitation for Semi-Wet Process		Limitation for Wet Process	
	BPT	BAT	BPT	BAT
Total Suspended Solids	0.0104	--	0.0229	--
Lead	--	0.0000626	--	0.000138
Zinc	--	0.0000939	--	0.000207

Source: Bureau of National Affairs 1992.

able (BAT). The BPT regulations also require the effluent pH to be in the range of 6.0 to 9.0. The BPT technology is assumed to be clarification and 95% recycle of wet air emission control scrubber water, and subsequent sludge dewatering. The BAT technology is assumed to be recycle system blowdown treatment comprising metals precipitation and pH control for steelmaking furnaces with wet air emission control systems. The BAT effluent flow is 110 gallons/ton.

## 5.6 Byproducts

### *Dust, Slag Are Two Major Byproducts*

The two major byproducts generated during EAF steelmaking are slag and dust. During melting, oxidation of phosphorus, silicon, manganese, carbon, and other materials occurs and a slag containing some of these oxidation products forms on top of the molten metal (Baker Environmental 1992). Electric arc furnaces produce between 110

and 420 pounds of slag for every ton of molten steel made, with an average value of about 230 pounds per ton (Szekely 1995a).

EAF slag is managed similar to BOF slag. Cooled, solidified slag is crushed and screened to recover metallics for recycle or reuse and the lower metallic aggregate is used in construction applications (Baker Environmental 1992).

Worldwide, about 77% of the slag produced in EAFs is reused; the remainder is landfilled or dumped (Szekely 1995).

EAF dust is made up of the particulate matter and gases produced during the EAF process and subsequently conveyed into a gas cleaning system. The particulate matter that is removed from emissions in a dry system is referred to as EAF dust; particulate matter removed from emissions in a wet system is known as EAF sludge.

## 5.7 Hazardous Wastes

### ***EAF Dust, Sludge Contain Valuable Components***

The dust (or sludge) that is removed from EAF emissions is a listed hazardous waste, K061. Most of the dusts are collected dry and thus pollution issues largely fall into a non-wastewater category (A.D. Little 1993).

EAF dust can vary greatly in composition depending on the composition of the scrap charge and on the furnace additives used. Table 5-5 shows the typical composition of EAF dust generated during the production of stainless and carbon steels. The primary component is iron or iron oxides; a typical EAF dust contains 24% iron by weight (Kolarik 1996). In cases where lower grades of scrap are used (generally for carbon steel production), EAF dust can contain large amounts of zinc and lead (as high as 44% ZnO and 4% PbO) (Baker Environmental 1992). Similarly, stainless steel production yields dust with high percentages of chromium and nickel oxides (as high as 12% Cr<sub>2</sub>O<sub>3</sub> and 3% NiO)

(Baker Environmental 1992). EAF dust also contains cadmium in concentrations on the order of about 0.1% by weight. Other possible EAF dust components include other metals and flux.

The primary hazardous constituents of EAF emission control dust/sludge are lead, cadmium, and hexavalent chromium. Because these constituents are leachable, most EAF dust from the production of carbon steel cannot be delisted.

As shown in Table 5-5, the carbon steel dusts are richer in zinc and lead because of the greater use of galvanized scrap. Generally, 20 to 40 pounds of EAF dust per ton of steel are generated, depending on the mill's specific operating practices, with an average of about 35 pounds per ton of steel melted (A.D. Little 1993 and Schmitt 1996).

Between 600,000 to 900,000 tons of EAF emission control dust are generated in the U.S. steel industry annually (Stubbles 1999). A 1992 survey conducted by A.D. Little for the EPRI Center for Materials Production found an average zinc concentration of 19%, unchanged from a similar survey performed in 1985.

### ***Majority of EAF Dust Treated in High-Temperature Metals Recovery Facilities***

As of 1992, the EAF dust treatment option chosen is no longer regulated by EPA based on the zinc content of the dust. Any dust treatment technology can be used if it meets the revised treatment standards, which cover the following fourteen elements: antimony, arsenic, barium, beryllium, cadmium, chromium, lead, mercury, nickel, selenium, silver, thallium, vanadium, and zinc.

Table 5-6 shows the typical ranges of concentration of each of these elements in EAF dust. Table 5-7 shows the maximum allowable concentrations of these constituents in K061 wastewaters and non-wastewaters for land disposal. If the dust is to be used for fertilizer manufacture, it is exempt from waste regulations.

<b>Table 5-5. Comparative Chemical Composition of Dust from Electric Arc Furnaces</b>		
<b>Chemical</b>	<b>Stainless Steel Dust (% by weight)</b>	<b>Carbon Steel Dust (% by weight)</b>
Iron	31.7	28.5
Zinc	1.0	19.0
Cadmium	0.16	<0.1
Lead	1.1	2.1
Chromium	10.2	0.39
Calcium Oxide	3.1	10.7 <sup>a</sup>

a Calcium oxide and magnesium oxide combined.

Source: A.D. Little for the EPRI Center for Materials Production 1993.

<b>Table 5-6. Concentrations of Fourteen Regulated Elements in Electric Arc Furnace Dust</b>	
<b>Element</b>	<b>Total Concentration (mg/kg)</b>
Antimony	5.0 - 294.0
Arsenic	10.2 - 400.0
Barium	24 - 400
Beryllium	<0.5 - 8.1
Cadmium	1.4 - 4,988
Chromium	<0.05 - 106,000
Lead	1.3 - 139,000
Mercury	<0.001 - 41
Nickel	<10 - 22,000
Selenium	0.07 - 600
Silver	2.5 - 71.0
Thallium	0.8 - 50.0
Vanadium	24 - 475
Zinc	3,900 - 320,000

Sources: Grieshaber et al 1994.  
U.S. Environmental Protection Agency 1988a.

Table 5-7. Maximum Allowable Constituent Concentrations in K061 for Land Disposal (mg/l)		
Regulated Hazardous Constituent	Concentration in Wastewaters	Concentration in Non- Wastewaters <sup>a</sup>
Antimony	N/A	2.1
Arsenic	N/A	5.0
Barium	N/A	7.6
Beryllium	N/A	0.014
Cadmium	0.69	0.19
Chromium (total)	2.77	0.86
Lead	0.69	0.37
Mercury	N/A	0.025
Nickel	3.98	5.0
Selenium	N/A	0.16
Silver	N/A	0.30
Thallium	N/A	0.78
Zinc	N/A	5.3

a Based on the Toxicity Characteristic Leaching Procedure (TCLP).

Source: Bureau of National Affairs 1995.

The treatment options available to EAF operators are:

- Transporting the dust to an off-site processor for thermal treatment and removal of zinc, chemical fixation, glassification, or fertilizer manufacture.
- On-site processing by agglomerating or briquetting and directly recycling back through the EAF (to concentrate the zinc content).
- On-site processing in a separate processing facility to glassify or vitrify the heavy metal content.
- On-site processing using hydrometallurgical or pyrometallurgical processes to upgrade the zinc values to zinc oxide or metallic zinc.
- Delisting by chemical fixation through solidification or vitrification for landfilling as a non-hazardous waste, or other uses allowed by regulations.
- Treatment for disposal in a secure landfill as a hazardous waste (A.D. Little 1993).

The 1992 A.D. Little survey found that the majority of EAF operators (accounting for nearly 87% of the dust generated) are shipping the dust off-site for thermal treatment to recover zinc using a high-temperature metals recovery (HTMR) process. About 11% of the dust was being disposed in landfills, 2% was being shipped for processing into fertilizer, and less than 1% was being treated with other methods or delisted.

A number of high-temperature processes have been developed in which the EAF dust is processed in a furnace or reactor with a reductant

(coke or coal) to recover the zinc, lead, and cadmium as metals or in the oxide state (Goodwill 1994). The element of the most value is zinc -- the quantity of zinc available for potential recovery from EAF dust each year is approximately 114,000 tons (A.D. Little 1993).

### ***Waelz Kiln Remains Dominant HTMR Process for EAF Dust Treatment***

By far the main HTMR processing method is the Waelz Kiln approach as practiced by Horsehead Industries; other pyrometallurgical processes (some not used anywhere in the United States) include flame reactor processing, plasma processing, ZTT Ferrolime, MF/Electrothermic, and the LaCledde Steel process. One U.S. plant is using a hydrometallurgical process offered by MRT. Only one significant glassification process has reached commercialization at this time. The Waelz Kiln process is considered to be the Best Demonstrated Available Technology (BDAT) by the U.S. EPA for the recycling of EAF dust containing greater than 15% zinc.

There are currently five Waelz kilns operating in the United States. In this process EAF dust, other zinc-bearing wastes, recycled materials, coke or coal, lime, and silica are mixed and fed to a rotary furnace. The zinc and other volatile non-ferrous metals in the feed are entrained in the furnace off-gas and are carried from the furnace to an external dust collection system.

The resulting oxide (zinc calcine) is a crude zinc-bearing product that is further refined at zinc

smelters. A byproduct of the process is a non-hazardous, iron-rich slag that can be used in road construction.

A recent estimate of the cost of Waelz Kiln TMR process in the United States is \$3 to \$5 per ton of steel, depending on the zinc content of the dust (Wrona 1997).

Solidification technologies change the physical form of the waste to produce a solid structure in which the contaminant is mechanically trapped. In 1995, the EPA ruled that stabilization and subsequent disposal in conventional landfills is permissible for all EAF dust as long as the stabilized product meets the TCLP leachate standards (Zunkel 1996). The resulting non-hazardous waste has lower transportation and disposal costs (approximately \$75 per ton) than the hazardous waste. However, solidification is not considered a long-term solution because it still involves landfilling, and it increases the volume of material to be landfilled (A.D. Little 1993 and Goodwill 1994).

Technologies for on-site recycling of the dust back into an EAF (e.g., briquetting, pelletizing, and pneumatic injection) are still being developed but have the potential to recover some of the iron oxide values in the dust while concentrating the zinc values. Concentrating the zinc values reduces final recycling costs because smaller quantities of dust will be shipped off-site, and the resulting dust has a higher zinc concentration (improving the cost efficiency of subsequent zinc recovery treatment).

# 6

# Refining and Casting

## 6.1 Process Overview

### *Molten Steel Refined Prior to Casting*

Ladle metallurgical furnace (LMF) processes are used to further refine the molten steel from the BOF or EAF prior to casting. These processes include reheating, refining, inclusion modification, and degassing.

Reheating of the steel using arc reheating or oxygen injection permits adjustment of the steel temperature to levels needed for uninterrupted sequential casting.

The refining of steel in the ladle includes the following operations (AISE 1998):

- deoxidation
- desulfurization
- controlled additions of alloying elements
- inclusion modification

The first step is typically the deoxidation of the steel with ferromanganese, ferrosilicon, silicomanganese, and aluminum. For steel grade requiring low sulfur contents, desulfurization will be performed.

Ferrous alloys and fluxes are added to the molten steel to achieve the desired chemistry. The steel in the ladle is stirred by argon gas bubbling in order to achieve a homogeneous bath temperature and composition, as well as remove non-metallic inclusions. Calcium treatment may be used to control inclusions that can clog nozzles during the continuous casting process.

In vacuum degassing, molten steel is subjected to a vacuum for composition control, temperature control, deoxidation, degassing (hydrogen removal), decarburization, and to otherwise remove impurities from the steel (EPA 1995).

EAF melting followed by argon-oxygen decarburization (AOD) is the predominant method for making stainless steel. Stainless and carbon steel scraps are melted together with less expensive high-carbon ferrochromium in the EAF, followed by carbon removal in a separate AOD vessel.

Multiple ladle furnaces are often used in a single LMF facility, with the residence time roughly on the same order as an EAF. After refining, the hot metal is transferred to a tundish that serves as a buffer between the ladle and the mold (caster).

## **Most Steel is Continuously Cast**

Approximately 96% of all steel produced in the United States in 1998 was continuously cast; the remaining 4% was ingot cast. Just 20 years ago, continuous casting accounted for less than 10% of cast production. In continuous casting, the molten steel is solidified into a semi-finished shape (i.e., billet, bloom or slab) for subsequent rolling in the finishing mill. Continuous casting eliminates the need for classical processes such as teeming into ingots; mold stripping; reheating; and primary hot rolling into semi-finished shapes. The continuous process has higher yields, quality, and productivity versus the ingot process, as well as higher energy efficiency.

In the continuous casting process, molten steel is delivered in ladles and poured into a reservoir or tundish from which it is released into the mold (for a single-strand machine) or molds (for a multi-strand machine) of the casting machine. The steel cools as it passes through the mold and forms a solid outer shell or "skin." As the steel proceeds onto the runout table, the center of the steel also solidifies, yielding a semi-finished shape at a specified width and thickness. Depending on the type of caster used, various shapes are produced. (Baker Environmental 1992 and EPA 1995). In recent years, the melting/casting/rolling processes have been linked while casting a shape that substantially conforms to the finished product.

In ingot casting, which is used for small batch sizes for specialty steels or for end products with certain shape specifications, the molten steel in the ladle is teemed into a series of molds and allowed to solidify to form ingots. After the molds are stripped away, the ingots are heated to uniform temperature in soaking pits to prepare them for rolling. The heated ingots are removed from the pits and rolled into slabs, blooms, or billets.

## **6.2 Summary of Inputs/Outputs**

Inputs: Molten steel  
Alloying elements  
Deoxidants  
Fluxes

Fuel (natural gas, coke oven gas,  
blast furnace gas)  
Electricity  
Oxygen  
Argon  
Water

Outputs: Semi-finished steel shapes  
Process wastewater  
Scale  
Sludge  
Waste oil and grease  
Air pollution control (APC) dust

Figure 6-1 illustrates the refining and casting processes with their major inputs and outputs.

## **6.3 Energy Requirements**

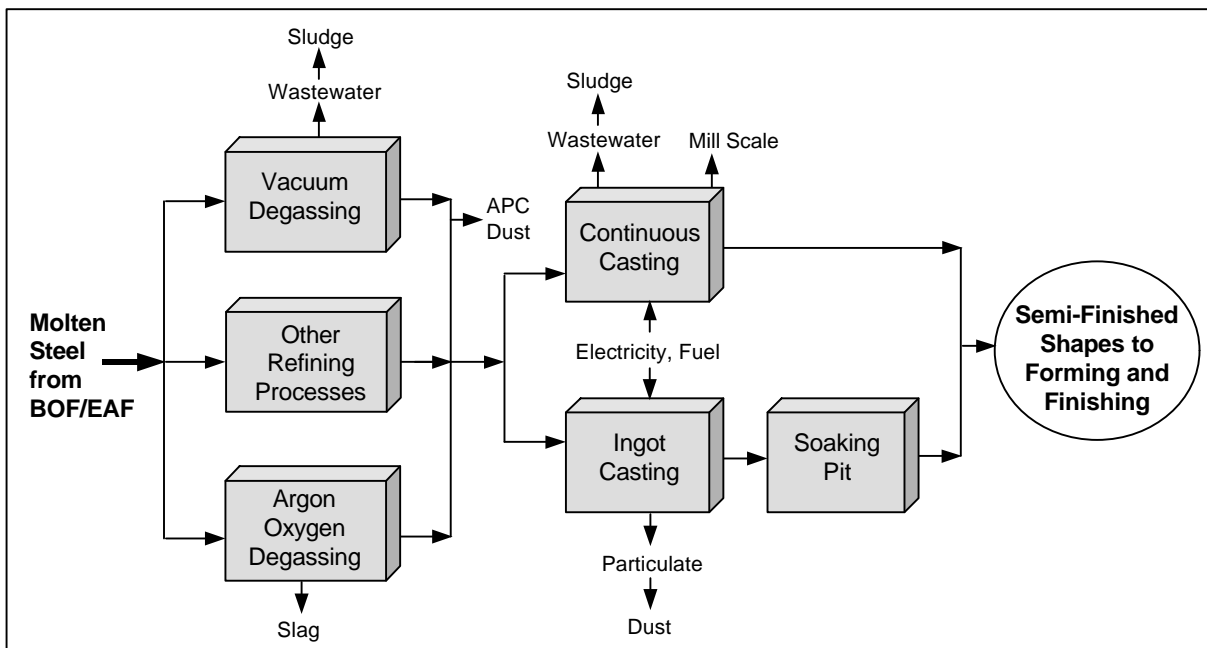
### ***Continuous Casting Much More Energy Efficient Than Ingot Casting***

Ladle furnace operations, ladle heating, baghouses, cranes, casters, and other auxiliary services consume an estimated 100 kWh/ton of steel (Stubbles 2000). Ladle furnaces are typically heated electrically, requiring about 25 to 30 kWh per ton of steel shipped. While some of this energy might have previously been used in heating steel in the EAF (in the case of EAF steelmaking), the trend is to produce higher quality steels that often require more refining time, adding to net electricity input (Goodwill 1998).

Table 6-1 presents estimated energy intensities for ingot and continuous casting. Continuous casting is much less energy-intensive than ingot casting because the former eliminates the need for soaking pits and primary rolling and generates less scrap, using approximately 10% the energy used per ton of cast steel in ingot casting and yielding 15% to 20% more product (Marsosudiro 1994).

Using the values in Table 6-1 to estimate the industry-wide energy consumption for casting in 1998 yields a total of 14 trillion Btu for ingot casting (based on 4.840 million tons cast in 1998) and 30 trillion Btu for continuous casting (based on 103.883 million tons cast in 1998) (AISI 1999).





<b>Key Energy and Environmental Facts - Refining and Casting</b>			
<b>Energy</b>	<b>Emissions</b>	<b>Effluents</b>	<b>Byproducts</b>
<p><i>Energy Use Per Ton of Cast Steel:</i></p> <p><i>Ingot Casting<sup>a</sup> - 2.78 10<sup>6</sup> Btu</i></p> <p><i>Continuous Casting - 0.29 10<sup>6</sup> Btu</i></p> <p><i>a - includes soaking pits</i></p>	<p><i>Largest Source - teeming into molds</i></p> <p><i>Particulate - iron and other oxides</i></p>	<p><i>Sources - vacuum degassing, continuous casting cooling water</i></p> <p><i>Typical Wastewater Volume Per Ton of Steel:</i></p> <p><i>Degassing - 25 gal</i></p> <p><i>Continuous Casting - &lt;25 gal</i></p>	<p><i>Mill Scale, Sludge - data on generation, reuse are included in totals for forming and finishing (Sect. 7)</i></p>

**Figure 6-1. Refining and Casting Flow Diagram**

## 6.4 Emissions

During ingot casting, particulate emissions are produced when the molten steel is poured (teemed) into the molds. The major emissions include iron and other oxides (FeO, Fe<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, CaO, and MgO). These emissions are either left uncontrolled or are controlled by side draft hoods that are vented to a baghouse.

Table 6-2 shows total combustion-related criteria pollutant and CO<sub>2</sub> emissions for casting operations in 1998. Ingot casting, while only used

for about 4% of the total steel cast in that year, emitted almost 850,000 tons of CO<sub>2</sub>, half as much as continuous casting.

Table 6-3 gives the particulate emission factors for teeming, together with emission factors of other air pollutants for both ingot and continuous casting. Operational changes in ingot casting such as bottom pouring instead of top pouring can reduce total emissions. Bottom pouring exposes much less of the molten steel to the atmosphere than top pouring, thereby reducing the formation of particulate (Marsosudiro 1994).

Table 6-1. Energy Intensities and Consumption of Ingot and Continuous Casting <sup>a</sup> - 1998				
Fuel	Ingot Casting <sup>b</sup>		Continuous Casting	
	Intensity (10 <sup>6</sup> Btu/ton casted)	Total Energy (10 <sup>12</sup> Btu) <sup>c</sup>	Intensity (10 <sup>6</sup> Btu/ton steel)	Total Energy (10 <sup>12</sup> Btu) <sup>c</sup>
Electricity <sup>c</sup>	1.57	7.6	0.29	30.1
Natural gas and other fuels	1.21	5.9	0	0
<b>TOTAL</b>	<b>2.78</b>	<b>13.5</b>	<b>0.29</b>	<b>30.1</b>

a Based on reported intensities and 4.840 and 103.883 million tons of ingot and continuous cast steel, respectively (AISI 1999).

b Includes soaking pit.

c Conversion factor is 10,500 Btu/kWh.

Sources: American Iron and Steel Institute 1999.  
Worrell 1994.  
LBNL 1998.

Table 6-2. Total Estimated Combustion-Related Casting Emissions- 1998 <sup>a</sup>				
Pollutant	Ingot		Continuous	
	lbs/ton steel	1,000 tons	lbs/ton steel	1,000 tons
SO <sub>x</sub>	2.28	6.5	0.42	21.6
NO <sub>x</sub>	1.03	2.9	0.16	8.2
CO	0.32	0.9	0.05	2.6
Particulates	0.63	1.8	0.12	6.0
VOCs	0.014	0.0	0.001	0.1
CO <sub>2</sub>	348	841.0	38	1,972.9

a Includes emissions associated with the generation of electricity used in casting.

Sources: American Iron and Steel Institute 1998 and 1996.

EPA does not list any particulate emission factors for continuous casting operations. Certain refining processes, including ladle metallurgy, generate particulate emissions. These emissions are typically collected in baghouses as air pollution control dust.

## 6.5 Effluents

### *Refining Generates Few Wastewaters*

Water usage for the LMF is similar to the EAF (e.g., cooling). Of all the refining processes,

only vacuum degassing uses process water and generates effluent streams. Vacuum degassing involves direct contact between gases removed from the steel and condenser water. The principal pollutants contained in the resulting effluent are low levels of total suspended solids (TSS) and metals (particularly lead and zinc, but also chromium, copper, and selenium) that volatilize from the steel.

Applied water rates for vacuum degassing are typically around 1,250 gallons per ton of steel, with discharge rates of 25 gallons per ton

Table 6-3. Emission Factors for Casting (lb/ton of steel)						
Source	Particulate	PM <sub>10</sub> <sup>a</sup>	SOx	CO	VOC	NOx
Leaded Steel, Teeming Uncontrolled (measured at source) Controlled by side draft hood vented to baghouse	0.81	0.36	--	--	0.002	--
	0.0038	--	--	--	--	--
Unleaded Steel, Teeming Uncontrolled (measured at source) Controlled by side draft hood vented to baghouse	0.07	0.03	--	--	0.002	--
	0.0016	--	--	--	--	--
Continuous Casting	--	--	--	--	0.0	0.05

a Particulate matter less than 10.0 microns in diameter.

Sources: U.S. Environmental Protection Agency 1995b and 1990.

achieved through high-rate recycle (EPA 1995a). Standard treatment includes processing the total recirculating flow or a portion of the flow in clarifiers for TSS removal, cooling with mechanical draft cooling towers, and high-rate recycle. Blowdowns are usually co-treated with steelmaking and/or continuous casting wastewaters for metals removal. Vacuum degassing plants are often operated as part of ladle metallurgy stations where additional steel refining is conducted (EPA 1995a).

### **Cooling Systems for Continuous Casting Use Large Amounts of Water**

Continuous casters usually include several separate closed-loop cooling water systems. Water use is categorized by function in the casting process:

- primary (mold)
- secondary (spray)
- auxiliary (equipment)

The primary cooling process is the non-contact cooling of the molten steel shell in the mold (or molds on a multi-strand machine). Closed-loop, non-evaporative cooling is primarily employed when high surface and strand quality are required. Secondary or spray cooling occurs as the strand

exits the mold, with contact water sprays covering the surface of the strand. Auxiliary cooling is non-contact or internal cooling of the casting equipment. Direct contact water systems are used for spray cooling and for flume flushing to transport mill scale from the caster runout table (AISE 1999).

Applied water rates for the contact systems are typically about 3,600 gallons per ton of cast product; discharge rates for the better controlled casters are less than 25 gallons per ton (EPA 1995a). For vacuum degassing the applied water rate is 1,400 gallons per ton.

The principal pollutants are total suspended solids, oil and grease, and low levels of particulate metals. As with vacuum degassing, chromium, copper, and selenium may be found in continuous casting wastewater. Wastewater treatment includes settling basins (scale pits) for scale recovery, oil skimmers, straining devices, mixed- or single-media filtration, and high-rate recycle (AISE 1998 and EPA 1995a). As with other contact systems, this system will typically utilize evaporative tower systems for cooling.

Table 6-4 presents the EPA's vacuum degassing and continuous casting effluent limitations using best practicable control technology currently

Table 6-4. Vacuum Degassing and Continuous Casting Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lb of steel)				
Pollutants	Limitation for Vacuum Degassing		Limitation for Continuous Casting	
	BPT	BAT	BPT	BAT
Total Suspended Solids	0.00521	--	0.0260	--
Oil and Grease	--	--	0.0078	--
Lead	--	0.0000313	--	0.0000313
Zinc	--	0.0000469	--	0.0000469

Source: Bureau of National Affairs 1992.

available (BPT) and best available technology economically available (BAT). The BPT for vacuum degassing is assumed to be sedimentation and recycle (98%) for condenser contact cooling waters; the BAT includes lime precipitation, sedimentation and pH control to remove dissolved and particulate toxic metals.

For continuous casting, the BPT limitations assume closed loop cooling for the casting machine and a mold cooling water system; and sedimentation, filtration, cooling, and recycle (96.3%) for spray water (EPA 1995a). There are no effluents associated with ingot casting. The BAT limitations assume increased recycle (99.3%) and recycle system blowdown treatment for spray water comprising metals precipitation and pH control. For both vacuum degassing and casting, the BPT case requires pH to be between 6.0 and 9.0.

## 6.6 Byproducts

### ***Refining Generates Small Amounts of Byproducts***

Wastes resulting from refining processes are very small in comparison to the wastes generated from ironmaking and steelmaking. The more common solid wastes generated include:

- Ladle metallurgy facility and capped argon bubbling APC dust
- Nozzle blockages

The air pollution control dusts from refining are non-hazardous and are either processed and recycled or else landfilled.

In addition, the use of argon oxygen degassing (AOD) generates a slag and dust that are typically disposed of in the same manner as the plant's EAF slag and dust. A 1991 survey sponsored by People's Natural Gas Company found that six of eight steelmakers generating AOD slag processed this waste on-site. In all eight cases, the metal from the slag was recovered and reused in-house. The processed slag was sold as roadbed in six cases; two plants were landfilling the slag.

The survey respondents reported widely varied processing and disposal costs. Processing fees varied from less than \$1 per ton to \$250 per ton. Disposal of slag off-site without prior processing costs between \$20 and \$50 per ton. One plant processed slag on-site and disposed of it off-site for less than \$10 per ton (Burke and Liebman 1993).

### ***Casting Byproducts Include Mill Scale, Sludge***

The major byproducts of continuous casting are scale and sludge. Scale generated during casting and subsequently washed off of the steel is periodically removed from the bottoms of the scale settling basins used for scale collection.

Fine-grained solids that do not settle out in the scale settling basins typically are removed by settling, flocculation/clarification processes or by filtration, depending on the level of water treatment required and the degree of water recycle practiced.

The scale is usually recycled and reused within the mill for sintering at integrated mills that operate sinter plants, or it is sold to such mills (Baker Environmental 1992). Scale may also be

landfilled (particularly by stainless steel producers) or even charged to an electric arc furnace (Burke and Liebman 1993). Sludge generated during continuous casting is either processed and recycled on-site or landfilled.

## **6.7 Hazardous Wastes**

There are no RCRA-listed hazardous wastes associated with refining or casting processes.



# 7

# Forming and Finishing

## 7.1 Process Overview

### ***Steel Shapes Produced Via Hot Forming Operations***

After casting, the slabs, billets, and blooms are further processed to produce strip, sheets, plate, bar, rod, and other structural shapes through various hot forming operations, which are sometimes followed by cold forming operations depending on the final product.

Slabs from the continuous caster are directed to the plate mill or the hot strip mill. Plate products range in thickness from less than one-quarter inch to more than one foot. The products of the hot strip mill include coils and rolled sheets. The output of the thin slab caster passes through a finishing mill or Steckel mill prior to entering the plate or hot strip mill. Blooms and billets are typically sent to mills that produce sections, bar and rod, or seamless tube.

Prior to hot forming, the semi-finished shape must first be heated to rolling temperatures (about 1,800°F to 2,100°F) in a reheat furnace. Both pusher furnaces and more modern walking beam furnaces are used. Upon exiting the furnace, the slabs may undergo a surface preparation step,

scarfing, which removes defects, prior to entering the rolling mill.

The most common hot forming process is hot rolling, where a heated steel slab is passed between two rolls revolving in opposite directions. Each set of rolls produces an incremental reduction in thickness in the slab. A hot strip mill typically contains a roughing mill, where initial reduction is achieved. Surface scale is removed from the heated slab by a scale breaker and water sprays prior to entering this mill. At the end of the roughing section, the steel enters the finishing mill for final reduction, after which it is cooled and coiled or slit.

In the plate mill, the cooled plates undergo cutting and shearing rather than coiling, and then are heat treated. The final shape and characteristics of a hot formed piece depend on the rolling temperature, the roll profile, and the cooling process used after rolling (EPA 1995).

### ***Hot-Rolled Shapes Cleaned in Pickling, Other Finishing Processes***

Finishing processes are used to clean the surface of the semi-finished, hot-rolled steel products prior to cold rolling or forming and/or coating operations. Mill scale, rust, oxides, oil, grease,

and soil are chemically removed from the surface of the steel using solvent cleaners, pressurized water, air blasting, abrasives, alkaline agents, salt baths, or acid pickling.

Salt bath descaling is a finishing process that uses the physical and chemical properties of molten salt baths to remove heavy scale from selected specialty and high-alloy steels. The two salt bath descaling operations are:

- oxidizing (or Kolene™) - removes scale using molten salt baths other than those containing sodium hydride; and
- reducing (or Hydride™) - removes scale using molten salt baths containing sodium hydride.

These two salt bath descaling processes may be either batch or continuous and are conducted prior to combination acid pickling (hydrofluoric and nitric acids).

Acid pickling processes include hydrochloric (the most common process), sulfuric, and combination acid pickling operations to remove oxide scale. Stainless steels are pickled with hydrochloric, nitric, and hydrofluoric acids or a combination of acids.

In continuous pickling processes, the flat rolled coils are welded end-to-end at the start of the line and are cut by torch at the end of the line. The steel is immersed in acid cleaning tanks and then in a series of water rinsing tanks. Alkaline cleaners may also be used to remove mineral oils, grease, and animal fats and oil (used in some rolling solutions) from the steel surface prior to cold rolling. Common alkaline cleaning agents include caustic soda, soda ash, alkaline silicates, and phosphates. After pickling the strip is immediately cold rolled before further oxidation can occur.

### ***Cold Forming Used to Modify Properties of Some Steels***

Steel that has been hot-rolled and pickled may be cold rolled to make a product thinner and smoother, suitable for a variety of uses from car bodies to tin cans. Pipes and tubes may also be

cold worked. Two main types of products are made in the cold mill:

- cold rolled sheets/coils for sale or for further processing in galvanizing and coatings lines; and
- cold rolled coils for subsequent tinning.

A few mills are producing a thin product off the hot mill (known as thin hot rolled strip) as a substitute for cold rolled product where the surface characteristics imparted by cold rolling are not required.

Like hot rolling, cold rolling uses a series of revolving rolls to mechanically reduce the steel's thickness; unlike hot rolling, the steel is processed unheated. Cold rolling hardens the steel, which must then be heated in an annealing furnace to make it more formable.

The annealing process involves heating the strip to about 1,300°F in an inert atmosphere to prevent oxidation, and then allowing it to cool such that the crystal structure of the steel changes. In batch annealing, gas burners are used to indirectly heat stacked coils. In continuous annealing the coils are unwound and passed through an extended furnace. In the case of tinplate, the steel must also be cleaned before it is annealed by passing the strip through a series of chemical baths.

After the steel has been softened in the annealing process, it is typically run through a temper mill to produce the desired flatness, metallurgical properties, and surface finish. Other ancillary processes, including shearing, slitting, and double reduction rolling, may also be performed.

## **7.2 Summary of Inputs/Outputs**

Inputs:    Semi-finished steel shapes (slabs, billets, blooms)  
              Process cooling, rinsing, and cleaning water  
              Pickling acids  
              Molten salts  
              Alkaline cleaners  
              Fuel  
              Electricity



Oxygen  
 Nitrogen  
 Hydrogen

Outputs: Cleaned steel products (e.g., sheets, plates, bars, pipe)  
 Process wastewater containing mill scale, oils, other pollutants, and low levels of metals  
 Wastewater sludge  
 Air pollution control (APC) dust  
 Spent pickle liquor (K062)  
 Spent pickle liquor rinse water sludge

Figure 7-1 illustrates the forming and finishing processes with their major inputs and outputs for steel sheet, a typical steel product.

### 7.3 Energy Requirements

The energy requirements of rolling and finishing processes include fuel used for slab reheating and heat treatment, and electricity used by rolling mills and cooling beds. The electricity requirement of rolling is determined by the initial and final gauges and quality of the steel; for hot rolling, it typically ranges from 0.6 to 1.2 million Btu/ton of steel (IISI 1998). Roll coolant pumps and hydraulic pumps in the cold rolling mill also consume electricity (IISI 1998).

Reheat furnaces are fired on a variety of fuels including natural gas blast furnace gas, coke oven gas, BOF gas, and fuel oil. A modern, efficient reheating furnace in a hot strip mill uses about 1.4 million Btu per ton of steel from cold start to heat slab, whereas an older furnace requires about 1.8 million Btu/ton (McPhail 1999). Efficient reheat furnaces with recuperators, low-NO<sub>x</sub> burners, computer controls for managing firing rates in relations to delays, and other improvements can reduce reheating energy for cold steel to around 1.1 million Btu/ton (Stubbles 2000).

In some flat-rolled EAF facilities, thin slabs are sheared and fed directly from the caster to an in-line tunnel furnace that acts as a buffer ahead of the hot strip mill. These tunnel furnaces have energy consumption in the range of 0.5 to 0.8 million Btu/ton of steel. Total natural gas consumption for reheating operations in the U.S.

steel industry is estimated at about 110 trillion Btu annually (Stubbles 2000).

The energy intensity of heat treating furnaces in the plate mill is on the order of 0.4 million Btu/ton. However, since far less than 100% of plate is typically heat treated, the specific energy consumption of treated plate can be much higher (IISI 1998).

Acid pickling utilizes steam generated from fuel to heat the pickling bath and preheat the incoming strip. Electricity is used to power extraction fans and in acid recovery. Acid recovery plants also use either steam or gas, depending on the type of acid employed (IISI 1998).

Both electricity and fuel are consumed in cleaning and annealing. A modern, hydrogen atmosphere annealing furnace with good recuperation would typically use 0.6 million Btu/ton, while an older furnace with poor recuperation would use about 0.9 million Btu/ton (IISI 1998). The cold rolling process itself consumes between 0.4 and 0.9 million Btu/ton of steel (IISI 1998).

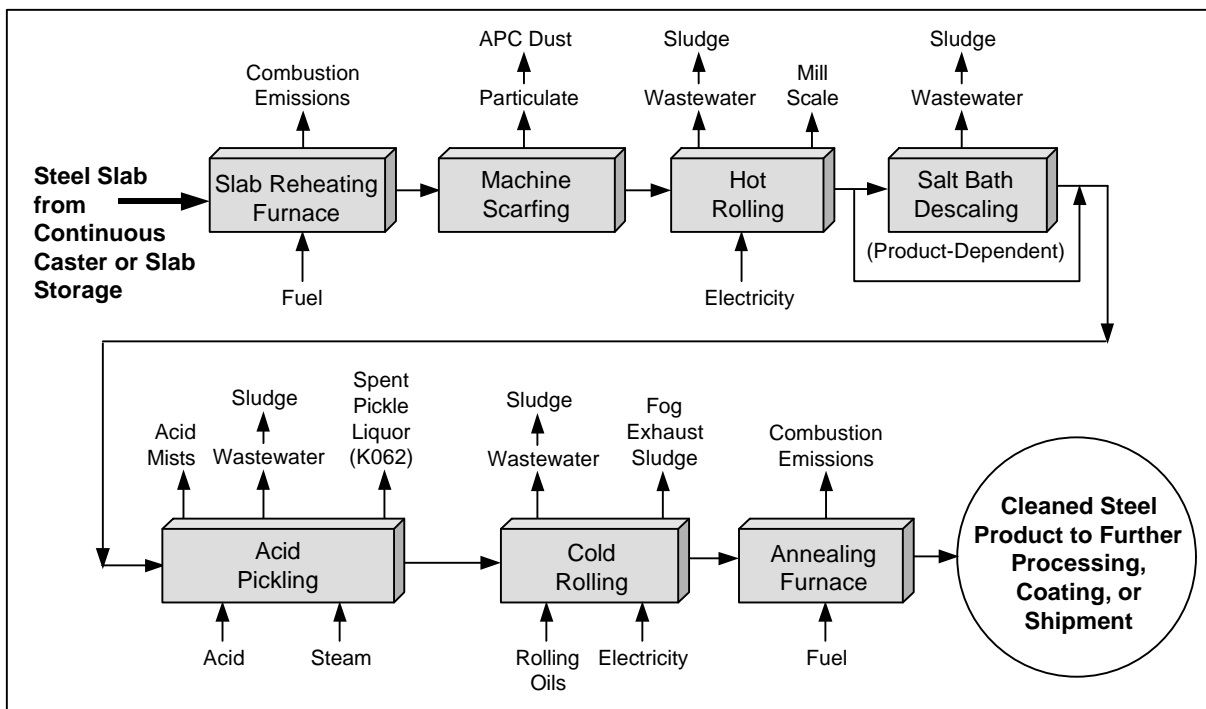
Table 7-1 shows typical energy intensities of slab reheating furnaces, hot rolling, acid pickling, and cold rolling (including annealing).

### 7.4 Emissions

#### *Auxiliary Processes Generate Emissions*

Significant emissions from forming and finishing are limited to only a few operations, including reheat furnaces, scarfing, and pickling. Emissions from reheat furnaces are limited to products of combustion, although these emissions are typically well controlled.

Hand- or machine-scarfing of semi-finished steel to remove surface defects volatilizes the steel at the surface of the slab or other shape, creating a fine iron oxide fume. Emissions from hand-scarfing are localized and in general are minor in comparison to machine scarfing.



<b>Key Energy and Environmental Facts - Forming and Finishing</b>			
<b>Energy</b>	<b>Emissions</b>	<b>Effluents</b>	<b>Byproducts/Hazardous Wastes</b>
<p><i>Energy Use Per Net Ton of Product:</i></p> <p>Reheat Furnace - 1.6 10<sup>6</sup> Btu average; 1.4 10<sup>6</sup> Btu for modern furnaces</p> <p>Hot Rolling - 0.8 10<sup>6</sup> Btu</p> <p>Acid Pickling - 1.2 10<sup>6</sup> Btu</p> <p>Cold Rolling - 0.7 10<sup>6</sup> Btu</p> <p>Cleaning/Annealing - 1.0 10<sup>6</sup> Btu</p>	<p><i>Largest Sources - machine scarfing, hydrochloric acid pickling (acid mists), reheat furnace (NOx)</i></p> <p><i>Particulate - iron and other oxides</i></p> <p><i>Typical Acid Mist Generation - &gt;10 tons/year per facility</i></p>	<p><i>Largest Sources - direct cooling and descaling</i></p> <p><i>Typical Wastewater Volumes (gallons per ton):</i></p> <p>Hot forming - 0 to &gt;6,000</p> <p>Descaling - 300 to 1,800</p> <p>Pickling - 70 to 1,000</p>	<p><i>Mill Scale</i> Total Generation - 3.7 10<sup>6</sup> tons/yr Reuse - most recycled</p> <p><i>Rolling Sludge</i> Total Generation - about 1.0 10<sup>6</sup> tons/yr Reuse - minimal</p> <p><i>K062 - Spent Pickle Liquor</i> Haz. Components - lead, nickel, chromium Total Generation - about 6 million tons/yr Reuse - some recycled</p>

**Figure 7-1. Forming and Finishing Flow Diagram (Sheet Production)**

The major pollutants emitted during scarfing are iron and other oxides (FeO, Fe<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, CaO, and MgO). Machine scarfing operations generally use an electrostatic precipitator or water spray chamber for control; most hand scarfing

operations are uncontrolled (EPA 1995b). Table 7-2 lists the particulate emission factors for machine scarfing, as well as other (small) emission factors associated with forming and finishing processes.

Table 7-1. Average Energy Intensities of Rolling and Finishing Processes (10 <sup>6</sup> Btu/ton of product)						
Fuel	Slab Reheat Furnace	In-line Tunnel Furnace	Hot Rolling <sup>a</sup>	Acid Pickling	Cold Rolling	Cleaning/Annealing
Fuel	1.4 - 1.6	0.7	--	--	0.7	--
Electricity <sup>b</sup>	--	--	0.8	0.8	--	0.9
Steam	--	--	<0.1	0.4	--	<0.1
<b>TOTAL</b>	<b>1.4 - 1.6</b>	<b>0.7</b>	<b>0.8</b>	<b>1.2</b>	<b>0.7</b>	<b>1.0</b>

- a Excludes the reheating furnace.  
b Conversion factor is 10,500 Btu/kWh.

Sources: Stubbles 2000.  
McPhail 1999.  
ISI 1998.  
LBNL 1998.

Table 7-2. Emission Factors for Forming and Finishing (lb/ton of metal processed)						
Source	Particulate	PM <sub>10</sub> <sup>a</sup>	SOx	CO	VOC	NOx
Reheat Furnaces	--	--	0.8	--	0.01	0.8
Machine Scarfing Uncontrolled	0.100	0.100	0.0	--	0.0	0.0
Controlled by ESP	0.023	--	--	--	--	--
Hot Rolling	--	--	--	--	0.08	--
Pickling	--	--	0.0	--	0.0	0.0
Cold Rolling	--	--	--	--	0.56	--

- a Particulate matter less than 10.0 microns in diameter.

Sources: U.S. Environmental Protection Agency 1995b and 1990.

### **Hydrochloric Acid Pickling Emits Acid Mists**

Acid mists are evolved from the hot acid baths used in acid pickling operations. Hydrogen chloride (from hydrochloric acid pickling) is the primary hazardous air pollutant associated with pickling, with emissions from surface pickling typically over 10 tons per year per facility (Marsosudiro 1994).

Control techniques for removing the mists from the exhausted air include packed towers and wet scrubbers. Wet scrubbing has been identified as the control technology achieving MACT floor control level (final MACT standards for hydrochloric acid pickling were promulgated in June 1999). Removal efficiencies in excess of 95% are common for hydrochloric and sulfuric acids; slightly lower efficiencies are achieved with the hydrofluoric acid systems typically used in stainless steel pickling.

## 7.5 Effluents

### **Hot Forming Generates Effluents During Cooling, Descaling**

In hot rolling operations water is used for direct cooling of mill stand work rolls and descaling of steel prior to rolling. It is also used between certain roll stands to maintain steel surface cleanliness, and to transport scale to the scale pits. In finishing operations (i.e., pickling, cold reduction, annealing, temper, cleaner, and coating lines), water is used primarily as non-contact cooling water, solution makeup, and rinse water. Non-contact cooling typically incorporates evaporative cooling towers or closed-loop systems (AISE 1999).

Water use and discharge rates from hot forming operations vary greatly depending upon the type of hot forming mill and the shapes produced. Applied process water rates typically range from 1,500 gallons per ton for specialty plate mills can exceed 6,000 gallons per ton for hot strip mills. Discharge rates can approach zero for mills equipped with high-rate recycle systems. Table 7-3 shows applied process water flow rates and discharge rates for several hot forming categories.

The principal pollutants are total suspended solids, oil, and grease. Low levels of metals -- chromium, copper, lead, nickel, and zinc -- are found in particulate form (EPA 1995a). Cooling and descaling water is normally discharged from the mill into scale pits where the heavier solid particles settle out. The semi-cleaned water is typically sent on to a treatment plant containing straining devices, solids removal, and/or deep bed filtration to remove fine particulate. Wastewater treatment may also include collection of fine mill scale, grease, hydraulic fluids, and rolling oils. The process water is then either recycled back to the mill and/or discharged (Hamling 1996).

Table 7-4 lists the hot forming effluent limitations (average of daily values for 30 consecutive days) using the best practicable control technology currently available (BPT). The effluents are also required to have a pH in the range of 6.0 to 9.0.

Because the EPA has determined that there are not significant quantities of toxic pollutants in hot forming wastewater after compliance with applicable BPT limitations, it has not promulgated more stringent BAT (best available technology economically achievable) limitations.

<b>Subdivision</b>	<b>Applied Flow</b>	<b>BPT Discharge Flow</b>	<b>BAT Discharge Flow</b>
Primary			
Without Scarfer	2,300	897	90
With Scarfer	3,400	1,326	140
Section			
Carbon	5,100	2,142	200
Specialty	3,200	1,344	130
Flat			
Hot Strip	6,400	2,560	260
Carbon Plate	3,400	1,360	140
Specialty Plate	1,500	600	60
Pipe and Tube	5,520	1,270	220

Source: AISE 1999.

Table 7-4. Hot Forming Effluent Total Suspended Solids (TSS) Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lbs of product)	
Hot Forming Operation	BPT Limitation
Primary Mills, Carbon and Specialty Without scarfing With scarfing	0.0561 0.0830
Section Mills Carbon Specialty	0.134 0.0841
Flat Mills Hot strip and sheet mills, carbon and specialty Carbon plate mills Specialty plate mills Pipe and tube mills, carbon and specialty	0.160 0.0851 0.0376 0.0795

Source: Bureau of National Affairs 1992.

The hot forming BPT limitations also are identical to the hot forming BCT (best conventional technology) limitations.

The BPT and BCT cases assume the use of sedimentation and oil skimming, partial recycle of scale pit effluents (61% for primary mills, 58% for section mills, 60% for flat mills, and 77% for pipe and tube mills), clarification and filtration, and sludge dewatering (EPA 1995).

### ***Descaling Effluents Arise During Quenching, Rinsing Processes***

Typical process wastewaters from finishing operations include rinses and spent concentrates from alkaline cleaners, pickling solutions, plating solutions, and electrochemical treating solutions.

Salt bath descaling wastewaters originate from quenching and rinsing operations conducted after processing in the molten salt baths. Process water flow rates for oxidizing operations range from 330 gallons/ton for continuous operations to 700 for batch operations for pipe and tube (AISE 1999). The principal pollutants in these effluents are total suspended solids, cyanides, dissolved iron, hexavalent and trivalent chromium, and nickel. Wastewater flows normally range from 300 to 1,800 gallons per ton, depending upon the

product and process. Descaling wastewaters are usually co-treated with wastewaters from other finishing operations (e.g., combination acid pickling or cold rolling) (EPA 1995a).

Table 7-5 shows the BPT limitations for 30 consecutive days for salt bath descaling effluents. These limitations also require the pH of each of the effluents to be in the range of 6.0 to 9.0. The BPT case assumes that oxidizing salt bath descaling operations utilize reduction of hexavalent chromium, oil skimming, metals precipitation, and sludge dewatering. Reducing descaling operations are assumed to use two-stage chlorination, metals precipitation, and sludge dewatering. The BAT limitations, which exist only for chromium and nickel, are identical to the BPT limitations for these metals.

### ***Acid Pickling Generates Several Effluents, One Considered Hazardous***

Acid pickling discharge water flows for the different pickling processes are

- between 280 and 1,020 gallons/ton for hydrochloric acid processes,
- between 90 and 500 gallons/ton for sulfuric acid processes,

Table 7-5. Salt Bath Descaling Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lbs of product)				
Salt Bath Descaling Operation	BPT Limitation for TSS	BPT/BAT Limitation for Chromium	BPT/BAT Limitation for Nickel	BPT/BAT Limitation for Cyanide
Oxidizing Batch, sheet and plate Batch, rod and wire Batch, pipe and tube Continuous	0.876	0.00117	0.000876	--
	0.0526	0.000701	0.000526	--
	0.213	0.00284	0.00213	--
	0.0413	0.000551	0.000413	--
Reducing Batch Continuous	0.0407	0.000542	0.000407	0.000339
	0.228	0.00304	0.00228	0.00190

Source: Bureau of National Affairs 1992.

- up to 1,500 gallons/ton for combination acid processes (AISE 1999).

Acid pickling wastewaters include spent pickling acids, rinse waters, and pickling line fume scrubber wastewater. Spent pickle liquor is listed as a hazardous waste because it contains considerable residual acidity and high concentrations of dissolved iron salts (see Section 7.7) Pickling done prior to coating may use a mildly acidic bath; such spent liquor is not considered hazardous.

Process water and wastewater flows vary greatly depending upon the product and process. Waste pickle liquor flows typically range between 10 and 20 gallons per ton of pickled product. Rinse water flows may range from less than 70 gallons per ton for bar products to more than 1,000 gallons per ton for certain flat-rolled products. The principal pollutants in rinse water include total suspended solids, dissolved iron, and metals. For carbon steel operations, the principal metals are lead and zinc; for specialty and stainless steels the metals found include chromium and nickel (EPA 1995a).

Table 7-6 gives the BPT effluent limitations for 30 consecutive days for sulfuric, hydrochloric, and combination acid pickling operations. The BAT limitations, which cover lead and zinc for

sulfuric and hydrochloric acid pickling and chromium and nickel for combination acid pickling, are the same as the corresponding BPT limitations. All of the effluents must have a pH in the range of 6.0 to 9.0 under the BPT limitations.

The BPT limitations assume recycle of fume scrubber waters, equalization, oil skimming, metals precipitation, and sludge dewatering. The BAT limitations assume acid regeneration plant absorber vent scrubber recycle and countercurrent cascade pickling rinses.

In-process controls for acid pickling include countercurrent rinsing, use of indirect heating versus direct steam sparging for acid solutions, and recycle and reuse of fume scrubber blowdowns. Some steel mills are equipped with acid recovery or regeneration systems for spent sulfuric and hydrochloric acids, respectively. After elementary neutralization, which raises the pH above 2.0, rinse waters are usually co-treated with wastewaters from cold rolling, alkaline cleaning, hot coating, and electroplating operations (EPA 1995a).

#### **Cold Rolling Effluents May Contain Fats from Rolling Solutions**

Process wastewater from cold forming operations results from using synthetic or animal-fat based rolling solutions, many of which are proprietary.

Table 7-6. Acid Pickling Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lbs of product)						
Pickling Operation	BPT Lim. for TSS	BPT Lim. for O&G	BPT Lim. for Lead	BPT Lim. for Zinc	BPT/BAT Lim. for Chromium	BPT/BAT Lim. for Nickel
Sulfuric Acid						
Rod, wire, & coil	0.0350	0.0117	0.000175	0.000234	--	--
Bar, billet, bloom	0.0113	0.00375	0.0000563	0.0000751	--	--
Strip, sheet, plate	0.0225	0.00751	0.000113	0.000150	--	--
Pipe, tube, other	0.0626	0.0209	0.000313	0.000417	--	--
Fume scrubbers	2.45	0.0819	0.0123	0.0164	--	--
Hydrochloric Acid						
Rod, wire, & coil	0.0613	0.0204	0.000307	0.000409	--	--
Strip, sheet, plate	0.0350	0.0117	0.000175	0.000234	--	--
Pipe, tube, other	0.128	0.0426	0.000638	0.000851	--	--
Fume scrubbers	2.45	0.819	0.0123	0.0164	--	--
Combination Acid						
Rod, wire, & coil	0.0638	0.0213	--	--	0.000852	0.000638
Bar, billet, bloom	0.0288	0.00960	--	--	0.000384	0.000288
Strip, sheet, plate						
Continuous	0.188	0.0626	--	--	0.00250	0.00188
Batch	0.0576	0.0192	--	--	0.000768	0.000576
Pipe, tube, other	0.0964	0.0322	--	--	0.00129	0.000964

Source: Bureau of National Affairs 1992.

The rolling solutions may be treated and recycled at the mill, used on a once-through basis, or a combination of the two. The principal pollutants are total suspended solids, oil and grease (emulsified), and metals -- lead and zinc for carbon steels and chromium and nickel for specialty and stainless steels. Chromium may also be a contaminant from cold rolling of carbon steels resulting from wear on chromium-plated work rolls. Toxic organic pollutants including naphthalene, other polynuclear aromatic compounds, and chlorinated solvents have been found in cold rolling wastewaters (EPA 1995a).

Process wastewater discharge rates may range from less than 10 gallons per ton for mills with recirculated rolling solutions to more than 400 gallons per ton for mills with direct application of rolling solutions (EPA 1995a). Conventional treatment of cold rolling wastewaters includes chemical emulsion breaking, dissolved gas flotation for gross oil removal, and co-treatment with other finishing wastewaters for removal of toxic metals.

Table 7-7 shows the BPT and BAT effluent limitations for 30 consecutive days for various cold forming operations. The BPT limitations also require a pH in the range of 6.0 to 9.0. These limitations assume the use of the following control technologies: primary oil removal, emulsion breaking, dissolved gas flotation, sludge dewatering, and contract hauling of waste rolling solutions for limited applications.

The BAT 30-day-average limitations, which cover chromium, lead, nickel, and zinc, are the same as the BPT limitations for those pollutants and assume use of the BPT technologies.

## 7.6 Byproducts

### *Mill Scale, Sludge Generated in Large Quantities*

The main byproducts associated with forming and finishing are scale (typically iron oxides), an oily sludge that results from lubricating the rolls (water treatment plant sludges), and air

Table 7-7. Cold Forming Effluent Limitations - Average of Daily Values for 30 Consecutive Days (lbs per 1,000 lbs of product)							
Cold Forming Operation	BPT Lim. for TSS	BPT Lim. for O&G	BPT/BAT Lim. for Chromium	BPT/BAT Lim. for Lead	BPT/BAT Lim. for Nickel	BPT/BAT Lim. for Zinc	
Cold Rolling Mills - Recirculation	Single stand	0.000626	0.000209	0.0000084	0.0000031	0.0000063	0.0000021
	Multiple stands	0.00313	0.00104	0.0000418	0.0000156	0.0000313	0.0000104
	Combination	0.0376	0.0125	0.000501	0.000188	0.000376	0.000125
Cold Rolling Mills - Direct Application	Single stand	0.0113	0.00376	0.000150	0.0000563	0.000113	0.0000376
	Multiple stands	0.0501	0.0167	0.000668	0.000250	0.000501	0.000167
Cold Worked Pipe & Tube Using water or oil solutions	0.000626	0.000209	0.0000084	0.0000031	0.0000063	0.0000021	

Source: Bureau of National Affairs 1992.

pollution control dusts associated with treating effluents and cleaning exhaust gases.

Coarse scale is separated from the sludge and collected in scale pits. The sludge, which is produced from the treatment of mill scale pit overflows, consists of oils, greases, and fine-grained solids that are collected in settling basins or other separation equipment.

The quantities of scale generated vary but tend to range between 10 and 80 lbs per ton for non-oily scale (averaging around 55 lbs per ton) and 4 to 60 lbs per ton for oily scale (averaging about 10 to 15 lbs per ton) (Szekely 1995 and IISI 1994). Oil content can range from 1% to 30%. In 1994 approximately 3.7 million tons of scale were produced in the U.S. (Hamling 1996 and Kolarik 1996). According to AISI data, approximately one million tons of rolling sludge is generated each year (Edgar 1996).

### **Scale Contains Valuable Iron Units**

Scale is usually sold or recycled and reused within the plant (usually for sintering), although recycling the oily scale without first de-oiling it may

cause problems with the opacity of the gaseous stream emitted from the plant or other operational problems.

The quantity of oily sludge produced is less than the quantity of scale produced. This sludge cannot typically be added to the sinter plant because of opacity problems. A number of sludge treating processes are used to de-oil fine sludges to as low as 0.1% at a reasonable cost (Weidner 1993). However, most oily sludge (containing more than 3% oil) is landfilled rather than recycled.

Hot rolling mills (but not cold rolling mills) have air pollution control equipment that collects dust/particulate. The dust is generated in scarfing, a method of surface treatment in which the surface layer of steel is burned off to remove imperfections. This dust is typically landfilled but can also be recycled to sinter plants.

### **Cold Rolling Generates Oily Sludge**

Unlike hot rolling, no scale is formed during cold rolling or reduction operations. However, much greater rolling pressures are required to form the metal, generating considerable heat that must be



dissipated by a system of flood lubrication. Lubricants applied to the product being rolled must serve the dual purpose of lubricating and cooling.

The water treatment plant sludge for cold rolling therefore contains more oil and grease, which are recovered for subsequent reuse (e.g., as a fuel) or recycle rather than for disposal. Solid waste generation in finishing facilities typically consists of central treatment plant (CTP) sludge. This metallic sludge, which contains fine grained iron oxide, can be further dewatered by mechanical filtration or by use of sludge drying beds.

The dewatered sludge is typically landfilled. The treatment of finishing facility effluents also generates both insoluble and soluble oils, which can be processed and sold for reuse (Baker Environmental 1992).

Another byproduct associated with cold rolling is fog exhaust sludge generated from the mist or fog produced during cold rolling. Fog exhaust systems are utilized to allow continuous observation of the strip during processing. Airborne particulates combine with steam and oil mist generated during cold rolling and are discharged to a settling chamber. The settled material is a sludge that is generally landfilled (Baker Environmental 1992).

## 7.7 Hazardous Wastes

### ***Lead, Nickel, Chromium Render Spent Pickle Liquor Hazardous***

Spent pickle liquor is considered a hazardous waste (K062) because it contains considerable residual acidity and high concentrations of dissolved iron salts. For example, spent pickle liquor and waste acid from the production of stainless steel is considered hazardous.

The hazardous constituents in K062 are lead, nickel, and hexavalent chromium. Table 7-8 shows the average concentration of these constituents (and other metals) in K062. Table 7-9 lists the maximum allowable concentration of these constituents for land disposal of K062.

Waste pickle liquor sludge generated by lime stabilization of spent pickle liquor is not considered hazardous unless it exhibits one or more of the characteristics of hazardous waste (RCRA 40 CFR 261.3(c)(2)(ii)(A)).

### ***Some Spent Pickle Liquor Reused or Recycled***

An estimated 6 million tons of spent pickle liquor are generated annually in the United States (Environmental Law Institute 1997). According to a 1996 workshop, spent pickle liquor is generated at approximately 240 plants. EPA estimates that these plants generate a total of close to 1,400 million gallons of spent pickle liquor annually as follows:

- sulfuric acid - 500 million gallons
- hydrochloric acid - 800 million gallons
- mixed acids - 74 million gallons

About half of spent pickle liquor is managed for recovery of iron, chromium, and nickel (EPA 1995). Metals recovery treatment options include shipping off-site to a high temperature metals recovery (HTMR) facility or processing on-site using chemical precipitation or other techniques.

Spent pickle liquor is generally sold as treatment aids for municipal and centralized wastewater treatment systems or as a replacement for ferric chloride solution used in the manufacture of fine ferric oxide powder. This waste can also be discharged or landfilled in a non-hazardous waste landfill once it is neutralized with lime and "delisted," or it can be injected into deep wells.

EPA estimates that 40% of mills using sulfuric acid treat and then dispose of the wastes to receiving bodies of water. Another 45% have the spent liquor hauled off site by private contractors, who treat the waste with lime stabilization or other methods, and then dispose of it in landfills or lagoons. The remaining 15% of mills use deep water injection, discharge the waste to a publicly owned treatment works, or engage in acid recovery (Environmental Law Institute 1997).

<b>Table 7-8. Average Concentration of Metals in Spent Pickle Liquor</b>	
<b>Element</b>	<b>Total Concentration (ppm)</b>
Cyanide	4.6
Arsenic	5.8
Cadmium	0.43
Chromium	
Total	12,400
Hexavalent	19
Trivalent	6,690
Lead	1,500
Nickel	10,450

Source: Krishnan et.al. 1993.

<b>Table 7-9. Maximum Allowable Constituent Concentrations in K062 for Land Disposal (mg/l)</b>		
<b>Regulated Hazardous Constituent</b>	<b>Concentration in Wastewaters</b>	<b>Concentration in Non-Wastewaters<sup>a</sup></b>
Chromium (total)	2.77	0.88
Lead	0.69	0.37
Nickel	3.98	N/A

a Based on the Toxicity Characteristic Leaching Procedure (TCLP).

Source: Bureau of National Affairs 1995.

It has been estimated that approximately 80% of spent pickle liquor industry-wide was either recycled through acid regeneration plants or used in municipal wastewater treatment (Hamling 1996). However, the Environmental Law Institute estimated in 1997 that only 2% of spent pickle liquor is reclaimed and reused, and a small amount reused in publicly owned treatment works and other industries.

Although economic factors contribute to the practicality of reclamation, a major barrier to the reclamation and reuse of spent pickle liquor is the definition of waste under RCRA. This definition precludes reclaimed wastes such as spent pickle liquor from qualifying under the recycling exemption to RCRA, and requires RCRA treatment of spent pickle liquor reclamation (Environmental Law Institute 1997).

# References

- Al-Samadi, R.A. 1998. Overview of state-of-the-art water treatment technologies. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- American Iron and Steel Institute (AISI). 2000. American Iron and Steel Institute Web Site <<http://www.steel.org>>. (March).
- American Iron and Steel Institute (AISI). 1999. *Annual Statistical Report 1998*.
- American Iron and Steel Institute (AISI). 1999a. American Iron and Steel Institute Web Site <<http://www.steel.org>>. (June).
- American Iron and Steel Institute (AISI). 1999b. Public Policy Statements. 1999-2000. 106<sup>th</sup> Congress.
- American Iron and Steel Institute. 1998. *Annual Statistical Report 1997*.
- American Iron and Steel Institute. 1998. News Release: *Steel Industry Says Developing Nations Must Be Included If Global Treaty Is to Succeed* (November 13).
- American Iron and Steel Institute. 1996. Survey of consumption of energy in the iron and steel industry for 1996 and previous years (unpublished).
- American Iron and Steel Institute. 1995. *Annual Statistical Report 1994*.
- American Iron and Steel Institute. 1993. Pollution prevention activities write-up for the Steel Pollution Prevention Work Group.
- American Iron and Steel Institute. 1991. *AISI Legislative Position - Clean Water Act*.
- American Iron and Steel Institute. 1988. *Annual Statistical Report 1987*.
- American Iron and Steel Institute and Steel Manufacturers Association. 1998. *Steel Technology Roadmap*. (March).
- Anderson, S.H., H.D. Goodfellow, and E.J. Evenson. 1998. EAF optimization increases productivity while reducing pollution and production costs. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.

- Argonne National Laboratory. 1994. *Vintage-Level Energy and Environmental Performance of Manufacturing Establishments*, ANL/DIS/TM-15. U.S. Department of Energy.
- Argonne National Laboratory. 1982. *Energy and Materials Flows in the Iron and Steel Industry*. U.S. Department of Energy.
- Arthur D. Little, Inc. 1993. *Electric Arc Furnace Dust - 1993 Overview*. CMP Report No. 93-1 (July). EPRI Center for Materials Production.
- Association of Iron and Steel Engineers (AISE). 1999. The Making, Shaping, and Treating of Steel: Ironmaking Volume. 11<sup>th</sup> Edition. D. Wakelin, editor
- Association of Iron and Steel Engineers (AISE). 1998. The Making, Shaping, and Treating of Steel: Steelmaking and Refining Volume. 11<sup>th</sup> Edition. R.J. Fruehan, editor.
- Baker Environmental, Inc. 1992. *Report on Steel Industry Waste Generation, Disposal Practices, and Potential Environmental Impact*. American Iron and Steel Institute.
- Barker, J.E. 1990. Letter to Linda Stuntz, Deputy Undersecretary, Policy, Planning and Analysis, U.S. Department of Energy (July 31).
- Barnett, D. 1998. Personal communication.
- Bechak, C. 1996. Personal communication (May).
- Bechak, C. 1995. *Will Scrap Shortages Affect the Growth of the Electric Furnace Industry?*
- Bouman, R.W. 1983. Energy requirements for ironmaking and steelmaking. *Iron and Steel Maker* (January).
- Bowman, B. 1995. Performance comparison update—A-C vs D-C furnaces. *Iron and Steel Engineer* (June).
- Boyd, G., S.H. Karlson, M. Niefer, and M. Ross. 1993. Energy intensity improvements in steel minimills. *Contemporary Policy Issues* 9 (July).
- Brown, H.L., B.B. Hamel, and B.A. Hedman. 1985. *Energy Analysis of 108 Industrial Processes*. U.S. Department of Energy.
- Bureau of National Affairs. 1995. Resource conservation and recovery act. *Environment Reporter*, 40 CFR 268 (March).
- Bureau of National Affairs. 1992. *EPA Effluent Guidelines and Standards for Iron and Steel Manufacturing*, 40 CFR 420.
- Burke, L. and M. Liebman. 1993. Steel production by-product wastes - a regional perspective. In *12th PTD Conference Proceedings*.
- Cairns, C.J. et al. 1998. *Energy Use in the Steel Industry*. International Iron and Steel Institute, Committee on Technology.
- Carmichael, K.R. and J.R. Carson. 1998. Process reduction of volatile organic compound emissions at a steel mill sinter plant. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Carson, J.R. and K.R. Carmichael. 1998. Heat recovery coke-making: minimizing environmental impact. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Darnall, R.J. 1994. Challenges facing the steel industry. *Iron and Steel Engineer* (September).

- DPRA Incorporated. 1992. *Cost and Economic Impact Analysis of Listing Hazardous Wastes K141-K145, K147, and K148 from the Coke By-products Industry*, CBPF-S0003. U.S. Environmental Protection Agency.
- Edgar, B. 1996. Comments on the *AISI Technology Roadmap for Steel Plant By-Product Residue Recycling*. Prepared for the U.S. Department of Energy.
- Energy Information Administration. 1997. *Manufacturing Consumption of Energy in 1994*. DOE/EIA-0512(94).
- Energy Information Administration. 1995. *Annual Energy Review 1994*. DOE/EIA-0384(-94).
- Environmental Law Institute. 1997. *Proceedings of the Workshop on Spent Pickle Liquor* (December 3, 1996).
- Electric Power Research Institute Center for Materials Production. 1995. *Microwave Separation of Oil-Water Sludges, Part 2: Application to Polymer-Treated Sludges* (October).
- Featherstone, W.B. and K.A. Holliday. 1998. Slag treatment improvement by dry granulation. *Iron and Steel Engineer* (July).
- Federal Register*. Volume 64, Number 109. June 8 1999, pp 30664-30688.
- Fenton, M. 1998. Iron and steel. *Mineral Industry Surveys, 1997 Annual Review*. U.S. Geological Survey, U.S. Department of the Interior.
- Fenton, M. 1998. Iron and steel scrap. *Mineral Industry Surveys, 1997 Annual Review*. U.S. Geological Survey, U.S. Department of the Interior.
- Frema, F. and B. Hong. 1999. U.S. Coal Supply and Demand: 1998 Review. U.S. Energy Information Administration.
- Fruehan, R.J. et al. 2000. *Theoretical Minimum Energies to Produce Steel for Selected Conditions*. Prepared for the U.S. Department of Energy, Office of Industrial Technologies.
- Fruehan, R.J. 1999. Personal communication.
- Glanders, G.A. 1998. EPA proposes new MACT standard for HCl pickling. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Goodwill, J.E. 1998. Changes in technology and the impact on steel industry electrical consumption. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Goodwill, J.E., R.J. Schmitt, and D.A. Purta. 1996. New developments in microwave treatment of steel mill sludges. *Iron and Steel Engineer* (February).
- Goodwill, J.E. 1994. *An Update on Electric Arc Furnace Dust Treatment in the United States*. EPRI Center for Materials Production.
- Grieshaber, K.W., C.T. Philip, and G.F. Bennett. 1994. Process for recycling spent potliner and electric arc furnace dust into commercial products using oxygen enrichment. *Waste Management*. 14:3-4.
- Haissig, M. 1998. *EAF Technology Beyond the Year 2000*. Presented at ISC '98, Linz, Austria (May).
- Hamling, J. and B. Kolarik. 1996. *AISI Technology Roadmap for Steel Plant By-product Residue Recycling*. U.S. Department of Energy.

- Heard, R.A. and Roth, J.-L. 1998. Optimizing energy in electric furnace steelmaking. *Iron and Steel Engineer* (April).
- Heyd, L.D. 1998. Strategic planning for the new particulate matter (PM2.5) and ozone standards. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Hogan, W. and F. Koelble. 1996. "Steel's coke deficit: 5.6 million tons and growing," *New Steel* (December).
- International Iron and Steel Institute. 2000. International Iron and Steel Institute Web Site <<http://worldsteel.org>>. (March).
- International Iron and Steel Institute. 1998. *Energy Use in the Steel Industry* (September).
- International Iron and Steel Institute. 1997. *Coke and Its Alternatives*. IISI Committee on Raw Materials.
- International Iron and Steel Institute. 1994. IISI survey of ferruginous iron and steelmaking by-products. *Steel Times* (November).
- Iron & Steelmaker*. 1999. Blast Furnace Roundup (August).
- Iron & Steelmaker*. 1999a *EAF Roundup* (May).
- Iron & Steelmaker*. 1999b. International Iron and Steel Institute Production Statistics (March).
- Isenberg-O'Loughlin, J. 1995. Ironing it out. *Metalproducing* 33 (May).
- Jones, J.A.T. 1998. Carbon utilization in the EAF: friend or foe? In *1998 Electric Furnace Conference Proceedings*.
- Jones, J.A.T. 1995. Interactions between electric arc furnace operations and environmental concerns. *Iron and Steel Engineer* (December).
- Joseph, T.J. and R.S. Mendt. 1998. Fully integrated steel mills and air quality permitting. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Kalyoncu, R. 1998. Slag – iron and steel. *Mineral Industry Surveys, 1997 Annual Review*. U.S. Geological Survey, U.S. Department of the Interior.
- Klessner, D.E. 1991. *Overview of Scrap Preheating Technologies*. EPRI Center for Materials Production.
- Kolarik, B. 1996. *AISI Technology Roadmap for Steel Plant By-Product Residue Recycling, Electric Arc Furnace*.
- Krishnan, E.R., P.W. Utrecht, A.N. Patkar, J.S. Davis, S.G. Pour, and M.E. Foerst. 1993. *Recovery of Metals from Sludges and Wastewaters*. Noyes Data Corporation.
- Lawrence Berkeley National Laboratory. 1998. Unpublished analysis of the iron and steel industry.
- McPhail, P. 1999. Personal communication.
- Marsosudiro, P.J. 1994. *Pollution Prevention in the Integrated Iron and Steel Industry and Its Potential Role in MACT Standards Development*, 94-TA28.02. U.S. Environmental Protection Agency.
- Martocci, A.P. 1995. *Energy: Consumption, Cost and Conservation in the Steel Industry*. Presented at the U.S. Department of Energy (June 13).

- Maysilles, J.H. 1998. EPA air toxics regulations for the metals industry: a status report. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Minerals Information Team. 1998. Recycling – metals. *Mineral Industry Surveys, 1997 Annual Review*. U.S. Geological Survey, U.S. Department of the Interior.
- Montauben van Swijndregt, J. 1983. Energy and the steel industry. *Iron and Steel Maker* (February).
- Mulrine, P. 1995. Unpublished information on emissions and controls for iron and steel mills, collected by the U.S. Environmental Protection Agency.
- Natural Gas Applications in Industry. 1993. *Oxy/Natural Gas Is Coming On Strong*.
- Nelson, D., P. Scheff, and C. Keil. 1991. *Characterization of Volatile Organic Compounds Contained in Coke Plant Emissions*. Presented at the 84th Annual Meeting & Exhibition of the Air & Waste Management Association (June).
- Nelson, J.G., P.D. Debski, and A.C. Larson. 1998. The conceptual design of waste heat recovery facilities and emission control systems for direct reduced iron rotary hearth furnaces. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Nilles, P.E. 1994. Alternative technologies in iron and steelmaking. In *1994 Ironmaking Conference Proceedings*.
- Oak Ridge Associated Universities. 1980. *Industrial Energy Use Data Book*. U.S. Department of Energy.
- Oxy/natural gas is coming on strong. 1993. *Natural Gas Applications in Industry* (Summer).
- Peters, A.T. 1991. *The Effects of the Clean Air Act Amendment of 1990 on the U.S. Coke and Steel Industry and Foreign Trade Balance*. U.S. Department of the Interior, Bureau of Mines (September).
- Robertson, S. 1994. Cleaning up big steel. *New Steel* (September).
- Rohaus, D. 1996. Handout materials from the *Basic Reheat Furnace Seminar* (September). American Iron and Steel Institute.
- Rupnow, M.R., S.E. Shelby, Jr., and A. Singh. 1998. New water treatment process for a coke plant. *Iron and Steel Engineer* (January).
- Schmitt, R. 1996. Comments on DOE/OIT *Steel Industry Technology Roadmap*. EPRI Center for Materials Production.
- Schuepphaus, K. and M. Platts. 1994. Improvement of ammonia removal, the first step to a future desulfurization. In *1994 Ironmaking Conference Proceedings*.
- Sharkey, A.G. 1994. *Steel Holds the Competitive Edge in an Increasingly "Green" Marketplace*. American Iron and Steel Institute.
- Steel Recycling Institute. 1998. *Facts About Steel—North America's #1 Recycled Material* (fact sheet).
- Steiner, B.A. 1998. Climate change policy and the U.S. steel industry. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.

- Steiner, B.A. 1998. Presentation at AISI. October 7.
- Steiner, B.A. 1996. Personal communication (May).
- Steiner, B.A. 1995. Letter to G. Jett of the U.S. Environmental Protection Agency -- comments on *Draft Iron and Steel Regulatory Review for Effluent Limitations Guidelines and Standards for the Iron and Steel Manufacturing Point Source Category* (June 30).
- Steiner, B.A. 1994. *Environmental Issues Facing the Steel Industry*. American Iron and Steel Institute.
- Steiner, B.A. 1993. Letter to Jeffrey Dowd, U.S. Department of Energy, Office of Energy Demand Policy (June 2).
- Steiner, B.A. 1991. *The Impact of the 1990 Clean Air Act Amendments on the Iron and Steel Industry*. Presented at the Annual Convention of the Association of Iron and Steel Engineers (September).
- Steiner, B.A. 1976. Air-pollution control in the iron and steel industry. *International Metals Reviews* (September).
- Stuart, L.M. 1994. *Innovative Coke Oven Gas Cleaning System*. U.S. Department of Energy (May 27).
- Stubbles, J. 2000. *Energy Use in the U.S. Steel Industry: An Historical Perspective and Future Opportunities*, prepared for the U.S. Department of Energy, Office of Industrial Technologies.
- Stubbles, J. 1999. A Retrospective of the North American Steel Industry. *Iron & Steelmaker* (April).
- Szekely, J. 1995. A research program for the minimization and effective utilization of steel plant wastes. *Iron and Steel Maker* (January).
- Szekely, J. 1995a. *Steelmaking and Industrial Ecology: Is Steel a Green Material?* The 1995 Yukawa Memorial Lecture (April).
- UEC Environmental Systems, Inc. 1993. *Compilation and Evaluation of NO<sub>x</sub> Emission and Control Technology Data from AISI Member Companies*.
- U.S. Department of Commerce. 1994. *Pollution Abatement Costs and Expenditures, 1993*, MA200(93)-1 (December).
- U.S. Department of Commerce. 1994. *U.S. Industrial Outlook 1994*.
- U.S. Department of Energy, Office of Industrial Technologies. 1994. *Hydrochloric Acid Recovery Systems for Galvanizers and Steel Manufacturers* (NICE<sup>3</sup> fact sheet), DOE/CH10093-233.
- U.S. Department of the Interior. 1998. Mineral Industry Surveys. Slag - Iron and Steel. 1997 Annual Review.
- U.S. Environmental Protection Agency. 1998. *1996 Toxic Release Inventory Public Data Release Report*.
- U.S. Environmental Protection Agency. 1998a. Iron and steel chapter of *Sector Notebook Data Refresh - 1997*.
- U.S. Environmental Protection Agency. 1998b. National ambient air quality standards for particulate matter: final rule, 40 CFR Part 50. *Federal Register - Rules and Regulations* 63:24 (February 5).
- U.S. Environmental Protection Agency. 1995. *Profile of the Iron and Steel Industry*, EPA 310-R-95-005.
- U.S. Environmental Protection Agency. 1995a. *Draft Iron and Steel Regulatory Review, 40 CFR Part 420, Effluent Limitations Guidelines and Standards for the Iron and Steel Manufacturing Point Source Category*.



- U.S. Environmental Protection Agency. 1995b. *Compilation of Air Pollutant Emission Factors, Vol. I: Stationary Point and Area Sources*, AP-42. 5th ed.
- U.S. Environmental Protection Agency. 1994. *Report to Congress on Metal Recovery, Environmental Regulation & Hazardous Waste*, EPA530-R-93-018.
- U.S. Environmental Protection Agency. 1993. *National Air Pollutant Emission Trends, 1900-1992*, EPA-454/R-93-032.
- U.S. Environmental Protection Agency. 1992. *Federal Register, Part III* (August 18).
- U.S. Environmental Protection Agency. 1990. *AIRS/Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants*, EPA 450/4-90-003.
- U.S. Environmental Protection Agency. 1990a. *Report to Congress on Special Wastes from Mineral Processing - Summary and Findings*, PB90-258492.
- U.S. Environmental Protection Agency. 1988. *Air Emissions Species Manual Volume I: Volatile Organic Compound Species Profiles* (April).
- U.S. Environmental Protection Agency. 1988a. *Final BDAT Background Document for K061* (August).
- van Rij, P.W., B. Campenon, and J.N. Mooij. 1997. Dezincing of steel scrap. *Iron and Steel Engineer* (April).
- von Oppenfeld, R.R., D.R. Brenden, and E.L. Hiser. 1998. Permit exemption strategies for onsite waste processing facilities. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Weidner, T.H. and J.D. Lynn. 1993. *Integrated Plant-wide Waste Management Planning*. Presented at the Conference on Pretreatment and Reclamation of Dusts, Sludges, and Scales in Steel Plants (May).
- Whitaker, J.B. 1998. Potential impact of the Great Lakes Water Quality Initiative on the metals industry. In *Environmental Innovations in the Metals Industry for the 21<sup>st</sup> Century: Proceedings of a Specialty Conference Cosponsored by the Air & Waste Management Association*.
- Winter, D. 1994. Steel hangs tough. *Ward's Auto-World* (September).
- World Energy Council. 1995. *Efficient Use of Energy Utilizing High Technology, An Assessment of Energy Use in Industry and Buildings* (September).
- Worrell, E., Martin, N., and L. Price. 1999. *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Iron and Steel Sector*. Lawrence Berkeley National Laboratory (January).
- Worrell, E. 1995. Advanced technologies and energy efficiency in the iron and steel industry in developing countries. Submitted to *Energy for Sustainable Development*. Unpublished draft.
- Worrell, E. 1995. Energy efficient technologies in the iron and steel industry. Appendix to *Efficient Use of Energy Utilizing High Technology, An Assessment of Energy Use in Industry and Buildings*. World Energy Council.
- Worrell, E. 1994. *Potentials for Improved Use of Industrial Energy and Materials*. CIP-Gegevens Koninklijke Bibliotheek. Den Haag, Netherlands.

Worrell, E., R.F.A. Cuelenaere, K. Blok, and W.C. Turkenburg. 1994. Energy consumption by industrial processes in the European Union. *Energy* 19:11.

Wrona, L.M. and G. Julien. 1997. Pollution prevention in the steel industry—toward a zero waste plant. *Iron and Steel Engineer* (June).

Zunkel, A.D. and R.J. Schmitt. 1996. Review of electric arc furnace dust treatment regulations and processes. In *Proceedings of the CMP Electric Arc Furnace Dust Treatment Symposium V* (January). CMP Report No. 96-3.