DOE F 241.3
(2-01) p. 1 of 4

ANNOUNCEMENT

UNITED STATES DEPARTMENT OF ENERGY (DOE)
Scientific and Technical Information (STI) For Financial
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OMB Control No.
1910-1400

PART I: STI PRODUCT DESCRIPTION
(To be completed by Recipient/Contractor)

A. STI Product Identifiers

1. REPORT/PRODUCT NUMBER(s)
None

2. DOE AWARD/CONTRACT NUMBER(s)
DE-FC36-01ID14209

3. OTHER IDENTIFYING NUMBER(s)
MTU #010236, E21710

B. Recipient/Contractor
Michigan Technological University, Houghton, MI

C. STI Product Title
Final Technical Report

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E. STI Product Issue Date/Date of Publication
03/28/2005 (mm/dd/yyyy)

F. STI Product Type *(Select only one)*

☒ 1. TECHNICAL REPORT
☒ *Final* ☐ *Other (specify)*

☐ 2. CONFERENCE PAPER/PROCEEDINGS
Conference Information (title, location, dates)

☐ 3. JOURNAL ARTICLE
a. TYPE: ☐ *Announcement Citation Only*
☐ *Preprint* ☐ *Postprint*
b. JOURNAL NAME
c. VOLUME *d. ISSUE*
e. SERIAL IDENTIFIER (e.g. ISSN or CODEN)

☐ OTHER, SPECIFY

G. STI Product Reporting Period (mm/dd/yyyy)
09/24/2001 *Thru* 12/31/2004

H. Sponsoring DOE Program Office
Golden Field Office

I. Subject Categories *(list primary one first)*
32: Energy Conservation, Consumption, and Utilization
Keywords
Steelmaking, microwave energy

J. Description/Abstract
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DOE F 241.3
(2-01) p. 2 of 4

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Section J. Description/Abstract

Steel is a basic material broadly used by perhaps every industry and individual. It is critical to our nation's economy and national security. Unfortunately, the American steel industry is losing competitiveness in the world steel production field. There is an urgent need to develop the next generation of steelmaking technology for the American steel industry.

Direct steelmaking through the combination of microwave, electric arc, and exothermal heating is a revolutionary change from current steelmaking technology. This technology can produce molten steel directly from a shippable agglomerate, consisting of iron oxide fines, powdered coal, and ground limestone. This technology is projected to eliminate many current intermediate steelmaking steps including coking, pellet sintering, blast furnace (BF) ironmaking, and basic oxygen furnace (BOF) steelmaking. This technology has the potential to a) save up to 45% of the energy consumed by conventional steelmaking; b) dramatically reduce the emission of CO_2, SO_2, NO_x, VOCs, fine particulates, and air toxics; c) substantially reduce waste and emission control costs; d) greatly lower capital cost; and e) considerably reduce steel production costs. This technology is based on the unique capability of microwaves to rapidly heat steelmaking raw materials to elevated temperature, then rapidly reduce iron oxides to metal by volumetric heating. Microwave heating, augmented with electric arc and exothermal reactions, is capable of producing molten steel. This technology has the components necessary to establish the "future" domestic steel industry as a technology leader with a strong economically competitive position in world markets.

The project goals were to assess the utilization of a new steelmaking technology for its potential to achieve better overall energy efficiency, minimize pollutants and wastes, lower capital and operating costs, and increase the competitiveness of the U.S. steel industry. The objectives associated with this goal were to a) generate a solid base of technical, marketing, economic, and policy data, b) develop energy, environmental, and economic targets, c) more definitively assess opportunities and barriers, d) accumulate knowledge and experience for defining direction for the next phase of development, and e) promote learning and training of students.

This project consisted of seven tasks:

Task 1 Direct Steelmaking Tests and Technology Assessment
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Task 6 Marketing and Economic Assessments
Task 7 Evaluation of Policies, Regulations, and Affected Agencies

After three years of successful investigation by Michigan Technological University's multi-disciplinary team, with assistance from steel companies, equipment suppliers, an engineering firm, and iron ore mining companies, the following accomplishments have been achieved.

- Successfully designed, built and continuously modified the world's first bench-scale MW/EAF furnace capable of producing molten steel from iron ore agglomerate in 15-30 minutes

- Successfully conducted a great number of steelmaking tests using this bench-scale MW/EAF furnace and a single mode microwave furnace. The produced steels were of good quality. Operation parameters and relationships among possible influencing factors have been established.

- A series of steelmaking tests were successfully conducted and have proven the technical feasibility, simplicity and extremely low equipment cost on the bench-scale level.

- The potential industry applications of this technology have been better defined based on the experiences and knowledge gained from the project.

- A solution has been found to build large MW/EAF steelmaking systems for industrial operations at low capital cost with present manufacturing technologies and capabilities.

- A general picture of potential changes in worker environment, and steel company and material supplier interaction and logistics has been established.

- A theoretical energy analysis and energy consumption calculation based on the best steelmaking test show a great potential for energy savings with this new steelmaking technology.

- Gas analyses on the off-gas generated during MW/EAF bench-scale steelmaking tests have shown no emission problems. The potential environmental benefits have been estimated.

- The marketing assessment identified a marketing strategy for this technology's commercialization.

- The economic assessment on this technology conduced by an experienced steelmaking engineering firm has shown great reductions in capital cost and operating cost.

- The study of policies, regulations and affected agencies did not find obstacles for implementation of this technology.

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FINAL TECHNICAL REPORT

Novel Direct Steelmaking By Combining Microwave, Electric Arc, and Exothermal Heating Technologies

DE-FC36-01ID14209

Project Period: September 2001 through December 2004
Submitted: March 31, 2005

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External Contributors: Noramco Engineering Corporation, Cleveland-Cliffs Inc., U.P. Steel, Cober Electronics, US Steel, and UP Fabricating Company

Acknowledgment: This report is based upon work supported by the U.S. Department of Energy under Award No. DE-FC36-01ID14209.

TABLE OF CONTENTS

Page

LIST OF APPENDICES

LIST OF FIGURES

Page

LIST OF TABLES

Page

EXECUTIVE SUMMARY

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INTRODUCTION

The American steel industry is vital to our economy and national security. Unfortunately, the industry is losing competitiveness in the world steel production. In the last several years, more than 30 steel companies have claimed bankruptcy, including long time giants such as LTV, Bethlehem, National, Weirton, Rouge, etc. Domestic steel production has shrunk from 130 million tons in 1976 to 90 million tons in 2003, while world steel production increased from 533 million tons in 1976 to 960 million tons in 2003. Currently, the U.S. is one of the largest importers of steel in the world, importing about 30 million tons per year. Our steel industry is no longer competitive in the world market. The shortage of steel and the recent skyrocketing prices have left many industries that utilize steel in desperation.

The U.S. government and the industry have realized the need to develop the next generation steel production technology. In 2001, the U.S. Department of Energy issued a RFP to look for the technology which would meet its technical feasibility, energy efficiency, cost savings, environmental goals, and eliminate the use of coke. Novel direct steelmaking by combining microwave, electric arc and exothermal heating technologies was selected as one of candidates.

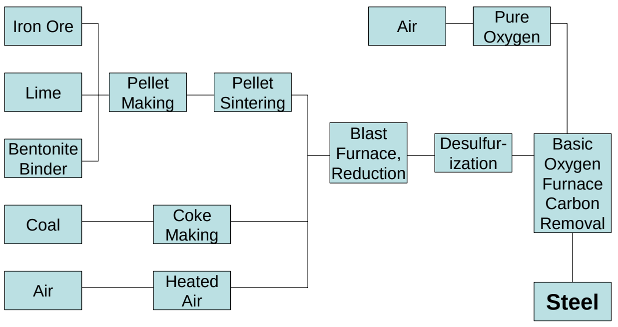
The steel produced in the U.S. comes from two types of operations: integrated mills and minimills. Integrated mills utilize a blast furnace (BF) to produce liquid iron from iron ore and then remove excessive carbon in liquid iron in a basic oxygen furnace (BOF) to produce high quality but expensive steel. Minimills employ electric arc furnaces (EAF) to melt steel scrap with DRI (Direct Reduced Iron) and produce generally lower quality but lower cost steel. The aging domestic integrated steel mills’ processes require the use of expensive, polluting coke, and will require huge investments to update their equipment. Integrated mills are losing market share to the minimills, and account for about 50% of the 90 million tons of domestic production.

The primary technical barrier for the U.S. steel industry is how to reduce iron oxide to iron with coal instead of coke or reformed gas in an efficient, economical and environmentally friendly way. Environmental regulations and high cost have caused the shut down of more than half of the domestic coke batteries (from 179 in 1979 to 78 in 1996), forcing the use of expensive imported coke (coke price has increased from $80 to $300-400/ton). Minimills traditionally enjoyed an abundant supply of domestic steel scrap; however, the recent strong demand for scrap internationally has doubled the price. DRI prices have also significantly increased due to high cost reformed natural gas, causing many DRI plant closings. The U. S. Steel industry needs breakthrough technology to overcome these critical barriers.

Existing Steel Production Technology

Blast furnace technology for iron production has been employed for approximately 150 years. Many incremental improvements have been made and it is the current dominant technology. As shown in Figure 1, fired iron ore pellets, coke and lime are charged into a blast furnace. Air is blown in at high speed to combust the coke to generate carbon monoxide and heat. Fired iron ore pellets are reduced to iron hot metal by the carbon monoxide and melted to form liquid iron. The liquid iron is then sent to a BOF where pure oxygen is blown into the liquid iron to remove the carbon and convert iron into steel (Figure 1). The fundamental problems associated with this steel production route are the needs for coke and intensified combustion. Coke making generates many pollutants and consumes large volume of water for coke quenching. Intensified combustion generates great amounts of dust and wastes energy in the form of exhaust gases. Treating hot dust needs large volumes of water and produces pollutants.

Figure 1
Current Steelmaking Process

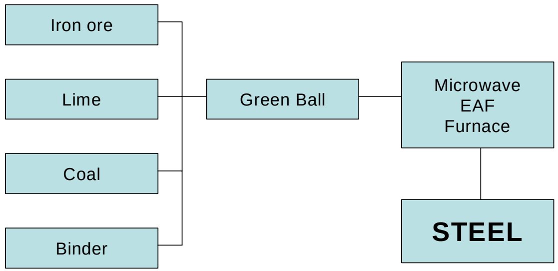


The New Steel Production Technology

The new microwave assisted EAF steelmaking technology is a revolutionary change from current technology. It is achieved through the combination of microwave, electric arc and exothermal heating. This technology can produce molten steel directly from a shippable agglomerate (green ball) consisting of iron oxide concentrate, coal, and fluxing agent without the intermediate steps of coking, sintering, BF ironmaking, and BOF steelmaking. The unique aspect of this technology utilizes the advantages of rapid volumetric heating, high energy efficiency, and chemical reaction acceleration through the use of microwaves. The viability of the technology lies in that iron ore and carbon are excellent microwave absorbers. This concept utilizes the combination of microwaves, electric arc, and exothermal reaction heating to provide the steelmaking energy. This new, simplified process translates into less capital cost, higher productivity, less environmental pollution and treatment cost, higher energy efficiency, and lower production cost. In addition, the concept remains flexible in that it can still produce molten steel from a scrap charge, thus allowing different feed stocks to be run through the same furnace.

In this new process, iron ore is crushed, ground, and concentrated by conventional processing. The concentrated iron oxide is mixed with pulverized coal and limestone, and then agglomerated at ambient temperature to provide strength for handling. Coal serves as a reducing agent for iron oxides and as an auxiliary heat source via an exothermal oxidation reaction. Limestone is used as the fluxing agent (Figure 2).

Figure 2
New Microwave/EAF Steelmaking Technology



Project Goals and Objectives

The goal of this project was to assess the utilization of a new steelmaking technology that has the potential to achieve better overall energy efficiency, minimize pollutants and wastes, lower capital and operating costs, and increase the competitiveness of the U.S. steel industry. The objectives associated with this goal were to a) generate a solid base of technical, marketing, economic, and policy data, b) develop energy, environmental, and economic targets, c) more definitively assess opportunities and barriers, d) accumulate knowledge and experience for defining direction for the next phase of development, and e) promote learning and training of students.

Project Work Plan

Michigan Technological University (MTU), as the primary project contractor, provided a multi-disciplinary team of engineers, scientists, faculty, technicians and students with expertise in metallurgical engineering, chemical engineering, and business and economics. This project also obtained assistances from steel companies, equipment suppliers, an engineering firm, and iron ore mining companies.

This project consisted of seven tasks as listed below.

Task 1 Direct Steelmaking Tests and Technology Assessment
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BACKGROUND

Information about the project team members and more details about microwave processing are provided in this section.

Project Team Members

The **Institute of Materials Processing** at **Michigan Tech** initiated the microwave steelmaking research using a single mode microwave sintering system in 1995. A working model combining microwave, electric arc, and exothermal heating was identified. Molten steel has been produced in the furnace in a few minutes. The early research was supported by the Institute’s internal research dollars. In 2001, Michigan Tech was awarded a grant by the DOE to conduct bench scale research utilizing the new microwave steelmaking invention. This research included technology assessment, flowsheet development, evaluation of equipment, evaluation of logistics, energy and environmental assessments, marketing and economic assessments, and evaluation of policies and regulations. A pilot plant scale up is the next logical phase.

U.P. Steel is a private company created in 2001. The founders of the company have extensive experience in mining, mineral processing and steelmaking, and identified microwave steelmaking as the most important and promising technology for the future of the industry. U.P. Steel licensed this technology for commercialization. U.P Steel has filed world wide patent applications and extensively marketed the process with $100,000 of current investment.

Cleveland-Cliffs Inc. is the largest domestic iron ore company. CCI participated in Michigan Tech’s DOE microwave steelmaking project by providing iron ore for steelmaking tests and assistance in evaluating test results and economics. CCI has closely watched the progress of the microwave steelmaking technology since 2001 and is actively involved in the proposed pilot plant planning and cost sharing.

U.P. Fabricating is a leading steel fabricating company in the Upper Peninsula of Michigan. This company has a long history of working with Michigan Tech in developing new mineral processing equipment. U.P. Fabricating has participated in the Michigan Tech’s DOE microwave steelmaking project by providing more than 20 magnetrons, a tiltable steel vessel and various fabrication assistances.

Noramco Engineering is a major engineering firm serving the iron and steel companies, and has been working with both Michigan Tech and U.P. Steel to evaluate the economics of the new steelmaking technology and scale up design. This company estimated that the capital per annual ton is $48 for microwave steelmaking in comparison with $1750 for traditional steelmaking and the operating cost per ton is $68 for microwave steelmaking in comparison with $120 for traditional steelmaking. Based on their experience and knowledge in steelmaking equipment, Noramco has completed a scale up design which can produce 500,000 to 1,000,000 tons of steel per year. Noramco’s involvement to date has been self funded.

Microwave/Material Interactions

Microwave in General

Microwaves have extensive application in the field of communication, but certain frequencies are allocated for industrial and scientific application. Microwaves are electromagnetic waves with frequencies that range from 0.3 to 300 GHz. Microwave frequencies include three bands: the ultrhigh frequency (UHF: 0.3 GHz to 3 GHz), the superhigh frequency (SHF: 3GHz to 30 GHz) and the extremely high frequency (EHF: 30 GHz to 300 GHz). Microwaves obey the laws of optics and can be transmitted, absorbed or reflected. The behavior of microwave depends on the type of materials interacted with.

Microwaves are generated from magnetrons. Microwave energy is converted from electric energy and the frequency of the generated microwave is a dominant parameter of the conversion efficiency. The frequency of a generated microwave depends on the design of the circuit associated with magnetrons. The microwave energy generated by a magnetron is dependent on the line voltage applied on the magnetron and on the amount of time the magnetron has been operated.

The basic power equation for a microwave oven is stated as follows:

$$P_G = P_R + P_A + P_D \tag{1}$$

The power generated by a magnetron, P_G, equals the power reflected back to the magnetron, P_R, plus the power absorbed by the microwave oven cavity and feed system, P_A, plus the power delivered to the load inside the microwave oven, P_D.

Behavior of Materials under Microwave Irradiation

Microwaves can be reflected, absorbed and transmitted by materials with which they interact. Reflection and absorption are due to the interaction of atoms inside materials with the electric field of microwave. Transmission is the result of partial reflection and incomplete absorption.

Materials reflect and absorb microwave energy to various degrees depending on their composition, structure, temperature and the frequency of the microwave. With regard to their response to microwaves, materials are divided into three categories: transmitters, absorbers or reflectors. Metals and graphite, at least in bulk form, are excellent reflectors and do not absorb microwaves at all. Some minerals (magnetite, iron titanite, galena et al.) are excellent absorbers.

The absorption degree of some materials can be changed through various methods, which include changing the temperature, adding absorbing constituents, altering the microstructure and defect structure of materials, changing the form of materials (e.g. bulk vs. powder), and changing the frequency of the incident microwave. At room temperature, many ceramics and polymers do not appreciably absorb microwaves with a frequency of 2.45GHz, however, their absorption can be increased by increasing the temperature of processing.

Mechanism of Interaction

Microwaves can interact with materials through either dielectric polarization or ionic conduction, as illustrated by Figure 3. Dielectric polarization involves the short-range displacement of a charge through the formation and rotation of electric dipoles. Ionic conduction involves the long-range transport of charge.

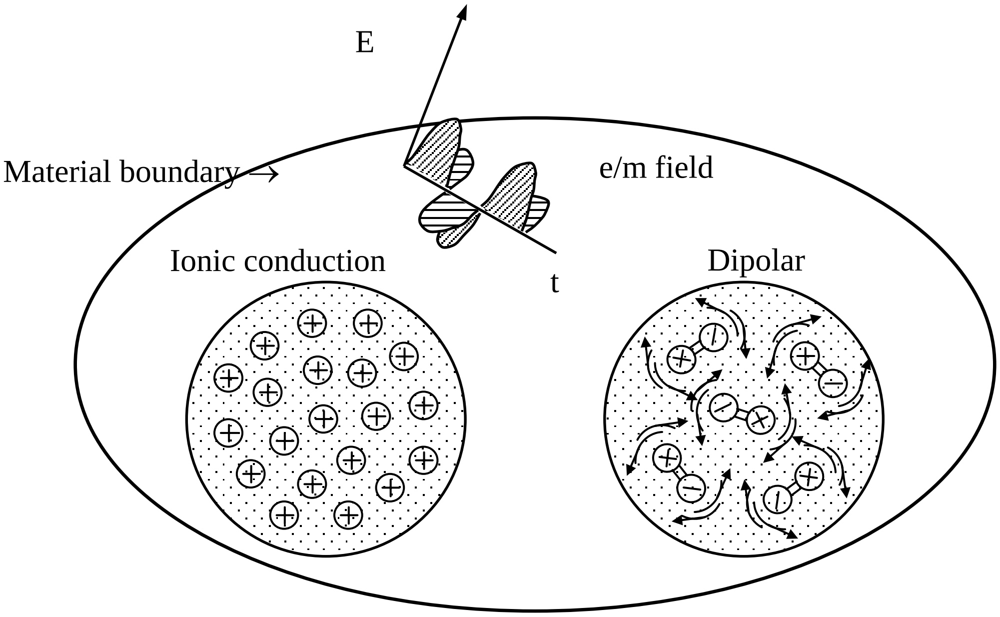

Figure 3. Mechanism of interaction between microwave and materials

Both processes result in the absorption of microwave energy by materials. Microwave energy loss through ionic conduction is due to the well-known ohmic losses, which occur when ions move through the materials and collide with other species. The time allowed for an ion’s transport in the direction of the field decreases with increasing frequency of microwave, so ionic conduction is the dominant process at low frequencies. In a microwave region, dipoles are formed and rotate to align themselves in phase with the reversing electric field. The extent of dipolar polarization depends on the power of the electric field, the strength of dipole’s moment, and the mobility of dipoles. Microwave energy loss through dielectric polarization results from the lag of polarization behind the change of the electric field. Dielectric polarization is the dominant process at high frequencies.

Microwave Absorption

At the macroscopic level, the microwave absorption by materials can be quantitatively stated as follows:

$$P_A = 2\pi f \varepsilon_0 \varepsilon'_{eff} (E)^2 \qquad (2)$$

Where P_A is the average absorbed power per unit volume, f is the frequency of microwave, ε is the permitivity of free space, ε'_{eff} is the relative dielectric loss factor, and E is the internal electric field. An internal electric field (E) is generated within the material when microwaves penetrate and propagate through a dielectric material. The internal electric field (E) is dependent on the relative dielectric constant ε' and ε'_{eff}.

Microwave Processing

Microwave processing of materials is a thermally activated process based on microwave energy absorption. In contrast to all other conventional heating methods, microwave processing allows volumetric heating of materials. Microwave energy transforms into heat inside materials in microwave processing, which eliminates the need for spending energy on heating the walls of the furnace. Due to volumetric heating, the role of heat transfer becomes less important; materials can be quickly heated in microwave processing. These unique features of microwave processing result in significant reduction of energy consumption and processing duration, which plays a decisive role in most applications of microwave processing.

Microwave processing also has other benefits over conventional heating methods: rapid heating of thermal insulators such as ceramics and polymers, precise and controlled heating, material selective heating, reduction of hazardous emissions, increased product yield, environmentally friendly (clean and quiet), and cost savings.

In general, microwave processing will achieve energy savings, ranging from 10 to 90% higher efficiency compared with that of conventional heating. It is reported that the efficiency of microwave use increases significantly when the size of the load is increased. Besides the well-known and extensive application in food manufacture and heating, microwave processing finds its way in many areas, which are roughly classified and summarized in Table 1.

Table 1. Applications of microwave processing

Processes	**Examples**
Recovery	Waste remediation, extraction of Zinc from EAF dust, Beneficiation of minerals
Synthesis	SiC synthesis, TiC synthesis, decomposition of PCS, Catalysis and synthesis of organic compounds
Removal of phases	Drying and anhydration of material, solvent volatilization, binder burnout
Fabrication	Ceramic joining, CVI, coating, reduction of metal oxides
Consolidation	Si_3N_4 sintering, alumina sintering, melting, Polymer curing, organic matrix composite curing
Post-Fabrication treatments	Annealing of Si_3N_4, surface modification, nucleation / crystallization, sealing
Sample digestion	Mineral leaching

Microwave Non-Thermal Effect

Numerous observations have been reported in the literature of enhanced mass transport and enhanced reaction rates during microwave processing of various materials. These empirical observations of microwave enhancements have been broadly called microwave effect or microwave non-thermal effect. One of the phenomena about enhanced mass transport first observed by Janney, was the enhancement of oxygen diffusion in sapphire crystals heated in a 28 GHz microwave furnace. A 40% decrease in the apparent activation energy for bulk diffusion was observed under microwave processing as compared to conventional heating. One of the phenomena about enhanced reaction rates was observed by Gedye et al. in their investigation of organic reactions. They observed that microwave processing increases the reaction rate about 10 to 1200 times, as compared to conventional heating.

The existence of microwave non-thermal effect means many unique benefits, which microwave processing can provide but conventional heating can not. These benefits include not only the benefits mentioned earlier but also improved quality and properties of the processed materials. In Bykov’s study on nanostructured porous alumina membranes, it was found that the porosity decreases consistently with increasing time of microwave processing, and that conventional heating causes no changes in the surface porosity of membranes.

Among the theoretical models for microwave non-thermal effect, the model based on the concept of non-equilibrium excitation seems natural and sound. The process of thermal energy absorption by materials is usually viewed as the excitation of lattice oscillations that have an equilibrium spectrum. Changes in the temperature of materials through thermally heating mean the slow evolution of the spectrum, which at all times remains in quasi-equilibrium. Microwave radiation not only increases the temperature of materials through microwave energy absorption, but also excites electron oscillations inside materials through interaction between electron and electromagnetic fields. Electron oscillations induce periodic distortion of the lattice potential and thereby modify the spectrum of lattice vibrations, that is, drive it from equilibrium. The fraction of energy stored in non-equilibrium excitations is determined by the time constant of the lattice vibrational modes and the electromagnetic field of microwave. The energy stored in non-equilibrium excitation is within the same order of magnitude as the energy of the electromagnetic field of microwave. Mass transport rate and reaction rate can be expressed in a general form as equation (3). Both the transport coefficient and the reaction coefficient are dependent on activation energy and temperature. The energy stored in non-equilibrium excitation will increase the activation energy for transport and reaction. The driving force is considered to be controlled by the concentration gradient or capillary stress, which are unaffected by microwave.

$$\text{Rate} = (\text{driving force}) \times (\text{coefficient}) \tag{3}$$

Microwave Processing Systems

A microwave processing system is made up of four basic components: power supply, magnetron, applicator (i.e., oven) for processing the target materials, and waveguide for transporting microwave from the magnetron to the applicator.

Currently, the maximum output power of single magnetron produced is 90 kW. Large microwave processing units can be built through connecting many magnetrons in parallel to multiply the power output.

Many companies such as Dennis Tool Co. (USA) and Fuji Denpa (Japan) offer standard microwave processing furnaces, and many companies will design and build a microwave processing system to meet their client's specification. Prices depend on the power output and frequency needed. The most inexpensive and common frequency used for microwave processing is 2.45 GHz.

Many systems used for microwave processing have been commercialized. An example of a commercial system is the Stoke-Type microwave system, which is developed by Dennis Tool Co. (USA) and is used to manufacture carbide.

Task Discussions

The following sections of this report describe the work conducted and the results obtained in each individual task. Each of the seven tasks addresses a separate aspect of the microwave steelmaking technology.

Task 1: Direct Steelmaking Tests and Technology Assessment

The steelmaking tests and technology assessment consist of three aspects: 1) baseline microwave steelmaking; 2) bench-scale MW/EAF steelmaking; and 3) iron ore reduction by microwave assisted hybrid heating.

The baseline microwave steelmaking was designed to generate a series of steelmaking data from small samples using an available microwave sintering furnace. The baseline tests provide guidance for the bench-scale MW/EAF steelmaking tests. During execution of the project, we realized a need for microwave assisted hybrid heating in three scenarios: enhance performance of current heating equipment by adding microwave heating capability, utilize off-gases to improve energy efficiency, and reduce the need for high powered microwave generators. The study of iron ore reduction by hybrid heating was designed to generate some preliminary results for those considerations.

1.1 Baseline Microwave Steelmaking

Michigan Tech has a single mode microwave furnace manufactured by Wavemet. This furnace is capable of heating ceramic materials to over 1800ºC. We had conducted a preliminary steelmaking test using this equipment to prove the concept of microwave steelmaking before the project. This commercial furnace has a good microwave control system and generates repeatable results when processing small samples (a few grams). This equipment is an ideal tool for investigating various factors which may affect steelmaking using microwave. The steelmaking results generated from this equipment provided good reference for bench-scale MW/EAF steelmaking which is capable of processing 1000 grams of materials.

The factors which may affect steelmaking cover a broad range - from raw materials, process methods, and process parameters. In this study, we varied iron ore, coal, coal to iron ore ratio, lime to iron ore ratio, binder used to make pellets, compact density of pellets, and heating time for the microwave steelmaking tests. The produced steels and slags were examined to evaluate the quality of microwave produced steels. The data showed the relationships among those factors and provided guidance on how to reach an optimum steelmaking result using microwave heating.

Experimental Method

Sample Designation

The sample's numbers were assigned as follows: the first letter denotes an iron ore type: M-magnetite, H-hematite followed by a percentage number; the second letter denotes a reducing agent type: G-graphite, A-active carbon, C-coal followed by a percentage number; the third letter denotes a fluxing agent followed by a percentage number; the fourth letter denotes a binder followed by a percentage number; and the fifth letter denotes either compact pressure or microwave heating time. Figure 1.1 gives an example how a sample in this study was identified.

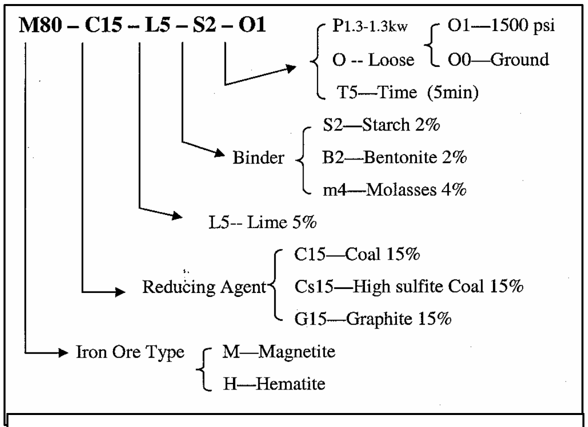

Figure 1.1. Sample Designation Explanation

Raw Materials

Both magnetite and hematite ores, provided by Cleveland-Cliffs Inc. (CCI), were used in this study. The compositions are given in Table 1.1. Both western coal and eastern coal were used as reducing agents in this study. Their compositions, as analyzed by Commercial Testing & Engineering Co., are given in Table 1.2. The other raw materials used for this study include starch, bentonite, graphite powder, and lime. Their compositions are given in Table 1.3.

Raw Materials Processing

The raw materials were processed to make feed materials for the microwave steelmaking tests. The procedure of the raw materials processing is given below.

1. Mix iron ore concentrate with lime and coal powders in different ratios. The binder is either starch or bentonite.
2. Compact the mixtures in a die under pressure of 1.5-3.0 ksi. Each compact weighs about 30 grams. The compacts were then dried in an oven.
3. Break the compact to pieces and passed them through a 10 mesh screen.
4. Charge 5-6 grams of such materials into small fireclay crucibles ready for microwave steelmaking tests.

Table 1.1. Composition of the ores (%)

Ore	**Fe**	**SiO_2**	**CaO**	**MgO**	**MnO**	**Al_2O_3**	**P**	**K_2O**
Magnetite	62.9	4.92	4.81	1.60	0.12	0.12	0.015	0.016
Hematite	61.6	4.51	4.31	1.62			0.034	

Direct Microwave Steelmaking

The equipment employed for microwave steelmaking was Wavemet MCR200 microwave furnace as shown in Figure 1.2. The steelmaking tests followed the procedure described below.

1. A sample in a small crucible was placed on the rotating stage of furnace chamber. The sample in rotating was heated by 1.4 kW microwave irradiation for 7 minutes in total, otherwise specified. The crucible outer surface reached a temperature about 1300-1400°C.
2. After shutting off the microwave power, the crucible was moved out the furnace and cooled down in air. Normally a steel ball can be seen in the center of the crucible and it was surrounded by slag.
3. Steel ball and slag of the sample were separated and weighed respectively. By knowing the raw material compositions, the steel yield can be calculated.

Table 1.2. Composition of the Coal (%)

	Western Coal		**Eastern Coal**		**Warehouse Coal**	
	As received	**Dry basis**	**As received**	**Dry basis**	**As received**	**Dry basis**
PROXIMATE ANALYSIS						
Moisture	1.61	xxxx	10.26	xxxx	12.66	xxxx
Ash	9.73	9.89	11.51	12.83	8.05	9.22
Volatile	29.76	30.25	32.09	35.76	38.72	44.33
Fixed Carbon	58.90	59.86	46.14	51.41	40.57	46.45
Btu/lb	13230	13446	10050	11199	9041	10352
Sulfur	1.01	1.03	3.40	3.79	0.79	0.91
MAF Btu		14922		12847		11403
ULTIMATE ANALYSIS						
Moisture	1.40	xxxx	10.26	xxxx	12.66	xxxx
Carbon	72.72	73.75	57.58	64.16	55.15	63.14
Hydrogen	4.76	4.81	3.83	4.27	3.63	4.16
Nitrogen	1.38	1.40	1.04	1.16	0.79	0.90
Sulfur	1.31	1.33	3.40	3.79	0.79	0.91
Ash	10.68	10.83	11.51	12.83	8.05	9.22
Oxygen	7.77	7.78	12.38	13.79	18.93	21.67

Table 1.3 Composition of Starch, Bentonite, Graphite and Lime (%)

Element	**Si**	**Mn**	**Fe**	**Mg**	**Al**	**Ti**	**Ca**	**Na**	**K**
Starch	3.01	0.01	0.31	0.02	0.18	0.00	0.09	0.40	0.67
Bentonite	36.83	0.02	2.08	2.28	6.44	0.15	1.39	0.46	2.73
Graphite	1.40	0.02	0.44	0.02	0.2	0.02	0.09	0.31	1.10
Lime	1.51	0.02	0.29	0.42	1.28	0.02	40.76	0.56	2.55

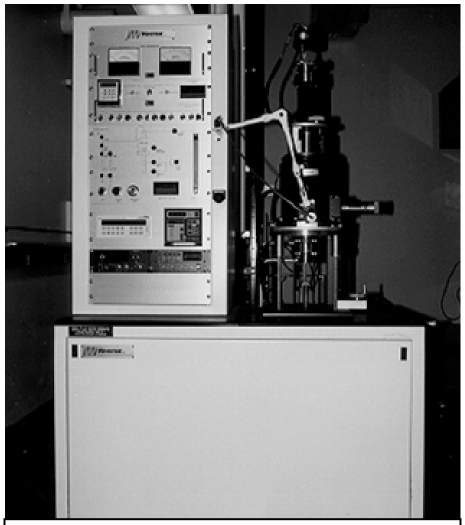

Figure 1.2. Wavemat MCR200 Microwave Furnace

Sample Examination

The chemical compositions of the produced steels and slags were analyzed using an electron microscope (Super-Probe), inductively coupled plasma spectrometer (ICP), or a carbon and sulfur analyzer. The samples for Super Probe analysis were prepared according to the following procedure.

1. The samples were molded in plastic holders by epoxy resin. Each sample contained one piece of metal and four pieces of slag. Hardening time was about 24 hours.
2. The molded samples were cut and polished.
3. The instrument used for chemical analysis of the produced steel and slag was JXA-8600,

SUPERPROBE. Three points of steel and three points of slag in each sample were probed, analyzed and averaged. The expected elements in steel were Fe, Al, Mn, P, S, and Si. The expected compounds in slag were FeO, SiO_2, CaO, P_2O_5, SO_3, Al_2O_3, TiO_2, Na_2O, K_2O, MnO, and MgO.

A single steel or slag sample was not large enough for ICP or C&S analysis. Three identical steelmaking tests were run to get three samples. The three samples were then treated together to meet the minimum analysis weight requirement.

Results and Discussions

More than 250 steelmaking tests have been run. Figure 1.3 is a view of the steelmaking samples. Figure 1.4 shows the cut section of the steel ball. Tables 1.4-1.6 present some steelmaking parameters and test results. The complete test parameters and results are given in Appendix A. Discussions on the test results follow.

Figure 1.3. Steelmaking samples

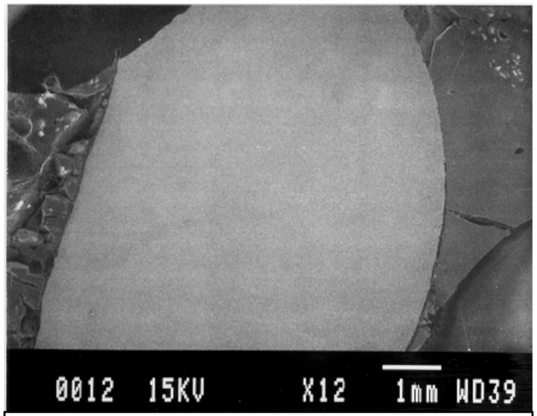

Figure 1.4 Cut section view of produced steel

Table 1.4 Pellet compositions and steel yields

Sample	Iron Ore %	Reducing Agent %		Lime %	Binder, % of total ore, reductant and lime		Slag Wt %	Steel Yield %
MG1	80	carbon #1	15	5	starch	3	23.3	95.59
MG5	81.6	carbon #1	13.8	4.6	starch	3	22.8	87.27
HG12	80	carbon #1	15	5	starch	3	23.6	92.22
MA4	78.4	carbon #2	16.2	5.4	starch	3	20.8	84.37
MA6	81.6	carbon #2	13.8	4.6	starch	3	41.6	72.77
MA8	80	carbon #2	15	5	bentonite	3	33.5	65.55
HA11	80	carbon #2	15	5	starch	3	28.7	89.40
MC10	80	coal #1	15	5	bentonite	3	43.2	74.93
HC13	80	coal #1	15	5	starch	3	45.4	72.09
MHC14	80	coal #1	15	5	starch	3	46.8	70.10

Magnetite ore, microwave heating only
carbon #1 is graphite (fixed C>90%), carbon #2 is activated carbon (fixed C>90%)

Table 1.5 Steel composition

Sample	Fe	P	Al	Si	Mn	S
MG1	99.175	0.023	0	0.807	0	0.002
MG5	99.301	0.026	0	0.643	0.021	0.009
HG12	99.167	0.073	0	0.713	0.045	0.002
MA4	94.030	0.205	0	5.742	0.025	0.007
MA6	99.861	0.045	0	0.010	0.031	0.053
MA8	99.220	0.084	0	0.668	0.024	0.004
HA11	99.804	0.176	0	0.023	0	0.043
MC10	99.963	0.039	0	0.002	0	0.013
HC13	99.956	0.033	0	0	0	0.017
MHC14	99.936	0.023	0	0.018	0.005	0.018

(Magnetite ore, microwave heating only)

Table 1.6 Slag composition

Sample	SiO_2	CaO	FeO	MgO	Al_2O_3	P_2O_5	SO_3	TiO_2	Na_2O	K_2O	MnO
MG1	58.027	27.519	0.579	4.243	8.786	0.014	0.007	0.041	0.415	0.278	0.09
MG5	50.481	34.597	2.349	3.637	7.861	0.006	0.017	0.165	0.357	0.233	0.297
HG12	50.193	33.86	1.546	4.637	8.348	0.002	0.009	0.248	0.32	0.223	0.612
MA4	58.294	25.619	0.384	3.352	10.78	0	0.414	0.182	0.466	0.303	0.209
MA6	42.782	24.331	22.22	1.988	7.525	0.064	0.046	0.112	0.478	0.236	0.22
MA8	49.528	34.539	2.413	3.646	8.452	0.017	0.142	0.133	0.583	0.252	0.295
HA11	54.307	21.494	8.613	4.061	9.674	0.066	0.048	0.272	0.547	0.268	0.65
MC10	58.954	14.266	13.55	2.145	9.844	0.062	0.036	0.081	0.635	0.322	0.1
HC13	44.491	19.609	23.67	2.355	8.5	0.092	0.085	0.155	0.411	0.239	0.393
MHC14	47.690	16.817	24.33	2.067	7.859	0.046	0.08	0.151	0.514	0.22	0.225

(Magnetite ore, microwave heating only)

Steel Yield

The steel yield varied from 0 to 100%. Steel yield mainly depends on the amount of reducing agent added into the iron ore pellets. More accurately speaking, steel yield depends on the iron oxide content of iron ore and the amount of fixed carbon in a carbonaceous reducing agent. No matter what type of reducing agent was used, selected from western coal, eastern coal, graphite powder or active carbon powder, any of the reducing agents can generate steel yield close to 100%, if enough fixed carbon exists. A low ratio of reducing agent results in low steel yield. However, the type of binder may have some effect on yield. With the other components held constant, using starch as the binder results in higher steel yield than bentonite and molasses. This is due to the fixed carbon contained in starch. Another phenomenon worth noticing is that there exists a critical ratio of carbon in the iron ore pellets. If the pellets contain too high of a ratio of carbon, normal steel balls and slag do not form during steelmaking. No matter what reducing agent is used, the critical percentage of the fixed carbon contained in the pellets is about 15% for the tested magnetite and hematite iron ores. That explains why more eastern coal, which contains less fixed carbon, is needed to get the same level of steel yield.

Sulfur in the Steel

Sulfur content in steel generally originates from coal. The amount of sulfur in the steel varies with the type of coal and the ratio of coal in the pellets as well. High sulfur containing coal and high amount of coal addition causes higher S content in the steel. For the western coal, the average S content fluctuates between 0.3%~0.5%. For the high S content Eastern coal, however, the concentration of S reaches as high as 1.14%~1.57%, while the graphite reduced steel contains only 0.027%~0.037% sulfur. Figure 1.5 illustrates the relationship of the steel sulfur content with reducing agent types and their additions.

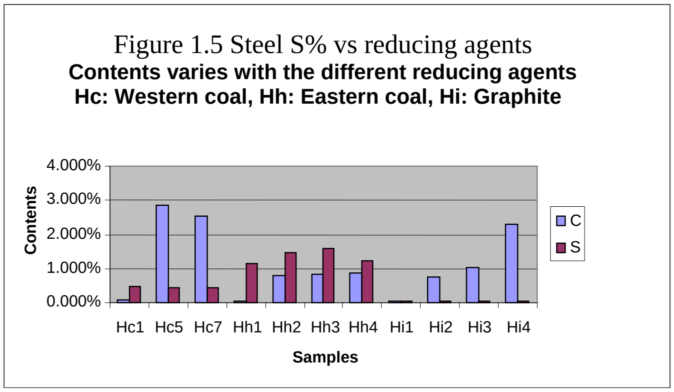
Figure 1.5 Steel S% vs reducing agents

Contents varies with the different reducing agents

Hc: Western coal, Hh: Eastern coal, Hi: Graphite

Promisingly, the high ratios of lime in the sample can significantly reducing the S content. By increasing lime ratio from 3% to 15%, the S content reduced from 0.50% to 0.16% as illustrated by Figure 1.6. Figure 1.7 shows the effect of lime addition on the sulfur content of slag. It is obvious that sulfur moves from steel into slag if lime addition is increased.

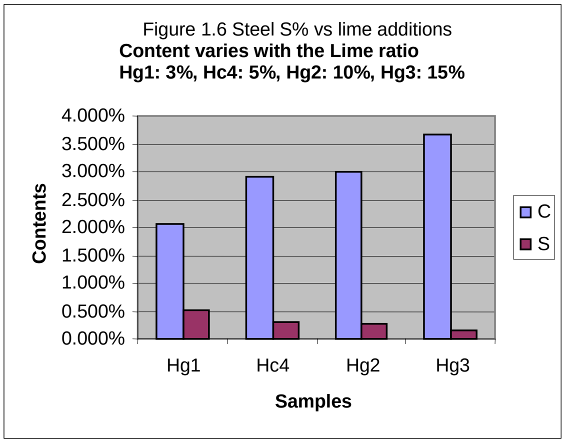
Figure 1.6 Steel S% vs lime additions

Content varies with the Lime ratio

Hg1: 3%, Hc4: 5%, Hg2: 10%, Hg3: 15%

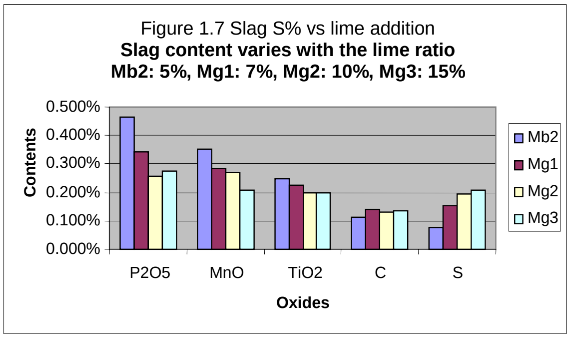
Figure 1.7 Slag S% vs lime addition

Slag content varies with the lime ratio

Mb2: 5%, Mg1: 7%, Mg2: 10%, Mg3: 15%

Carbon in the Steel

Carbon concentration in the steel is effected in several ways. First, the ratio of carbon in the pellets can affect it. Carbon concentration increases if the ratio of carbon in the pellets increases. However, this increase stops after the ratio of carbon reaches a certain level, as illustrated in Figure 1.8. Second, extended heating time has little effect on C content as seen in Figure 1.9. Third, C content varies closely with the ratio of lime. High lime ratio correlates to a high C content. The C content goes up from 2.05% to 3.66%, while lime ratio increases from 3% to 15% as shown in Figure 1.6.

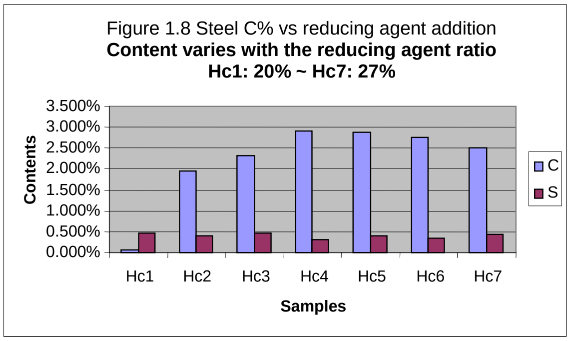
Figure 1.8 Steel C% vs reducing agent addition

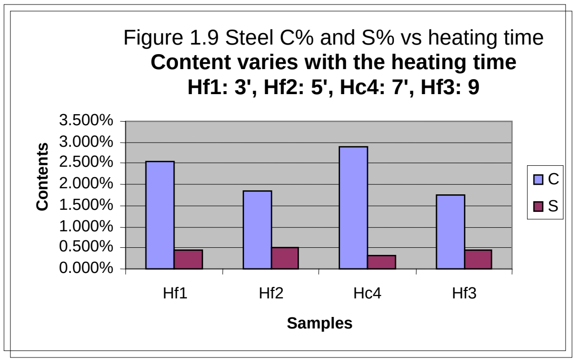
Figure 1.9 Steel C% and S% vs heating time

<u>Phosphorus in the Steel</u>

Phosphorus content in the steel mainly comes from iron ore. But its concentration is higher than that of iron ore because the weight of the produced steel is less than that of the iron ore. Phosphorus content changes with steel yield. Higher steel yield results in higher P content. An interesting phenomenon is that the P content in the steel varies with the microwave heating power. Low microwave power correlates to low concentration of P. The P concentration in the steel is around 0.02 to 0.05.

<u>Effects of Iron Ore Types</u>

There is no significant difference between steels made of magnetite and hematite. There is not much difference in slag composition either. The only noticeable difference is that the TiO_2 and MnO content in hematite slag are approximately three times higher than those in magnetite slag.

<u>Effects of Binder Types</u>

Starch can provide some extra fixed carbon for iron ore reduction. In the situation where insufficient fixed carbon is provided by coal, the starch in the pellets shows assistance to iron ore reduction. The steel yield will be higher and FeO in slag will be lower.

<u>Pellet Compact Density</u>

Among the three groups of samples (loose powder feed, 1.5 ksi and 3.0 ksi compacted agglomerates), there was no noticeable difference in steel yield, carbon and sulfur content.

Conclusion

The type of reducing agent has a significant effect on the steel yield. Steel yield strongly depends on the fixed carbon of a carbonaceous reducing agent. The fixed carbon must be more than a critical value in order to obtain high steel yield. Graphite has the highest fixed carbon. The least amount of graphite is required to achieve a high steel yield in comparison with coals. Enough addition of any carbonaceous reducing agent can result in a steel yield close to 100%. However, an excess amount of fixed carbon is detrimental to steel and slag separation and wastes energy. Volatiles in coal escape at temperatures below iron ore reduction temperature. Therefore, the volatiles do not participate in iron ore reduction. It is a big energy waste.

The carbon content of produced steel varies from to 0.026% to over 3% depending on the amount of fixed carbon in steelmaking raw materials.

The sulfur content of produced steel varies from 0.002% to over 1%. The sulfur primarily comes from coal. Low sulfur carbonaceous reducing agent results in low sulfur steel. Sulfur in steel can be removed by adding lime into the steelmaking raw materials.

The phosphorus content in microwave produced steel varies from 0.023% to 0.193%. Phosphorus in steel comes from steelmaking raw materials.

There are no surprising differences in steel and slag produced by microwave steelmaking compared to steel and slag produced by conventional steelmaking. The microwave produced steel is of good quality.

1.2 Bench-Scale MW/EAF Steelmaking

Microwave Assisted Electric Arc Furnace Design

The bench-scale microwave assisted electric arc furnace (MW/EAF) is the key apparatus for investigating and optimizing the processes involved in the new steelmaking technology. The bench-scale MW/EAF system consists of microwave heating subsystem, electric arc heating subsystem, cooling subsystem, emission evacuation subsystem, refractory vessel (crucible), insulating materials and furnace shell. The structure of the MW/EAF furnace is illustrated schematically in Figure 1.10.

The microwave heating subsystem includes six parallel sets of microwave generators, waveguide, electric current monitor and control devices. Every microwave generator consists of accessory components and one water-cooled magnetron, which is a commercial SHARP RV-MZ A296WRL magnetron with fixed output power of 1000 W and frequency of 2.45 GHz. Microwave radiation is delivered into the furnace cavity through the waveguides from three lateral sides of the furnace for homogeneous microwave heating.

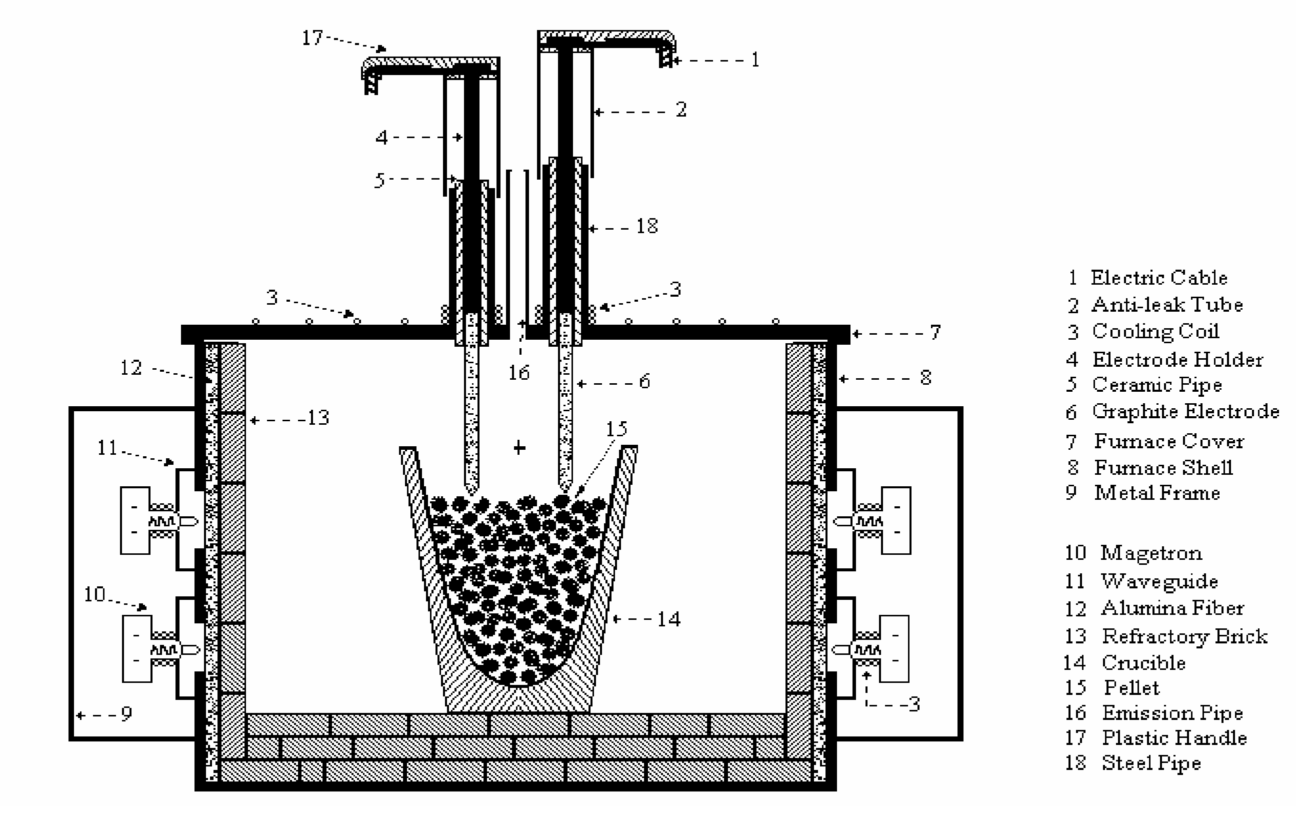

Figure 1.10 Schematic diagram of microwave assisted electric arc furnace

The electric arc heating subsystem mainly includes a low-voltage electric power system and two graphite electrodes. The electric power system is a Hobart Brothers Company's Arc Welder

(Model ML-304), with adjustable supply of AC voltage and maximum supply voltage of 100 V. The operating voltage and current are monitored by two indicating meters.

The cylindrical graphite electrode is 0.5” in diameter and 24’’ in length. The electrodes are manually controlled by furnace operators, and can only move vertically during operation. The ceramic pipe around the cylindrical electrode serves as an electric and thermal insulator. The steel pipes around the electrodes are shrouded by plastic tapes for electric insulation and safety.

The cooling subsystem includes air-cooling and water-cooling subsystems. Lab compressed air is ducted into the three outside frames of the furnace and blown on the microwave generators for temperature control. The water-cooling subsystem provides more effective temperature control to some critical components of the furnace. Water-cooled copper coils were welded onto the magnetron tubes, the furnace cover, and the lower part of the steel pipes around the electrodes for better cooling.

The interior wall and bottom of the furnace consist of refractory bricks and alumina fibers. Those refractory materials can withstand the variety of destructive influences caused by elevated temperature; they also protect the furnace shell and prevent it from absorbing excessive heat.

The emission evacuation subsystem includes an exhaust pipe welded on the furnace cover, a steel duct, an exhaust fan and a laboratory ventilation system. During operation, the exhaust fan withdraws gases from the furnace cavity to the ventilation system through the steel duct connected to the pipe. Gas analytical equipment can be connected to the pipe through a three way pass.

During operation, one refractory crucible contains the charge (i.e. pellets) and is placed in the center of the furnace cavity. There is a viewing window in the furnace cover, through which the furnace operator can observe the charge and precisely control the position of the electrodes.

The features of the bench-scale MW/EAF furnace offer great convenience for the investigation of direct steelmaking. During operation, only graphite electrodes are consumed and no metal is dissolved. It is easy to obtain the actual value of the yield of iron ores. The allowance for the vertical movement of both electrodes is large enough so that the effect and operation of electric arcing can be readily controlled. The special design in joining graphite electrodes with the metal holders almost eliminates the problem of electrode breakage.

Experimental Method

Apparatus

Reducing magnetite ore through microwave heating and electric arcing methods was carried out in the bench-scale MW/EAF furnace. Temperature measurements were made with Omega Engineering Inc.’s infrared thermometer (Model OS3722).

Materials

Ten pellet samples with different compositions and different binders were used. The compositions of the pellet samples in weight ratio and in weight percentage are respectively listed in Table 1.7 and Table 1.8. Magnetite ore concentration was grade B magnetite from Prince Manufacturing Company. The powdered coal was high volatile bituminous coal. The compositions of raw materials are listed in Table 1.9 and Table 1.10. Magnesium oxide used as crucible lining material has 99% purity.

Table 1.7. Pellet composition by weight ratio

Pellet	Magnetite	Bentonite	Molasses	Starch	Lime	Coal
# 1	100	5	0	0	10	20
# 2	100	5	0	0	10	40
# 3	100	0	0	10	5	50
# 4	100	0	0	7.5	10	25
# 5	100	0	6	0	10	25
# 6	100	0	0	7.5	25	45
# 7	100	0	6	0	35	45
# 8	100	0	0	7.5	35	45
# 9	100	0	0	7.5	10	45
#10	100	0	0	7.5	15	45

Table 1.8. Pellet composition by weight percentage

Pellet	Magnetite	Bentonite	Molasses	Starch	Lime	Coal
# 1	74.07	3.70	0	0	7.41	14.81
# 2	64.52	3.23	0	0	6.45	25.81
# 3	60.61	0	0	6.06	3.03	30.30
# 4	70.18	0	0	5.26	7.02	17.54
# 5	70.92	0	4.26	0	7.09	17.73
# 6	56.34	0	0	4.22	14.08	25.35
# 7	53.76	0	3.23	0	18.81	24.19
# 8	53.33	0	0	4.00	18.66	24.00
# 9	61.53	0	0	4.62	6.15	27.69
#10	59.70	0	0	4.48	8.96	26.86

Table 1.9. Chemical composition of raw materials (wt %)

	Si	Mn	Fe	Mg	Al	Ti	Ca	Na	K
Magnetite ore	3.27	0.09	58.65	0.56	1.67	2.55	0.25	0.42	0.76
Starch	3.01	0.01	0.31	0.02	0.18	0	0.09	0.40	0.67
Bentonite	36.83	0.02	2.08	2.28	6.44	0.15	1.39	0.46	2.73
Lime	1.51	0.02	0.29	0.42	1.28	0.02	40.76	0.56	2.55

Table 1.10. Composition of coal (wt %)

	Moisture	**Ash**	**Volatile materials**	**Fixed Carbon**	**Sulfur**
As Received	1.61	9.73	29.76	58.90	1.01
Dry Basis	0	9.89	30.25	59.86	1.03

Procedures

Reduction of Pellet Sample in MW/EAF

800g or 600g pellet samples were weighed and put into a crucible. The crucible was placed in the center of the MW/EAF furnace cavity. After the cooling subsystem and emission evacuation subsystem of the MW/EAF furnace were turned on, microwave heating was started. The pellet sample was heated for up to 20 minutes. Electric arcing then started. The applied direct voltage reached 50 V. At the beginning, graphite electrodes were positioned to contact the top layer of the pellet sample, and the electric arc current was set to 150 A. After the pellet sample melted down, the graphite electrodes were lowered slowly to keep the electric arc current constant. When slag and molten steel were formed and the required heating time was reached, arc heating and microwave heating were turned off. Through the watch window of the MW/EAF furnace, the temperature was measured immediately. Then the crucible was taken from the furnace to cool.

Coating Crucible Internal Surface

- Crush lime or magnesium oxide
- Mix lime or magnesium oxide with a binder and water
- Stir mixture until it is uniform
- Coat the interior of crucible with the slurry evenly
- Dry crucible in an oven at temperature 100 ºC for 24 hours

Results and Discussion

The experimental parameters and results of magnetite reduction through microwave and electric arc heating are summarized in Appendix B. Figures 1.11 to 1.14 provide several views during a steelmaking test. Figure 1.11 is the bench-scale MW/EAF furnace used for the steelmaking tests. Figure 1.12 shows a technician loading the fireclay crucible containing iron ore pellets into the furnace chamber. Figure 1.13 shows the molten slag and steel in the crucible upon completion of a steelmaking run. Figure 1.14 shows the produced steel.

Figure 1.11. Bench-scale MW/EAF furnace

Figure 1.12. Technician loading fireclay crucible into the furnace chamber

Figure 1.13. After completion of electric arcing

Figure 1.14. MW/EAF produced steels

Binders and Lime in Pellet Sample

The weight percentages of the three binders in pellet samples were similar, but their bonding capabilities were very different. Dried pellet samples with starch binder had excellent strength and toughness. The pellets were still in good shape after storing for a long time. Excessive lime addition above 25% deteriorated the pellet properties significantly. None of the experiments showed any obvious effect from different binders on the steel yield.

Temperature

Temperature measurements indicates that after microwave heating for about 5–7 minutes, pellet samples reach temperatures between 850ºC – 900ºC and remained in that temperature range until electric arc heating started. The temperature of the molten materials during the final stage of electric arc heating is in the range of 1350 – 1500ºC.

Start Time of Electric Arcing

The experimental results indicate that electric arc heating could be applied to heat a pellet sample (#3) after it was processed for as short as 7 minutes by microwave heating. Microwave heating for more than 10 minutes guaranteed the start of electric arc heating on the pellet sample (#3) every time. After microwave heating for 20 minutes, most pellet samples were heated successfully by electric arcing. Pellet samples with a lime ratio of 35/100 had difficulty of electric arcing.

The minimum start time of electric arcing to a specific pellet sample relates to the applied voltage and the electric conductivity of the pellet sample, which depends on the percentage of reduced iron and the composition of the pellet sample. High applied AC voltage makes the start of the electric arc easier, such as 200-800 V in an industrial EAF. Lime particles are not melted during microwave heating. These particles prevent good contact and growth of reduced iron particles. Excessive lime in pellet samples increased the minimum start time of electric arcing.

In order to make an early start of electric arcing, the lime content of the pellet sample should be less than 25%.

Steel Yield

Experimental results indicate that steel yield approaching 100% can be achieved for a pellet sample with appropriate composition after 6 minutes of electric arcing. Electric arc heating time and composition of the pellet sample significantly affect the steel yield of the new steelmaking process.

Figure 1.15 illustrates the effects of electric arcing time and pellet sample's composition on steel yields. It is indicated that steel yield can be increased by increasing electric arcing time. During the period of electric arcing, reduced iron particles melt and separate from slag. After melting is complete, a certain holding time is required for complete separation. The separation contributes to steel yield increase. Long electric arcing time guarantees an enough holding time for separation.

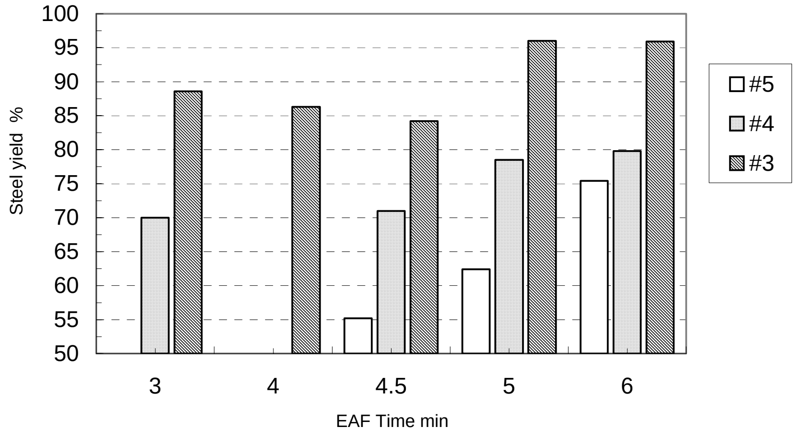

Figure 1.15. Effects of electric arcing time and composition on steel yield

Many pellet samples with appropriate composition can achieve steel yield above 95% after 6 minutes of arcing. Therefore electric arcing time for the bench-scale MW/EAF furnace can be set at 6 minutes.

Electric arcing time could be reduced significantly by replacing the present AC electric arcing subsystem with ultra high DC voltage equipment. Two changes contribute to the decrease of electric arcing time under high voltage. The time to melt a pellet sample is decreased due to rapid heating and the time to complete reduction is decreased because most of the iron ore is reduced at high temperature.

Figure 1.15 also illustrates that steel yields of pellet samples with different compositions are different even when electric arcing time is the same. High steel yield can be achieved by using a pellet sample with more coal or starch, which serves as both a binder and as a reductant.

Figure 1.16 illustrates the variation of steel yield with respect to coal content of pellet samples. Pellet samples with high coal content generally guarantee high steel yield.

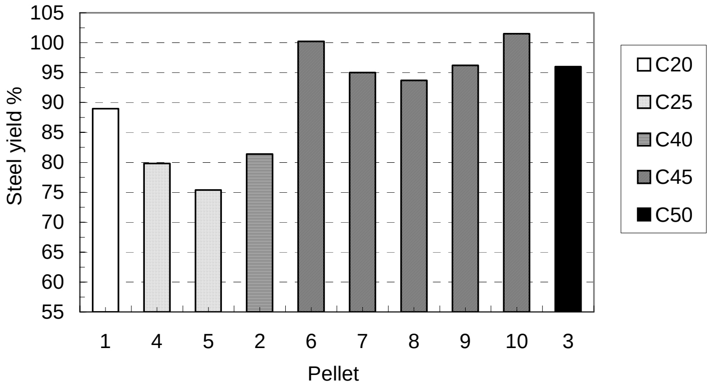

Figure 1.16 Variation of steel yield with coal

Coal serves as a reductant in the new steelmaking process. Variations of steel yield with coal content of pellet samples mainly result from incomplete reduction of iron ore due to lack of coal. If coal in the pellet sample is greatly more than necessary, both MW and EAF heating times need to be increased. Microwave heating time needs to be increased because coal has a more inferior microwave absorbing capability than magnetite ore. Excessive coal mixed with slag increases the slag's viscosity, which retards steel separation from the slag. In order to achieve a reasonable steel yield, electric arcing time has to be increased.

Powdered coal primarily consists of volatile materials, fixed carbon, and ash. Volatiles come out of coal and escape from the furnace during early stages of MW heating. The volatiles do not contribute to heating the pellet samples or to their reduction. It was totally wasted. In the reduction process, some fixed carbon is transferred through the Boudouard reaction into carbon monoxide, which reduces magnetite ore into iron. Some fixed carbon is oxidized into carbon dioxide and then emitted as exhaust gas. A small amount of fixed carbon is ejected out of the crucible due to arcing.

The ratio of the fixed carbon as reductant to the fixed carbon wasted depends on the operating temperature, the ratio of microwave heating time and electric arcing time, and the operating conditions of the furnace. Elevated temperature can increase both the rates of the Boudouard reaction and the reduction reaction, so fixed carbon can be utilized more efficiently under high operating temperature. Electric arcing can easily and rapidly elevate the temperature of the furnace charge. Different conditions of furnace operation related to the emission evacuation subsystem can affect reaction rates by varying the concentrations of gases inside the furnace cavity.

The theoretical minimum ratio of coal to magnetite for complete reduction is from 9.52 to 14.03 depending on the fixed carbon content of coal and iron ore quality (see Task 5: Energy Assessment). The coal to magnetite ratio under present experimental conditions is 20/100 to 50/100, so there is great room to reduce the amount of coal used in MW/EAF process by optimizing furnace operation and careful control of raw materials.

Figure 1.17 illustrates the variation of steel yield with respect to the lime content of the pellet sample. Figure 1.16 indicates that the effect of lime content on steel yield is not significant. When compared with the effect of coal content on steel yield, the effect of lime content is not significant. When lime content varies from 5/100 to 35/100, the steel yield only varies about 6%.

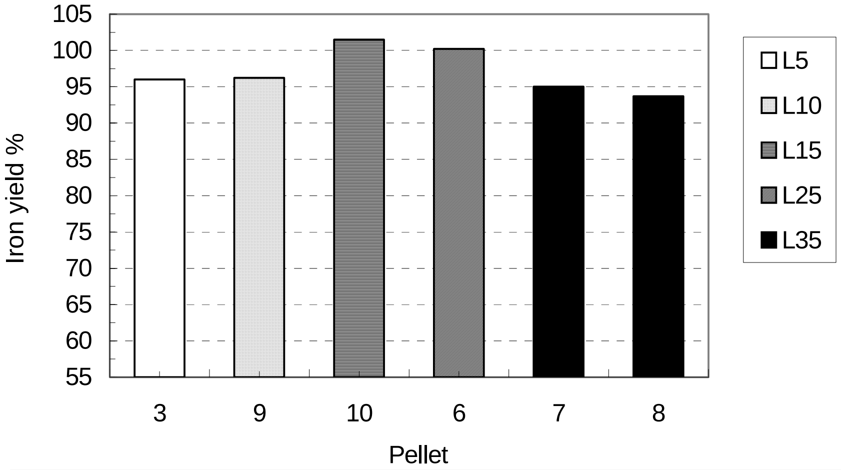

Figure 1.17. Variation of steel yield with lime

Lime content affects steel yield by altering slag viscosity. Pellet samples with different lime contents produce slags with different composition, which have different viscosity at the same temperature; therefore, the extent of steel separation from slag is correlated with the lime content of the pellet sample.

Summary

Steel yield of more than 95% can be easily achieved using the MW/EAF process, therefore this direct steelmaking technology is practical for producing steel directly from iron ore and coal. For most pellet samples, steel can be produced in the bench-scale MW/EAF after 10 minutes microwave heating and 6 minutes electric arc heating.

The start time of electric arcing is greatly affected by the lime content of the pellet sample. The more lime in the pellet sample, the more microwave heating time is required.

The steel yield of the MW/EAF process varies with electric arcing time, coal content, and lime content of pellet sample. Other constituents of the pellet sample and the concurrency of microwave and electric arc heating have little effect on steel yield.

Minimum electric arcing time is needed to achieve high steel yield. For pellet samples with appropriate composition (mainly coal content), steel yield of more than 95% can be achieved after 6 minutes of electric arc heating.

Steel yield varies with both the coal and lime contents of pellet samples. In order to achieve high yield, the quantity of coal in the pellet sample must guarantee complete reduction of the iron ore. The lime content of pellet sample correlates with steel yield via affecting the extent of steel separation from slag.

Steel and Slag Evaluation

Introduction

The objective of this study is to evaluate the steel and slag samples obtained from the previously described steelmaking tests, and to find an effective method to produce low sulfur steels in the MW/EAF process.

Slag is a major byproduct in the MW/EAF process. It is formed from the impurities of iron ore, fluxing materials, ash in coal, and refractory materials. In order to generate hot steel with consistent quality, the behavior of molten slag is a major consideration. Molten slag’s behavior is dependent on the temperature and composition of the slag. The behavior of slag can be characterized by properties of slag such as viscosity, fluidity, surface tension, and basicity ratio.

Basicity ratio is evaluated through adding together the basic constituents of slag and dividing by the sum of the acid constituents of slag. For slags containing low concentration of P_2O_5, the slag basicity ratio can be represented by the mass concentration ratio: $B = (\%CaO + 1.4 \times \%MgO)/(\%SiO_2)$.

In the MW/EAF process, the produced steel contains elements such as carbon, silicon, sulfur and manganese. The steel dissolves some carbon and sulfur because of its intimate contact with coal. Sulfur dissolved in the hot steel reaches equilibrium with sulfur compounds in the slag. If iron ores contain appreciable amounts of calcium phosphate and apatite, the steel also dissolves most of the reduced phosphorus. Other soluble elements of the steel such as silicon and manganese come from reduction of their oxides. Reduction of silica and manganese oxides do not take place until the temperature is above 1490 ºC and 1370 ºC respectively in the presence of carbon. The temperature of slag and steel has an effect on the silicon and manganese content of steel, because the distribution of silicon or manganese between steel and slag is determined by the temperature-dependent equilibrium constant of the reduction reaction.

With a very few exceptions, sulfur is considered undesirable in steel, and there is an increasing demand for steels with lower sulfur levels. Problems associated with sulfur are mainly due to the harmful effects of sulfide inclusions. There are three main methods by which the sulfur content of molten steel may be controlled at a lower level during the melting process. The first method is to mix iron with metallic additions such as magnesium, which in combination with sulfur form very stable sulfides. The second method is to add compound additives such as calcium carbide or soda ash. The third method is to increase the basicity ratio with lime or limestone. Lime will react with sulfur in molten steel to form calcium sulfide in slag. The liquidus isotherms of the ternary system CaO – SiO_2 – FeO is shown in Figure 1.18. The low melting point areas in pseudo-wollastonite and wollastonite of the diagram are those areas that have the highest sulfur removing capacity.

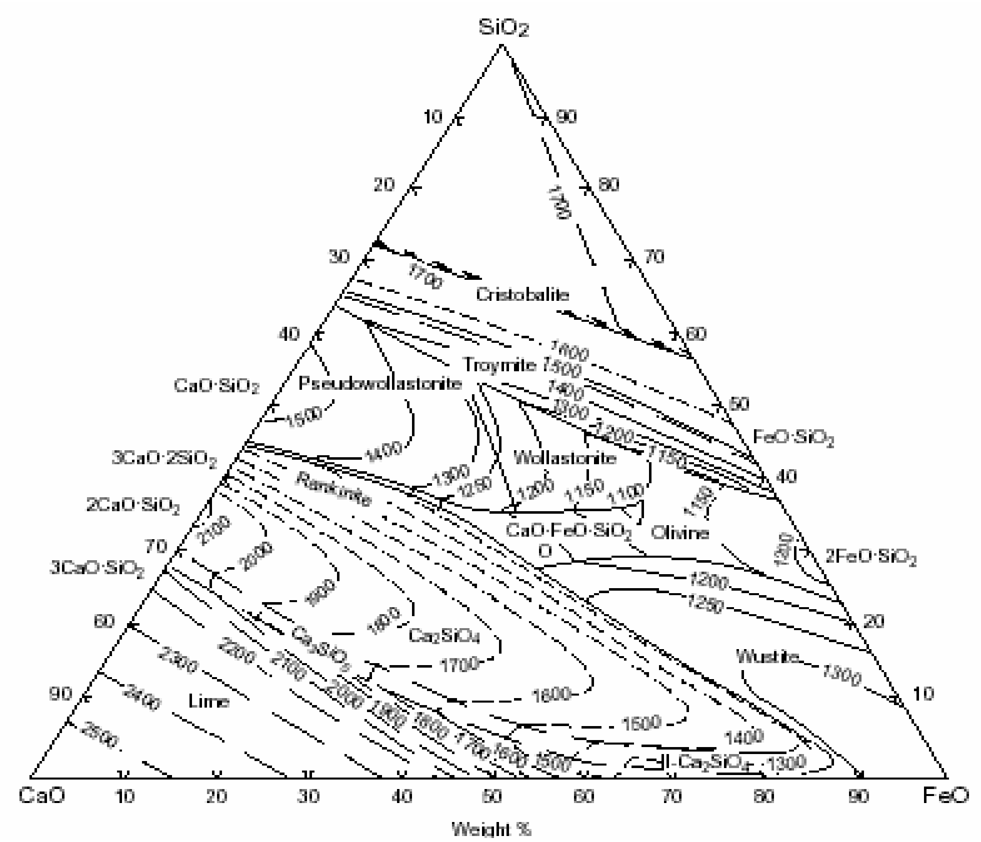

Figure 1.18. Liquidus isotherms of CaO – SiO_2 – FeO system

In these experiments for controlling sulfur content of produced steel, only the third method was investigated, and lime was used as the additive. There are many approaches to add lime into slag; some methods are complicated or may have a negative effect on the steelmaking processes. The simple approach is to blend lime into the pellets.

Crucibles are subject to corrosion at elevated temperature, and some oxide components of crucible may be dissolved into slag. Different crucibles interact with slag differently and have different effect on slag composition. Magnesia crucibles have high refractoriness and good resistance to basic slags. Fireclay crucibles mainly consist of silica and alumina that can form some compounds when reacting with lime in slag. Since the melting points of alumina and lime are higher than silica, the compounds such as tridymite and anorthite formed at temperatures below 1500°C contain more than 50% by weight silica.

Experimental Method

Apparatus

The carbon and sulfur contents of steel samples were analyzed by using a LECO CS-400 combustion analyzer. Other elements were analyzed using a glow discharge spectrometer (GDS). A CARVER laboratory hydraulic press and SPEX 800 Mixer / Mill were used to crush and pulverize slag. An EDXRF spectrometer (Jordan Valley Ex-6600) was used to analyze the chemical compositions of slag samples.

Materials and Procedures

The compositions of pellet samples and raw materials are the same as listed in Tables 1.7 through 1.10. All steel and slag samples for analysis were obtained from these experiments which were summarized in Appendix B, in which all steel and slag sample names are listed.

Steel composition analysis

Steel samples were analyzed by a commercial lab. The steel samples were polished to remove metal oxides, and the clear surfaces were used for analysis.

Sample preparation for XRD study

Three slag samples were used for XRD study. Before loading into the XRD equipment, slag samples were crushed and sieved through a No. 100 mesh copper sieve.

Slag treatment and composition analysis

- Crush slag into small chips using a hydraulic press
- Pour all slag chips into steel mixing jar and pulverize for 5 minutes
- Sieve powdered slag through a No. 100 mesh copper sieve
- Fill a XRF sample cup approximately 1/2 full with sieved slag
- Cap XRF sample cup with a piece of polypropylene film and seal it using plastic ring

- Label sample cup appropriately and place it into XRF spectrometer
- Scan spectrum of sample and standard samples
- Set up analysis procedure using the spectrum of standard samples
- Compute the composition of slag using a defined analysis procedure

Results and Discussion

Steel Composition

The chemical compositions of steels produced from different pellet samples under different experimental parameters are listed in Table 1.11. The silicon and manganese levels are very low, generally less than 0.01%, the carbon content varies in the range of 0.12% – 3.35 %, and the phosphorus contents are very low, generally around 0.015%. The sulfur contents vary significantly, and the lowest sulfur content of steel is 0.046%.

The measured composition of steel sample **tt9** does not represent actual composition of the steel. The measured silicon, titanium and vanadium contents of the steel are higher than that of other steels; it is thought that there is a large slag inclusion in the measured area.

Table 1.11. Chemical composition of steels (wt %)

Steel Sample	C	Si	Mn	Cr	V	S	P	Ti
tt1	2.28	< 0.01	< 0.01	0.08	0.25	0.7	0.011	< 0.01
tt2	2.33	0.1	< 0.01	0.13	0.42	0.64	0.009	0.09
tt3	2.4	0.23	< 0.01	0.08	0.31	0.65	0.014	0.01
tt4	1.08	< 0.01	< 0.01	0.05	0.08	0.41	0.016	0.02
tt5	0.6	< 0.01	< 0.01	< 0.01	< 0.01	0.37	0.014	0.01
tt6	2.07	< 0.01	< 0.01	< 0.01	0.07	0.43	0.012	< 0.01
tt7	0.12	0.01	< 0.01	0.02	< 0.01	0.44	0.01	< 0.01
tt8	0.91	< 0.01	< 0.01	< 0.01	0.05	0.41	0.016	< 0.01
tt9	3.35	2.94	< 0.01	0.08	0.75	0.18	0.025	0.22
tt10	1.83	< 0.01	< 0.01	0.01	0.12	0.37	0.013	< 0.01
tt11	0.65	< 0.01	< 0.01	< 0.01	0.13	0.4	0.012	< 0.01
td1	1.22					0.156		
td3	0.566					0.0505		
td4	2.51					0.526		
td5	0.427					0.072		
td6	1.55					0.0469		
td7	1.02					0.469		
td8	1.57					0.486		
td9	2.32					0.306		
td10	2.96					0.318		

The very low silicon and manganese contents of steels indicate that the amounts of silica and manganese oxides reduced in the MW/EAF process are minimums. It is consistent with the facts that the temperature during electric arc heating is about 1350ºC – 1500ºC, and the temperatures for initializing the reduction reaction of silica and manganese oxides are 1490ºC and 1370ºC respectively in the presence of carbon. Low silicon and manganese contents of steel imply that oxide inclusions inside the steels are low. Due to low silicon and manganese contents of hot steel, no effort is needed to remove silicon and manganese via blowing oxygen during steel composition control. The phosphorus level of steels produced by the MW/EAF process is low. This is mainly because the raw materials contain minimal phosphorus compounds.

Slag Composition

The chemical compositions of slags obtained from different pellet samples under different experimental parameters are listed in Table 1.12.

Table 1.12. Chemical composition of slags

Slag Sample	**SiO_2**	**CaO**	**TiO_2**	**MnO**	**FeO**	**Al_2O_3**	**V_2O_5**	**MgO**
sf1	71.82	10.062	6.8977	0.8277	3.6631	5.0624	0.002	1.665
sf2	67.50	10.301	7.5172	1.0863	7.6955	4.2202	0.002	1.681
sf3	69.336	10.564	7.7079	1.114	5.8988	3.5897	0.002	1.7874
sf4	66.957	10.004	3.789	0.429	14.085	3.0805	0.002	1.6545
sf5	65.635	10.629	4.0269	0.5272	13.281	4.121	0.002	1.778
sf6	68.363	11.238	4.2557	0.5572	9.8919	3.8122	0.002	1.8793
sf7	66.135	9.3987	3.7009	0.4539	15.147	3.429	0.002	1.7337
sf8	67.343	9.7843	3.8504	0.4116	13.005	3.4211	0.002	2.1829
sf9	64.194	25.099	2.751	0.4663	4.8182	2.6701	0.002	1.544
sf10	65.987	25.372	2.1318	0.2572	2.9426	3.3075	0.002	1.6098
sf11	63.78	19.331	4.3952	1.2178	2.3426	5.8533	0.002	3.0768
sd1	40.905	40.906	1.8943	0.709	9.5618	3.38	0.002	2.6359
sd3	42.416	46.31	2.5667	0.5188	3.3657	3.0761	0.002	1.7441
sd4	67.605	20.252	2.7342	0.4506	3.1068	1.923	0.002	3.9216
sd5	38.629	44.725	1.813	0.9377	9.6628	0.8187	0.002	3.4094
sd6	38.27	44.365	5.5944	1.1577	4.1715	2.9705	0.002	3.4664
sd7	54.034	31.334	4.2549	0.7529	1.3392	5.4964	0.002	2.785
sd8	50.918	34.666	1.979	0.6567	3.1147	5.5108	0.002	3.1508
sd9	47.631	29.51	4.4842	0.6375	2.8286	4.7509	0.002	10.155
sd10	49.936	32.088	3.1404	0.8548	1.0779	3.6481	0.002	9.2526

Table 1.12 illustrates that slag composition varies significantly and the major constituents of most slags are SiO_2 and CaO. Some slags contain a large quantity of unreduced iron ore. Some contain a large quantity of magnesia due to magnesia in the crucible lining material. Compared

with BF slags, the alumina level of these slag samples is lower, because the fluxing material for the MW/EAF process is mainly lime.

Figure 1.19 exhibits two diffractograms of slags. The slags contained a high glass phase content. Some unreduced iron ores in the slags were transformed into pseudo-brookite (Fe_2TiO_5) and some still existed as iron oxide.

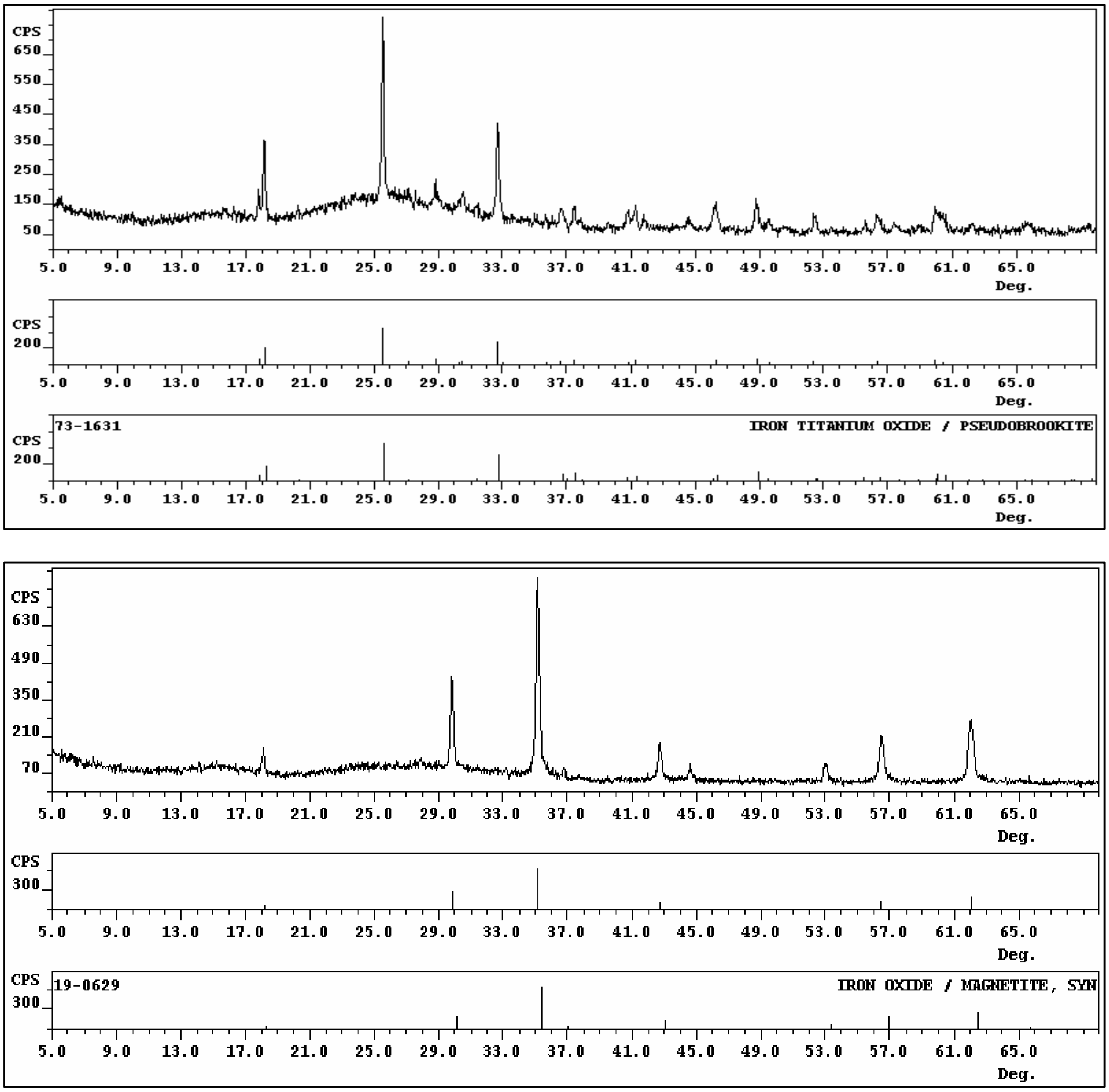

Figure 1.19. XRD spectrums of low steel yield slag

A broad background feature on the baseline displays a high content of glass phase. The first spectrum in Figure 1.19 indicates that the slag contained a crystalline phase component pseudo-brookite (Fe_2TiO_5). The second spectrum in Figure 1.19 indicates that the slag contained magnetite; this crystalline phase component is thought to be unreduced iron ore.

Effect of Coal Ratio on Carbon Content of Steel

Figure 1.20 illustrates the variation of the carbon content of the steel samples with respect to the coal to magnetite ratios of pellet samples. The steels produced from high coal pellets have higher carbon content than that of steels produced from lower coal pellets. The minimum carbon content and the average carbon content of steels, with a steel yield over 95%, are 0.427% and 1.49% respectively.

Figure 1.20 also indicates a wide variation of carbon content of steels produced from the same pellet samples. It is an indication of unstable furnace operations. Different operators may generate very different steelmaking results.

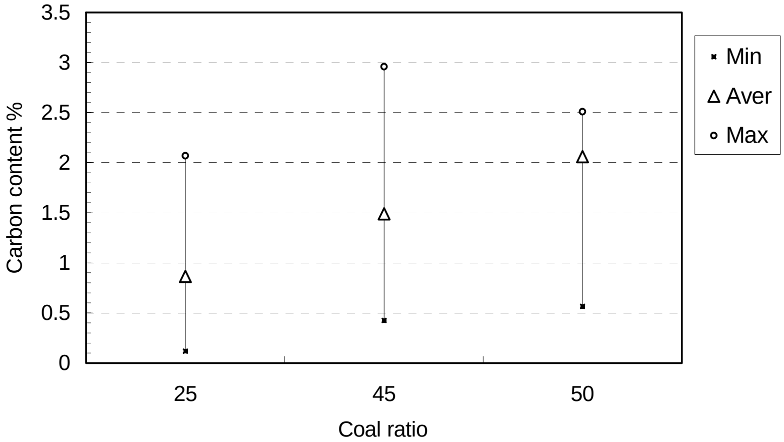

Figure 1.20. Variation of carbon content with pellet coal ratio

Factors Effecting Sulfur Content of Steel

Figure 1.21 illustrates the effect of slag's basicity ratio on the sulfur content of steel. The average sulfur content of the steel decreases as the slag basicity ratio increases. When the slag basicity ratio was between 1.0 – 1.3, both the average sulfur content of the steels and the maximum sulfur content of the steel produced were the lowest among the three groups of steels.

In these experiments, slag basicity is mainly dependent on the lime-magnetite ratio of the pellet sample, crucible used, and crucible lining materials. All slag with a basicity ratio greater than 1.0 was actually generated using magnesia crucibles, as illustrated by Figure 1.22.

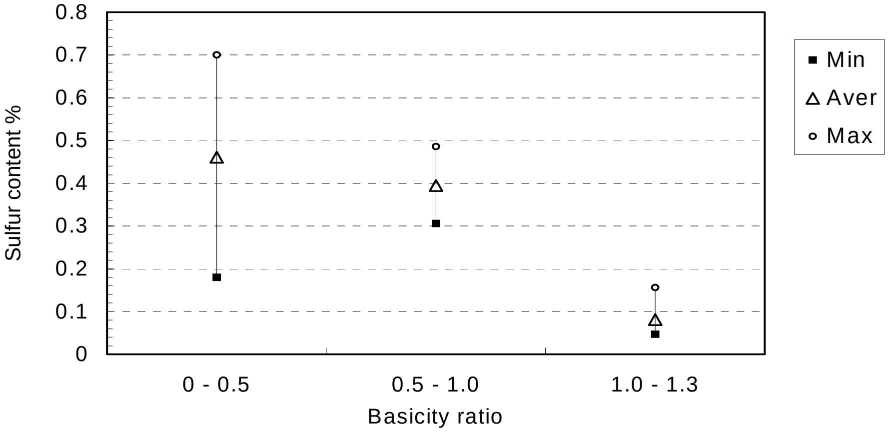

Figure 1.21. Effect of basicity ratio on sulfur content of steel

Figure 1.22 illustrates the effects of crucible and lining on the sulfur content of steel. The sulfur content of the steel samples can be significantly reduced by using magnesia crucibles in combination with lime lining. Steel with minimum sulfur content of 0.047% were achieved by using magnesia crucibles and lime lining. The sulfur content of steels produced by fireclay crucibles with magnesia lining is a little lower than that of steels produced by fireclay crucibles with lime lining.

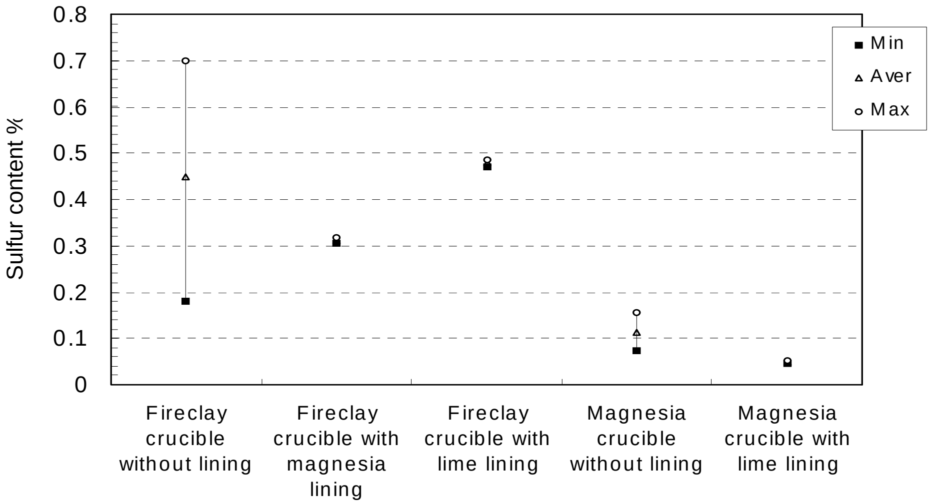

Figure 1.22. Effects of crucible and lining on sulfur content of steel

The average sulfur content of steels produced using fireclay crucibles is nine times higher than that of steels produced when using magnesia crucibles with lining, and is four times higher than that of steels produced by using magnesia crucibles. The change in the basicity ratio of slag due to the interaction between crucible, lining materials and slag results in the significant differences. More information was determined after post-mortem analysis of fireclay crucibles. Fireclay crucibles, even when coated with lining, were severely corroded and most of the interior of the crucible dissolved into slag. But the magnesia crucibles were not corroded. The lower portion of the lime linings coating fireclay crucibles were totally dissolved into slag, but the low portion of lime linings coated on magnesia crucibles were only partially dissolved into slag. The dissolved crucible or lining materials definitely changes the basicity ratio of slag, so crucible and lining composition are important factors for producing steels with lower sulfur levels.

Slag Basicity

Figure 1.23 illustrates the variation of the slag basicity ratio with the lime-magnetite ratio of pellet samples when using fireclay crucibles. Figure 1.23 indicates that the basicity of slags generated in fireclay crucibles by pellet samples with a lime-magnetite ratio less than 35/100 were below 0.4; Pellet samples with high lime-magnetite ratios usually generated slag with high basicity.

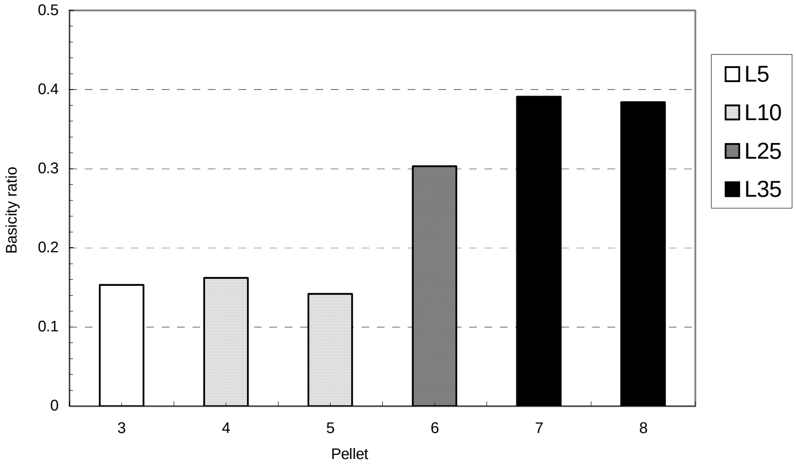

Figure 1.23. Variation of slag basicity ratio with lime ratio of pellet sample when using fireclay crucible

Due to the reaction with lime in slag, the fireclay crucible interior eroded badly and dissolved into slag. Assuming that no materials from the crucible are dissolved, the theoretical basicity of slag formed by pellet sample #6 is

2.2. Based on the temperature of slag and the theoretical basicity of slag, it can be deduced that the major proportion of the dissolved oxides is acid oxide silica. So simply increasing the lime ratio of pellet samples is not an effective method for increasing the basicity of slags in fireclay crucibles.

Figure 1.24 illustrates the basicity ratios of some slag generated in fireclay crucibles coated with different lining materials. No significant difference between lime and magnesia linings was observed, and lining can increase the basicity ratio of slag formed in fireclay crucibles.

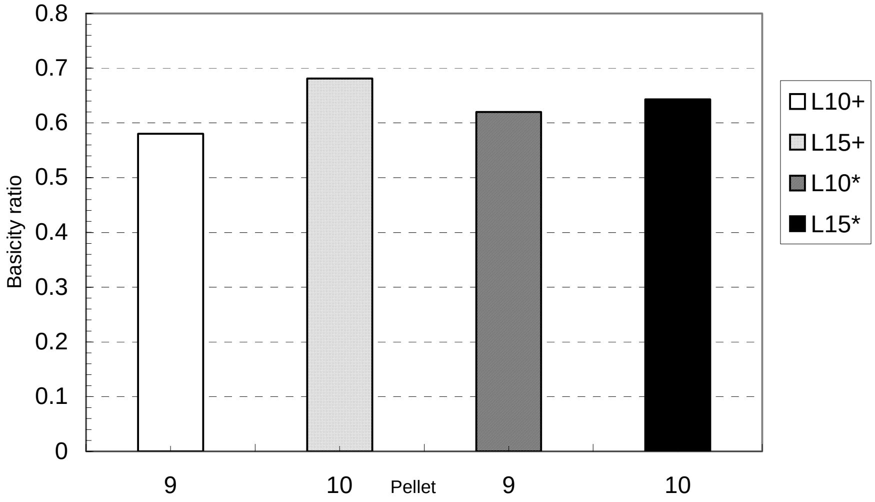

Figure 1.24. Basicity ratio of slag generated in fireclay crucible with lining Where + indicates lime lining, and * indicates magnesia lining

The slags generated from pellet samples with a lime ratio 10/100 or 15/100 in coated fireclay crucibles had basicity ratios in the range of 0.55 – 0.7. Comparing with the basicity ratios of the slags in Figure 1.23, the increase of slag basicity ratios by using linings was considerable. Lining layers of about 0.5 inches thick had a small temperature gradient, so it could not lessen the extent of crucible corrosion by hot slags, and the increase of slag basicity came from the solution of lime or magnesia into the slag.

Figure 1.25 illustrates the basicity ratios of slags generated in magnesia crucibles with or without lime lining. The basicity ratios of the slags generated in magnesia crucibles were generally higher than that of slags generated in fireclay crucibles and were in the range of 1 – 1.2. Lime lining could increase the slag basicity ratio about 0.05 – 0.15. The increase of slag basicity due to lime lining was dependent on pellet samples. The less the lime ratio of pellet samples, the more increase in the basicity ratio of the generated slag.

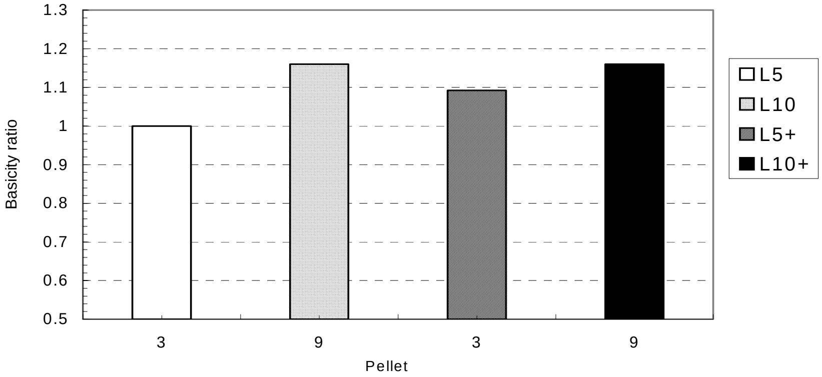

Figure 1.25. Basicity ratios of slag generated in magnesia crucible with or without lining. Where symbol + means lime as lining

As illustrated by the liquidus isotherms of ternary system CaO – SiO_2 – FeO, molten slag with very low iron oxide content and high content of molten lime mainly consists of compounds 3CaO-SiO_2, 2CaO-SiO_2 and 3CaO-2SiO_2. These compounds have a basicity ratio in the range of 1.3 – 2.3, and their melting points are above 1500 °C. So the basicity ratio of slag generated by using a magnesia crucible with lime lining at temperatures below 1500 °C had already reached the maximum possible value.

Conclusions

Most of the steels produced using the MW/EAF process had silicon and manganese levels less than 0.01% and an average phosphorus level of 0.015%. The carbon levels of the steels were in the range of 0.12% - 3.35 %.

The minimum carbon content and the average carbon content of produced steels were 0.472% and 1.49%. The steel carbon content correlates with the coal ratio of pellet samples. The minimum carbon content and the average carbon content of steels produced from pellet samples with a high coal ratio generally are higher than that of steels generated from pellet samples with a low coal ratio.

The sulfur content of steel correlates with the slag basicity. When slag basicity is in the range of 1.0 – 1.3, both the average sulfur content of steels and the minimum sulfur content of steel are the lowest. The lowest sulfur content of steel produced from the MW/EAF steelmaking tests is 0.0469%.

Slag basicity is dependent on the lime ratio of the pellet sample, the type of crucible and lining material. Slag basicity increased with the increase of the lime ratio of the pellet sample. Crucible lining can increase slag basicity to some extent. Lime is a slightly better lining material than magnesia for obtaining both high basic slags and steels with low sulfur level.

Slag with high basicity can not be obtained using fireclay crucibles, even though the lime ratio of the pellet sample is as high as 35/100 and different lining materials are used. In order to obtain slag with basicity in the range of 1.0 – 1.3, magnesia crucibles must be used and the lime ratio of the pellet sample can be as low as 10/100.

All steels with lower sulfur levels (around 0.05%) were obtained using magnesia crucibles with lime as lining and pellet samples with a lime ratio of 5/100 or 10/100. Consequently, it is unnecessary to use pellet samples with very high lime ratios in order to produce low sulfur steel, if magnesia crucibles with lime lining are used.

1.3 Iron Ore Reduction by Microwave Assisted Hybrid Heating

Experiments conducted in baseline microwave steelmaking and bench-scale MW/EAF steelmaking have shown that the majority of the volatiles in coal do not participate in iron ore reduction or iron ore heating in an open reactor. The volatiles come out of the iron ore pellet mass before iron ore reduction starts. In addition, excessive fixed carbon in iron ore pellets reacts with oxygen to form CO, which is also released from the iron ore pellet mass. Both the volatiles and CO contain a great amount of chemical and thermal energy. These gases burned above the iron ore pellet mass in our experiments and had no contribution to the heating of iron ore pellets. This chemical and thermal energy must be utilized. One way of utilization is to preheat iron ore. If successful, the energy utilization can reduce the microwave power requirement. The hybrid heating concept could be further extended to conventional heating equipment such as conventional DRI production. An addition of microwave heating to conventional heating could greatly improve heat transfer to thick mass materials. This experiment was designed to provide some preliminary results.

Experimental Method

Apparatus

The experiments were conducted using a self-made thermo-gravimeter shown in Figures 1.26 to 1.28. Figure 1.29 shows a schematic diagram of the apparatus. A mullite pipe (OD=2", ID=1.97", L=48") is put through the microwave oven (GE RVM1335, 900W). The pipe, which lies in the cavity of the microwave, is covered by electrical heating elements (2400 W); the remainder of the cavity is filled with alumina oxide bricks and fiber glass for heat insulation. A stainless steel sheathed thermocouple is inserted through the top of the pipe for monitoring and controlling the temperature in the reactor.

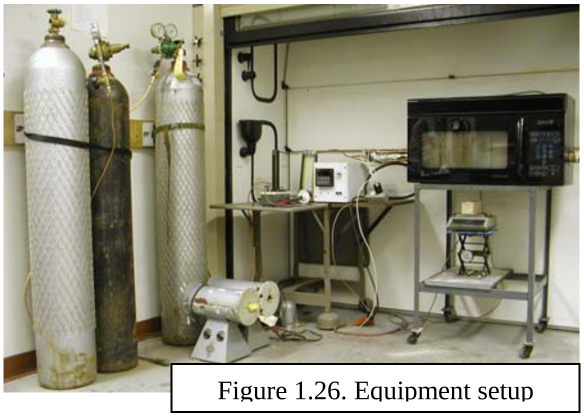

Figure 1.26. Equipment setup

One end of the mullite pipe is connected to the outlet of the gas cylinder, and the flow rate of the gas is controlled by the flow meter. The other end of the mullite pipe is open to the air for the release of the reaction and product gases. The entire reactor system is installed in a fume hood in order to minimize exposure to potentially noxious gases.

Figure 1.27. Equipment control (temperature controller, flow meter, microwave detector)

Figure 1.28. Reactor portion of the apparatus (microwave oven, mullite pipe and digital balance)

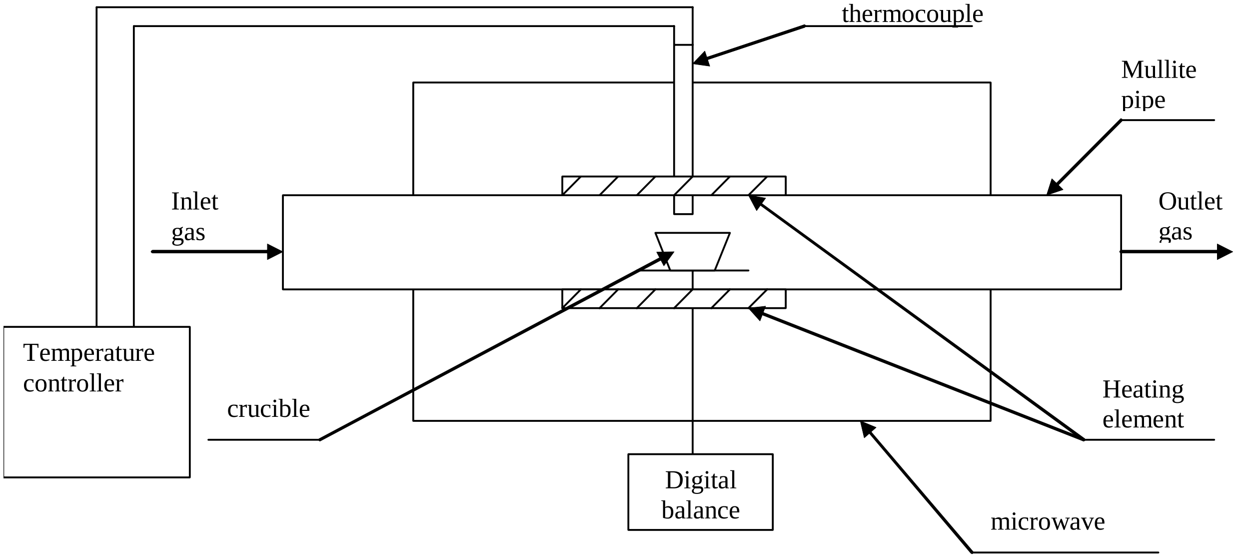

Figure 1.29. Schematic diagram of hybrid heating apparatus

According to experiments done by J.A. Aguilar, temperature information provided by either stainless sheathed thermocouples or optical pyrometers are in good mutual agreement. The disadvantage of an optical pyrometer is that it can only measure the surface temperature, while the disadvantage of a thermocouple is that it is difficult to obtain a readable signal (values on the display are changing too fast when microwaves are applied). Also according to J.A. Aguilar, high purity aluminum oxide crucibles will not affect reducibility. In our system, we used aluminum oxide crucibles and stainless steel sheathed thermocouples to address these factors.

Materials

Pure synthesized Fe_3O_4 powder provided by Harcros Pigments Inc. (11 Executive Dr., Suite 1 Fairview Heights, IL 62208) was used in this study.

Reducing Agents

Volatiles consist of hydrocarbons and can be reformed into H_2 and CO. Both gases are good iron ore reducing agents. In this study, both gases were used, either singly or as a mixed gas, as the reducing agent. Ar and N_2 were used to dilute both gases. These were selected to protect the reduced iron from being re-oxidized because the reduced iron in this system is highly reactive and can be easily re-oxidized.

Experimental Procedure

- Weigh the sample using the digital balance
- Turn on the hood

- Add sample in the crucible
- Put the crucible charged with sample on the crucible holder in the mullite pipe
- Adjust the balance
- Connect one end of the mullite pipe to the flow meter
- Turn on the Argon or Nitrogen, adjust the gas flow rate and let the gas flow for 15 minutes to purge the oxygen from the mullite pipe
- Turn on the reducing gas, adjust the flow rate and let the reducing gas flow for 10 minutes to make sure the concentration in the mullite pipe is uniform
- Turn on the power of the conventional heating or microwave heating, and record the time, temperature, and balance data.
- After the experiment, analyze the sample.

Results and Discussion

Four different experiments were conducted to evaluate the following scenarios: 1) reduce magnetite by conventional heating held at 500ºC; 2) reduce magnetite by conventional heating held at 1000ºC; 3) preheat magnetite by conventional heating up to 500ºC and then turn on microwave heating and shut off conventional heating; and 4) heat magnetite with conventional and microwave heating simultaneously from ambient temperature to 500ºC and then continue microwave heating and shut off conventional heating. A mixture of Ar and H_2 was used as the reducing agent. The gas flow rates were the same for all four tests. The weight loss of the magnetite sample over time was recorded. Reduction degree is defined as the degree of oxygen atom loss in iron oxide. Using the weight loss of the magnetite sample, reduction degree can be calculated. H_2 is known as a better reducing agent than CO for iron ore due to lower reduction temperature, around 500ºC, and higher diffusion rate. Several existing DRI processes such as fluidbed DRI process use hot hydrogen as both a heating source and reducing agent.

The experimental data is plotted in Figure 1.30. We can see that microwave assisted heating dramatically decreased the reduction time of conventional low temperature reduction. And, in comparison with conventional high temperature reduction, microwave assisted heating further shortens reduction time. Microwave assisted heating can be combined with conventional heating in two ways: concurrent heating or conventional preheating followed by microwave heating. Concurrent heating can enhance existing heating equipment with the addition of microwave heating. A second option, hybrid heating, could utilize off-gases for pre-heating, followed by microwave heating.

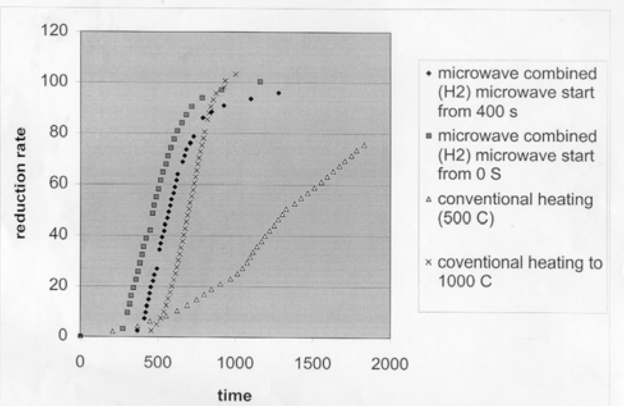

Figure 1.30. Comparison of conventional and microwave assisted magnetite reduction

Reforming volatiles will generate a mixture of CO and H_2. It has been reported that a mixture of CO and H_2 at a ratio of 3:1 is a better reducing agent than either CO or H_2 because reduction by CO is weakly exothermic and reduction by H_2 is strongly endothermic. Using the gas mixture, reduction takes place with almost no release of heat. Figure 1.31 compares using either CO or H_2 as the reducing agent or two mixtures of CO and H_2 as the reducing agent for microwave assisted magnetite reduction. A mixture of CO and H_2 as the reducing agent can significantly decrease reduction time under microwave irradiation conditions.

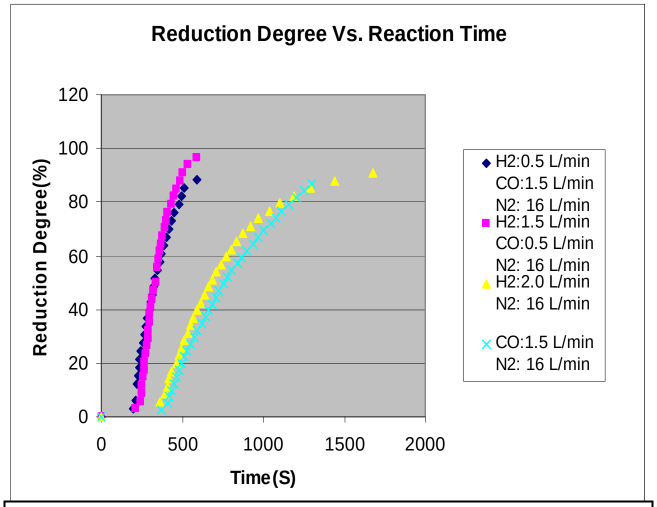

Figure 1.31. Reduction degree versus time (start microwave after conventional heating up to 773 K)

During our experiments, we found that there is an abrupt increase of temperature in microwave combined heating. In order to investigate this phenomenon, we ran the test without any iron oxide sample in the system. The experimental result is shown in Figure 1.32. The temperature increases from 773ºK to 1073ºK in less than 10 seconds. Then the temperature remains stable around 1073ºK. This temperature is the gas temperature due to the microwave induced plasma. Several experiments were repeated to verify the phenomena and the results are also shown in Figure 1.32. We found that only a reaction system where hydrogen exists can generate microwave induced plasma, once the hydrogen was turned off, the microwave induced plasma disappeared. This phenomenon is in agreement with data reported in the literature. The source of additional power corresponding to the elevated temperatures may be an energetic reaction of atomic hydrogen caused by a resonance energy transfer between hydrogen atoms and Ar+.

According to R.L. Mills, the average electron temperature **Te** for the Argon-Hydrogen was high, 11,600 ±5%ºK. This high electron temperature may be another reason why microwave combined heating can increase the reduction rate of iron oxide.

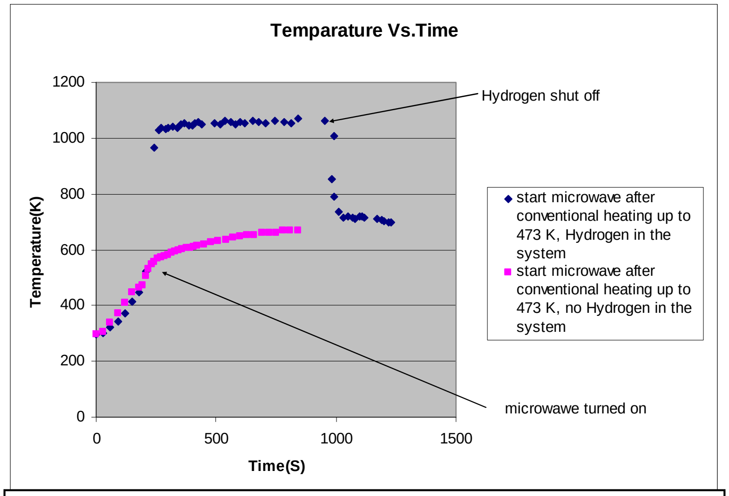

Figure 1.32. Temperature versus time (Ar: 10 L/min, H_2:2 L/min)

We conducted a similar test, changing H_2 to CO. As shown in Figure 1.33, the phenomenon is the same as the test done using H_2. The test was repeated, changing the inert gas from argon to nitrogen. From the experiment result shown in Figure 1.34, we can see that microwave induced plasma also occurred in the N_2 system.

The initial temperature at which the microwave is turn on plays an important role in the generation of microwave induced plasma. Only when the initial temperature reaches a certain point does microwave induced plasma occur, as shown in Figure 1.34. There appears to be a threshold temperature triggering the microwave induced plasma. Of course, for different reducing gas, different inert gas, and different flow rate, the threshold temperature should be different. In the future, for a specific system, the critical threshold temperature should be found and optimized.

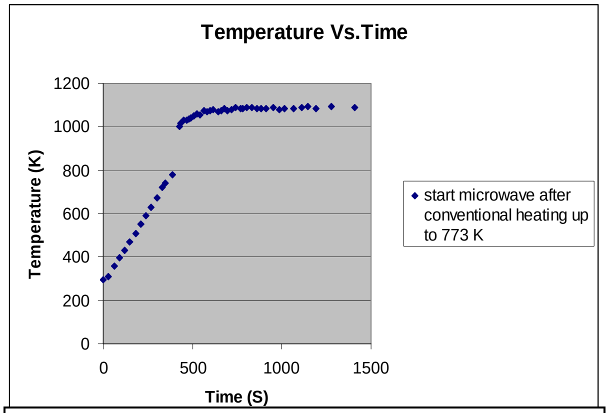

Figure 1.33. Temperature versus time
(Ar: 10 L/min, CO: 1.5L/min)

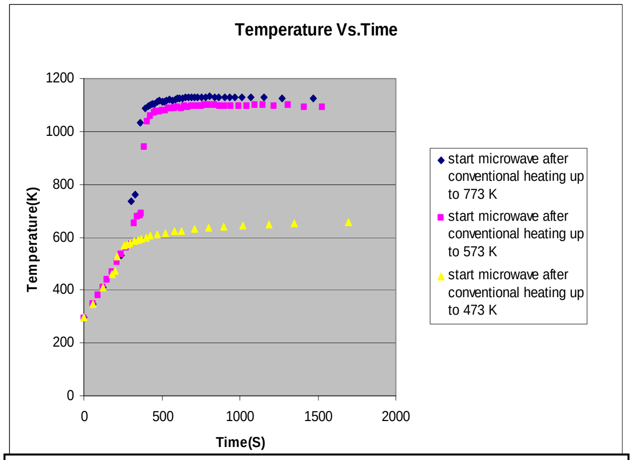

Figure 1.34. Temperature versus reaction time
(N2:16L/min, H2:0.6 L/min)

Conclusions

In comparison with conventional heating, microwave assisted hybrid heating can significantly reduce iron oxide reduction time.

A mixture of H_2 and CO is a better reducing agent than either H_2 or CO alone as the reducing gas for iron ore reduction under microwave assisted heating. The mixture can significantly reduce reduction time.

Microwave assisted heating can have a “temperature jump” phenomenon in both Ar and N_2 atmosphere. The generation of the “temperature jump” phenomenon depends on the reducing gas flow rate, the temperature at which microwave irradiation starts, and the inert gas. In general, at the same flow rate of reducing gas and by using the same inert gas, it is easier to find the “temperature jump” phenomenon when microwave irradiation starts at a higher temperature.

Task 2. Potential Applications and Flowsheet Development

During the execution of this project, we conducted many experiments, collected and reviewed related literature, and discussed the MW assisted steelmaking technology internally and externally. We have envisioned various alternative scenarios in which MW energy could be utilized for steelmaking. These alternatives have both advantages and disadvantages in one way or another. It is premature to conclude which one is the best and rule out the others. These alternatives are presented and discussed in this section.

A flowsheet represents activities and subsequent flow pattern of input and output of a process. The activities are usually discrete in purpose and are performed using certain types of equipment. The flow patterns of input and outputs have certain characteristics such as phase, composition, and volume that have to be addressed relative to the process's main purpose. Thus the flowsheet represents a visual illustration that defines some technical, economic and environmentally based logic to accomplish the main purpose. With still limited knowledge of MW assisted steelmaking, we can only propose conceptual flowsheets.

It is possible to utilize MW energy to assist steelmaking in several alternatives. From the operation point of view, these alternatives could be divided into batch and continuous operations. From the equipment point of view, these alternatives could be divided into MW/EAF integrated units and MW/EAF separated units. From the product point of view, these alternatives could be divided into direct steelmaking and DRI production. To facilitate discussions, we distinguish these alternatives in six groups: 1) direct steelmaking by batch operation, 2) direct steelmaking by continuous operation, 3) MW/EAF integrated units, 4) MW/EAF separated units, 5) MW assisted DRI production, and 6) MW only DRI production.

Each alternative implies significant impact on equipment requirements, production line and management, and has associated advantages and disadvantages. The concept of MW assisted steelmaking can be considered as a revolutionary change to the current steelmaking processes. To reduce obstacles of executing this new technology, it seems best to maximize utilization of existing equipment and technologies, or in the other words, combine MW heating with existing equipment and technologies to achieve the maximum economic benefit. The discussions on possible alternatives follow.

1) Direct Steelmaking by Batch Operation

This alternative is to produce molten steel directly from a shippable agglomerate consisting of iron oxide concentrate, coal, and fluxing agent without the intermediate steps of coking, sintering, BF ironmaking, and BOF steelmaking. To achieve this goal, a commonly used EAF furnace could be modified with the introduction of microwaves into the chamber through a single or multiple waveguides or through multiple windows if MW generators are mounted on the wall of the furnace chamber. The viability of this alternative relies on rapid (30 minutes or less) iron ore reduction in the furnace by MW irradiation. The cycle time of each batch operation including raw material charging, MW heating, EA heating, slag discharge, refining, and molten steel discharge is less than 60 minutes.

In this alternative, iron ore is crushed, ground, and concentrated by conventional processing. The concentrated iron oxide is mixed with pulverized coal and limestone, and then agglomerated at ambient temperature for shipping strength. The coal serves as a reducing agent for iron oxides and as an auxiliary heat source via exothermal reaction in the presence of oxygen. Limestone is used as the fluxing agent.

The potential application of this technology is to modify EAFs with an auxiliary microwave heating system as shown in Figure 2.1. A port (101) is created in the cover (102) of a conventional EAF to introduce microwaves (103) into the chamber (104) through a waveguide (105). A charge of iron oxide/coal/limestone (ICL) agglomerate (106) is loaded into the chamber. Microwave energy is introduced through the waveguide, where the agglomerates absorb microwave energy and their temperature rises to the point of coal ignition.

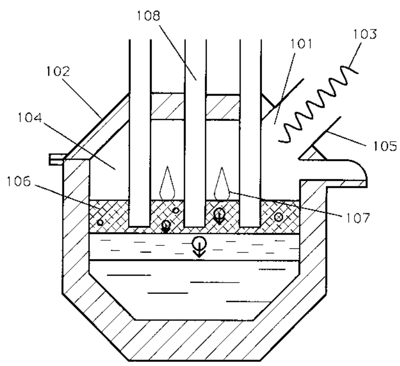

Figure 2.1. Batch Operation Microwave Electric Arc Furnace

Exothermal heat from the carbon/oxygen reaction (107) is generated to further increase temperature. The iron oxide then reacts with the reductant to become directly reduced iron. The EAF electrodes (108) then descend to provide electric arcing energy to the material, producing molten steel and slag. The molten slag and steel are removed by conventional methods utilizing the tilting of the furnace chamber. Thus the furnace can use feed ranging from 100% scrap to 100% ICL agglomerates.

This alternative requires intensified MW input to the chamber in order to achieve very quick iron ore reduction. It is a challenge for the current MW equipment manufacturers to manufacture an integrated high power MW generator at low cost. Multiple small MW generators could be a solution to this problem.

The advantages of this alternative include minimum reduction needed, to the degree of being a good electric conductor, continuous reduction by MW and EAF heating, no reoxidation, and a single furnace for both reduction and smelting. The disadvantages include difficulty of MW seal and difficulty of residual heat utilization.

2) Direct Steelmaking by Continuous Operation

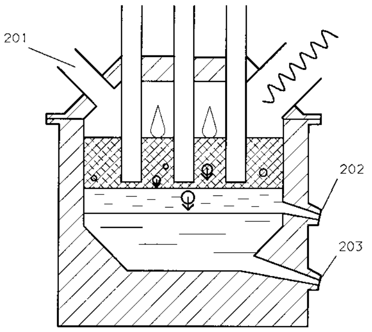

Figure 2.2. Continuous Operation Microwave Electric Arc Furnace

The second alternative is to design and build a submerged arc electric furnace which can be operated continuously as depicted in Figure 2.2. The furnace chamber will be stationary and corporate the steps of the first alternative, but in continuous fashion, utilizing feed chute (201) and tap holes for steel (202) and slag (203) discharge. The design will incorporate issues of geometry, timing, and durability of materials of construction. During operation, the raw materials are continuously fed into the chamber and molten steel and slag accumulate on the bottom of furnace. After molten steel or slag reaches a certain level, it will be discharged through its tap hole. The tap hole will be blocked after completion of discharging until the next cycle. This continuous operation is similar to the continuous operation of BF.

Direct steelmaking using either of these two microwave alternatives will greatly simply current steelmaking. Figure 2.3 compares the flowsheets of the MW assisted direct steelmaking with the flowsheet of traditional steelmaking.

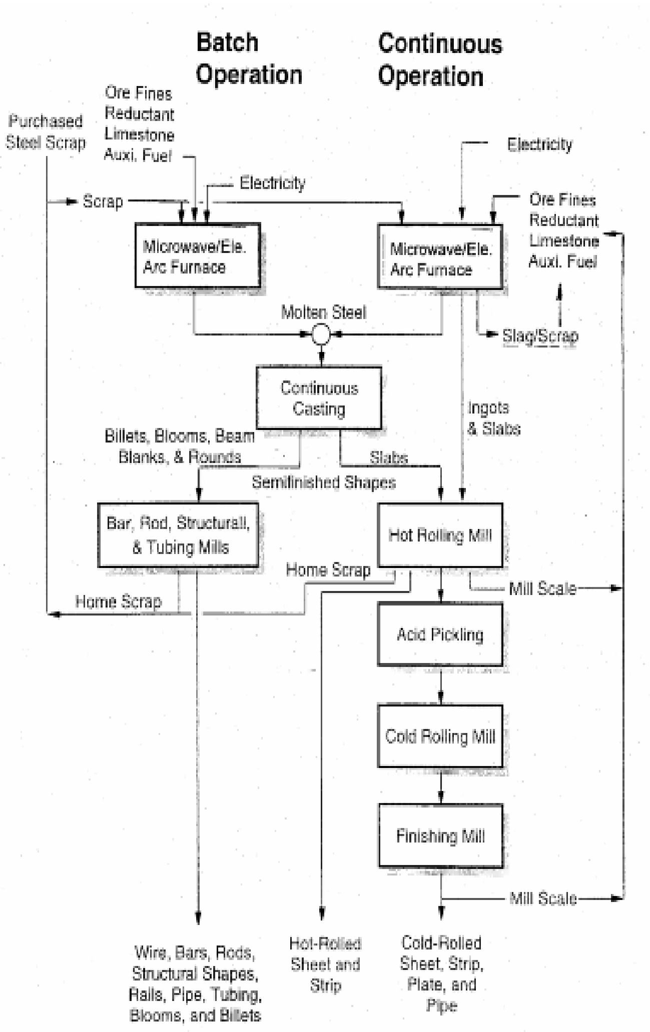

Figure 2.3. Flowsheet comparison of conventional versus MW/EAF steelmaking

From the comparison we can see that many intermediate steps would be eliminated if MW assisted steelmaking technology is adopted. Downstream hot and cold processes remain intact.

3) MW/EAF Integrated Units

The alternatives described above are integrated MW/EAF units. The integrated units simplify the operation in that there is no hot metal transfer and associated problems. However, an integrated unit may lower the maximum use of valuable capacity. For example, MW and EAF heating capacities are very valuable and should be used to their extremes. In integrated units, the EAF power is idle during MW reduction and MW power may be partially idle during EAF heating in the first alternative. To effectively use both MW and EAF heating, MW and EAF heating could be separated. In such arrangement, MW heating will focus on iron ore reduction and EAF heating will focus on smelting and refining.

4) MW/EAF Separated Units

There could be many sub-alternatives of separated MW/EAF units dependent on how to design the two units and link them together. One common feature of the sub-alternatives we define herewith is the transfer of hot DRI directly into an EAF. A simple case is to design a separate MW unit for reduction and use an existing EAF for smelting with a hot DRI transfer mechanism. Such MW/EAF separated units will create fewer disturbances to current EAF operation. Effort can be focused on the new MW assisted iron ore reduction unit. The unit could precede an EAF operation, forming a line of iron ore reduction, hot metal charge and smelting. Transfer of hot DRI and capacity matching between DRI and EAF need to be carefully designed for this type of setup. Figure 2.4 presents a flowsheet of steelmaking based on the use of MW/EAF separated units.

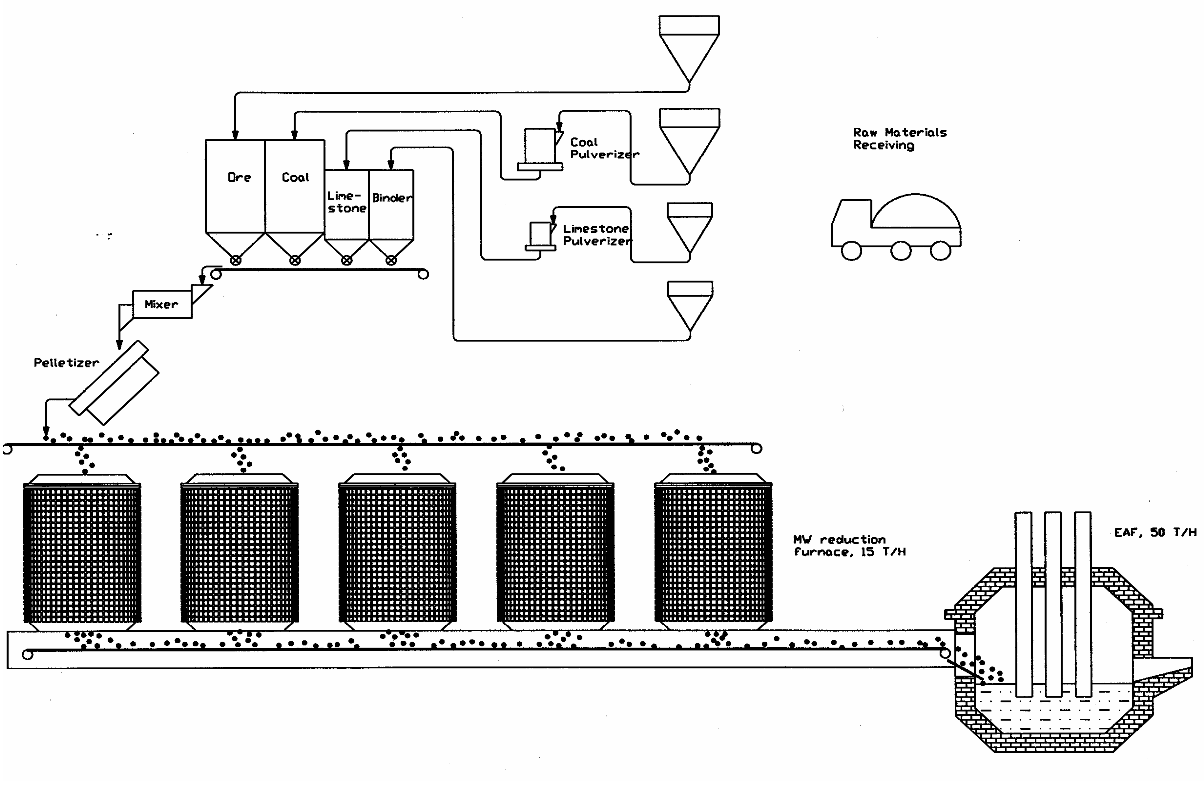

Figure 2.4. Flowsheet for steelmaking using separated MW/EAF units

A totally new, separated MW/EAF unit could be designed as well. Noramco, a steelmaking engineering firm, constructed a conceptual design of how to build a MW/EAF unit based on multiple 1.5 kW MW generators. Figure 2.5 presents the conceptual design. In the design, fourteen iron oxide reducing hoppers are set above a submerged are furnace (SAF). Each reducing hopper has multiple 1.5 kW magnetrons mounted on its wall. Mixed raw material is fed into each hopper through an annular slipstick conveyer. Iron oxide is reduced by MW irradiation and discharged into the underneath SAF. Molten steel and slag are continuously produced.

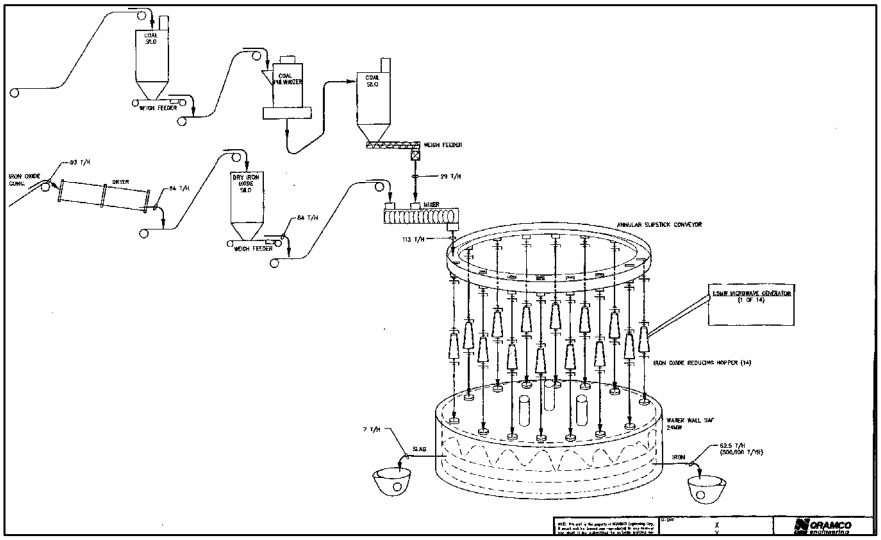

Figure 2.5. Conceptual design of MW/EAF unit based on 1 kW MW generator.

The MW unit could be totally separated from the EAF and operated as an independent entity, producing cold DRI as its product. This MW entity could sell DRI to mini mills. That method of operation may lower overall energy efficiency and cause reoxidation due to hot DRI cooling. However, it eliminates the problem of matching two operations.

5) MW Assisted DRI Production (Hybrid Heating)

As an alternative to direct steelmaking in an integrated MW/EAF unit as discussed above, there is the possibility of utilizing MW heating to assist DRI production. In this alternative, DRI is produced by combining conventional heating with MW heating. The purpose is to significantly shorten the reduction time and lower the reduction temperature of currently used DRI processes.

The current DRI processes can be classified into four categories: Gas/Shaft, Gas/Fluid Bed, Coal/RHF, and Coal/Fluid Bed. The common problem in conventional DRI processes is low reduction efficiency due to 1) slow heat transfer from outside to inside through the powdered, poorly thermal conducting material, and 2) slow mass transfer of reducing gas and product gas between outside and inside through the porous iron ore pellets. Possible use of MW heating in these processes to improve their performance is discussed in the following sections.

Gas/Shaft Process

Figure 2.6 illustrates an example of the gas/shaft process. This process blows hot CO and H_2 through iron ore contained in a shaft furnace to reduce the ore. The hot mixture of CO and H_2 is the only heating source to heat the ore. CO and H_2 also function as the reducing gases. To generate the mixture of CO and H_2, natural gas is utilized. The natural gas is mixed with CO_2 and/or H_2O and heated by a fuel in a reformer to form CO and H_2. The gas is of low heat capacity. It passes heat to iron ore primarily through convection heating. It is not practical to get CO and H_2 to very high temperature for increasing heat transfer. The gas operation temperature is about 900°C. There are also many heat losses in the entire system. The energy efficiency is low.

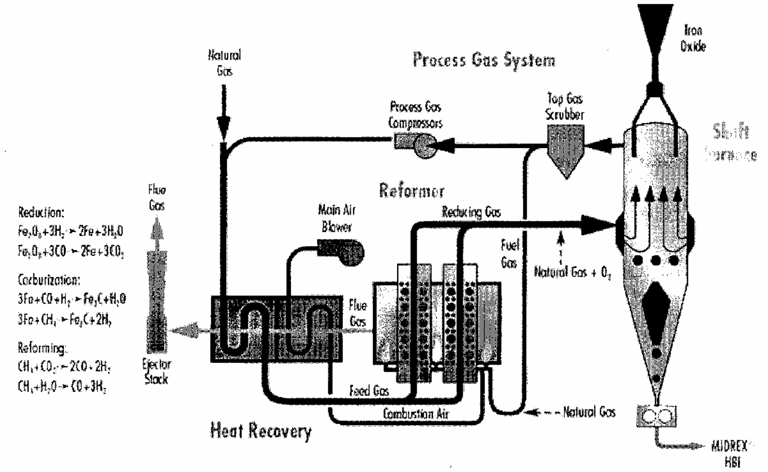

Figure 2.6. Gas/shaft DRI process

MW heating can be utilized in this process to eliminate the reformer and change the heating source from hot gases to iron ore volumetric heating. Figure 2.7 illustrates the potential change. In this alternative, MW will heat iron ore in the shaft to the desired reducing temperature in a very short time. Natural gas will be circulated through the shaft in conjunction with exhaust gases, which are the source of CO_2 and H_2O. The hot bath of iron ore is an in-situ reformer to convert hot natural gas into hot CO and H_2 which will be the reducing agents. This modified DRI process has the potential of higher energy efficiency and higher production rate.

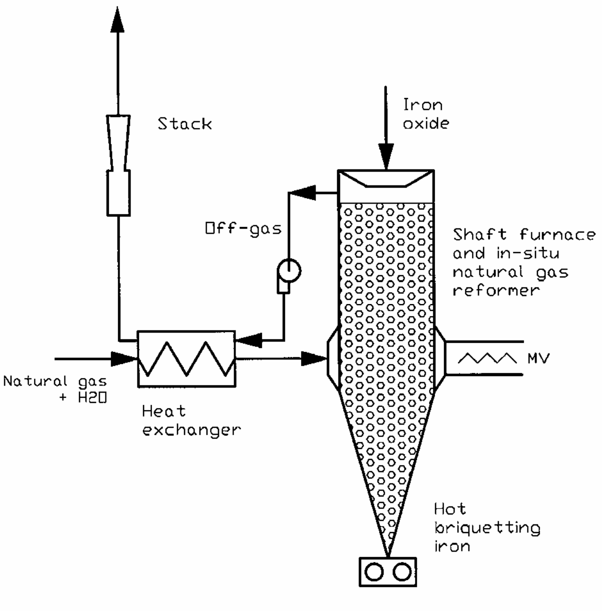

Figure 2.7. MW assisted gas/shaft process

Rotary Kiln

Figure 2.8 presents a flow diagram of this type of DRI processes. This process uses coal as the reducing agent. Iron ore blended with limestone and coal is fed into a rotary kiln. Natural gas or oil is used as fuel to produce flames to heat the materials and the wall of kiln. Heat is transferred to the materials through radiation, convection and direct contact with the rotating wall. A large amount of heat is lost, carried away by exhaust gases, because of large free space above the materials in the kiln. The energy efficiency is low in this kind of furnace.

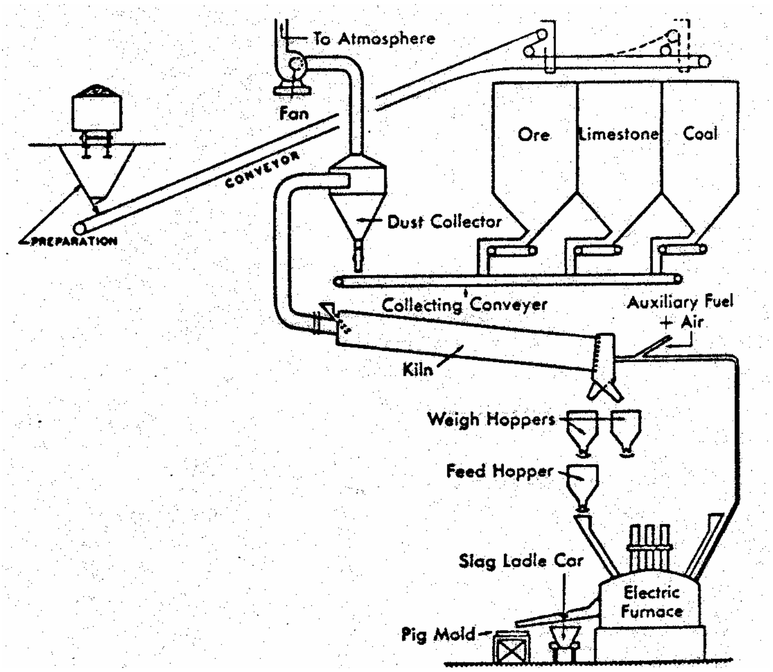

Figure 2.8. Rotary kiln DRI process

It is possible to replace fuel combustion with MW heating in a rotary kiln DRI process. The MW heating zone will be located near the exit port of the kiln. The raw material in that region will be heated to an elevated temperature in a short period of time. The coal in the raw materials will react initially with O_2 in air to form CO. In the reducing atmosphere at the elevated temperature under MW catalytic irradiation, iron ore will be quickly reduced. The exhaust gases consisting of volatiles from coal, CO/CO_2, H_2O and other gases will pass through the rest of the materials in the kiln to transfer heat from the gases to the materials. Because the exhaust gases at the exit port of kiln still contain fairly high amounts of hydrocarbons, CO and H_2, the gases will be circulated back to the kiln as a gaseous reducing agent. The hydrocarbons in the coal volatiles will be converted into CO and H_2 in the MW heating region with the presence of CO_2 and H_2O. If necessary, additional air and water will be injected into the stream to facilitate the formation of CO and H_2. Because there won't be air required for combustion, the raw materials can be more fully charged into the kiln. There will be much less exhaust gases released to air. Therefore the energy efficiency is expected to be much higher. There is potentially no need for a dust collector. The dust will be circulated back into the kiln along with the exhaust gases. Figure 2.9 illustrates the concept.

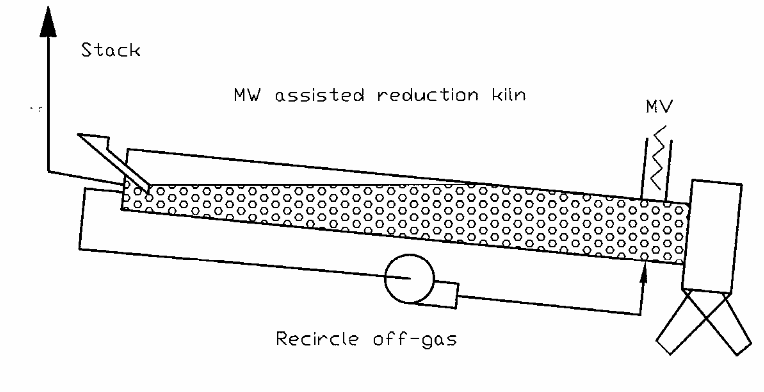

Figure 2.9. MW assisted rotary kiln DRI process

Fluidbed DRI Process

Figure 2.10 is the flow diagram of a fluid bed DRI process. This process uses nearly pure hydrogen as the reductant. Iron ore in the size of -10 mesh + 325 mesh is preheated to 900-1000°F in a rotary kiln or a fluid bed heater. The hot ore is then transferred to a charge hopper which is pressurized to 600-650 psi. The ore is transferred continuously from the charge hopper to the topmost bed of the reactor. A portion of the total reduction is done in the top bed by partially spent hydrogen. The solids are then dropped to the next lower bed which has been emptied by dropping its solids to yet a lower bed. Further reduction continues in the second bed and the solids are transferred in like fashion to the next lower bed. The beds from bottom to top are treated successively with reducing gas lower in hydrogen content, the bottommost bed receiving the gas of highest hydrogen content and therefore of greatest reducing potential. Reduced fines, pyrophoric in nature, are transferred from the bottom bed to a pressurized dump hopper. The dump hopper is purged of hydrogen and pressurized to 150 psi with a non-oxidizing gas to permit transporting of the powder to subsequent processing steps of passivation and compacting. Charging and dumping are carried out without depressurizing the reducer or interrupting the flow of hydrogen. The reduced fines have essentially the same size consist as that of the feed.

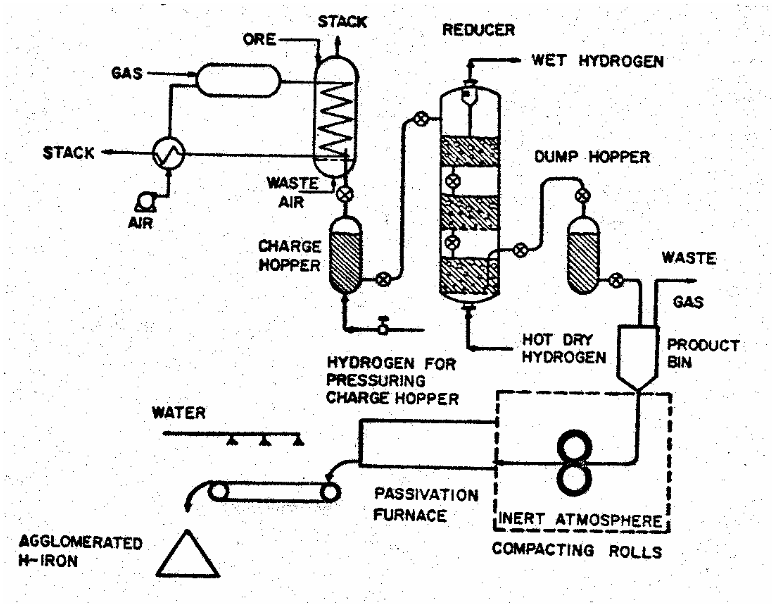

Fig. 9. Flow diagram of ore processing for the H-Iron process. Source is reference 40.

Figure 2.10. Fluidbed DRI process

In this process, the iron ore and hydrogen have to be preheated in separate facilities using a fuel. If MW heating is utilized, we believe it could dramatically simplify the system and increase its energy efficiency. MW irradiation can be easily introduced into the fluid bed reducer by waveguides. Iron ore fines will be heated and held at a desired reducing temperature by MW heating. The exhaust gas will be circulated back into the reducer for auxiliary heating and reduction. The atmosphere is controlled by continuously charging fresh reducing gas into the reducer. Figure 2.11 illustrates the new flow diagram of the MW heated fluid bed DRI process.

Traveling Grate Process

Traveling grates are widely used in the combustion of coal, charring of carbonaceous matter, metallic ore sintering, thermal extraction of sulfur, pelletizing of ore concentrates, production of Portland cement clinker, calcination of limestone, and production of

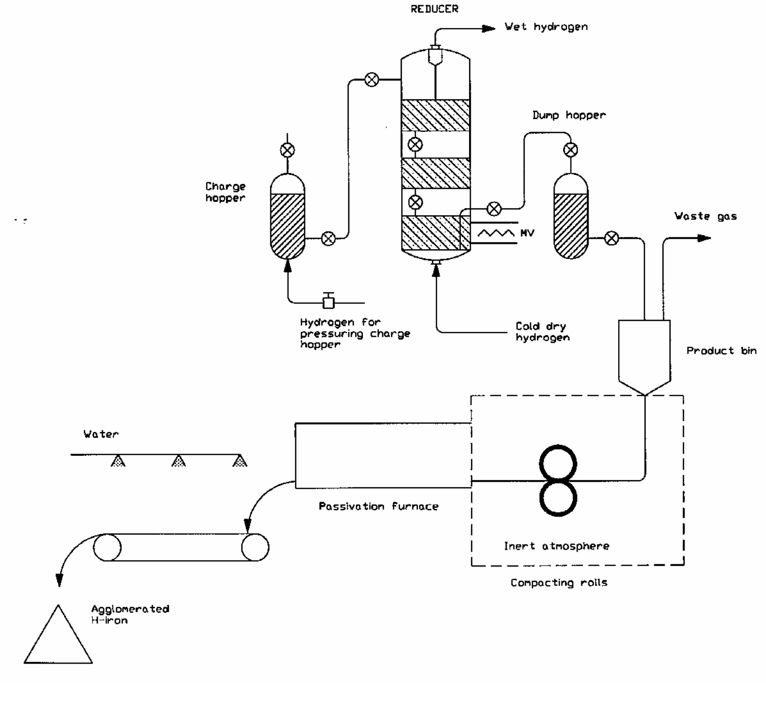

Figure 2.11. MW assisted fluidbed DRI process

lightweight aggregate. These traveling grates can be divided into three types: chain, circular and Dwight-Lloyd. Dwight-Lloyd and circular traveling grates have been used for DRI production. Figure 2.12 illustrates the flow-sheet of Dwight-Lloyd traveling grate application. In this application, the feed material consisting of iron ore, returned fines, limestone and coal is mixed, pelletized using a flying saucer, and charged into the traveling grate, where the feed material is heated by burners. The coal in the feed material is the reducing agent and assures a reducing atmosphere in the chamber. The coal is over dosed in order to reduce iron with higher carbon content, even to form iron carbide. To achieve quick heating and reduction, the feed material is thinly layered on the grate and the grate chamber temperature is as high as 2500°F. The feed material is heated primarily through radiation and convection. Similar to the rotary kiln and shaft processes, the energy efficiency is low. The carbonized pellets are then fed into a submerged arc electric furnace to produce molten slag and iron.

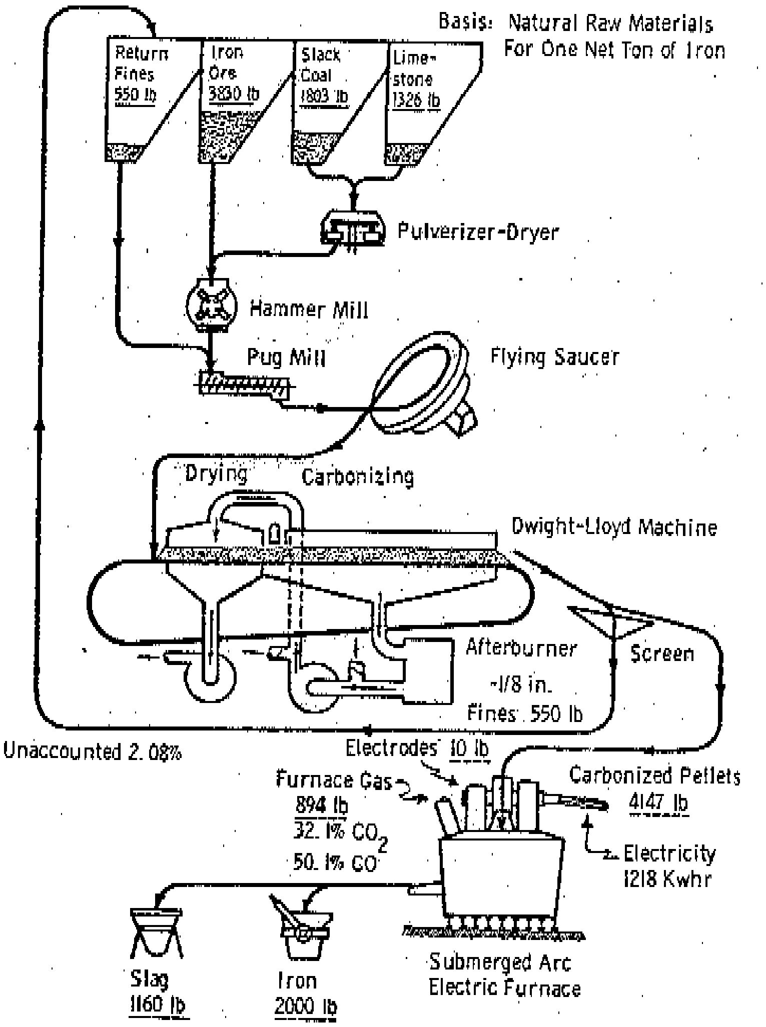

Figure 2.12. A traveling grate DRI Process

The traveling grate DRI processes could be modified by replacing the burners with MW heating. In this application, MW will be introduced into a traveling grate reduction chamber, or a Dwight-Lloyd Machine near the discharge port of the grate as shown in Figure 2.13. The feed material may not change but could be layered on the grate much thicker in comparison with a conventional traveling grate DRI process. The coal in the feed material still will be the reducing agent. The exhaust gas containing hydrocarbon, CO, CO_2, H_2O and heat will be circulated back in near the

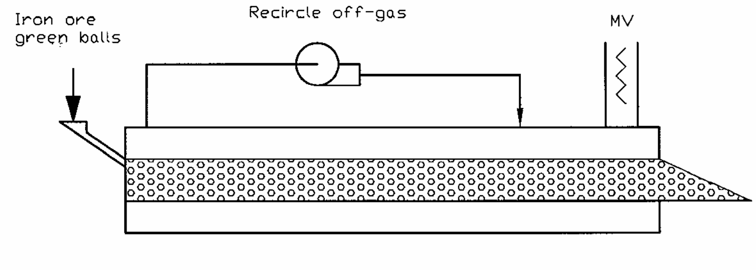

Figure 2.13. MW assisted traveling grate DRI process

discharge port of the grate to utilize the thermal and chemical energies of the gas. Again, due to the replacement of external heating by burners with internal heating by MW irradiation, it is expected to greatly improve energy efficiency and production rate as well as lower the reduction temperature and increase traveling grate life.

Rotary Hearth DRI Production

This process is similar to a circular traveling grate process. Instead of using a circular traveling grate, this process uses a rotary hearth to carry out the reduction as shown in Figure 2.14. MW irradiation could be introduced into the rotary hearth as auxiliary heating with the potential benefits of thicker layer of iron ore, shorter reduction time, lower reduction temperature, higher production rate, greater energy efficiency, and lower production cost.

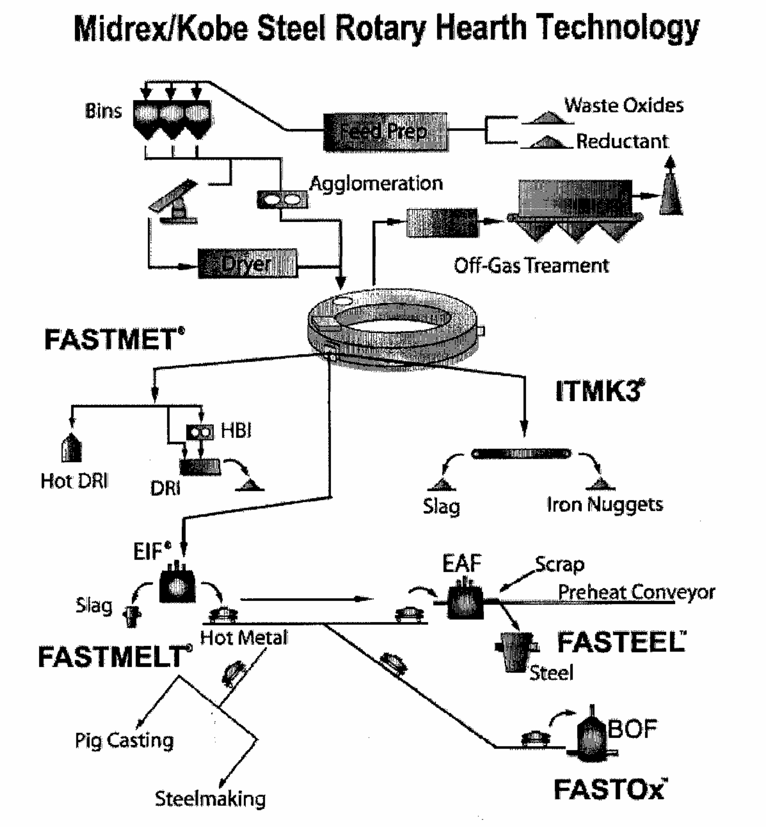

Figure 2.14. Rotary hearth DRI production

6) MW only DRI Production

Our experiments have shown that an enclosed MW reactor has much higher energy efficiency and higher productivity than an open MW reactor when used to reduce iron ore. Our experiments and theoretical analysis on energy efficiency indicate that the exhaust gas contains a great amount of energy in the form of hot and combustible gases, which should be utilized. However, if the concentrations of the combustible gases are not controllable or high enough, it will be difficult to effectively utilize these gases, which is the situation many combustion facilities are facing. A MW reactor does not depend on air or oxygen flow for heating. It is possible to control the generation or the concentration of combustible gases in the exhaust stream of an enclosed MW reactor. To take advantage of an enclosed MW reactor and meet the need for high efficiency DRI production, a MW-only, enclosed DRI production unit could be developed. In this alternative, iron ore is mixed with pulverized coal in an amount over what is needed for reduction. At the beginning of MW heating, highly combustible volatile matter will come out of the coal and exhaust as a fuel through a pipe in the enclosed reactor. As the temperature goes up and all volatiles exhaust, O_2, CO_2 or H_2O could be injected into the chamber to react with the hot coal and generate CO or H_2 during iron ore reduction. The MW enclosed reactor functions as a coal gasifier or natural gas reformer to some extent. The targets

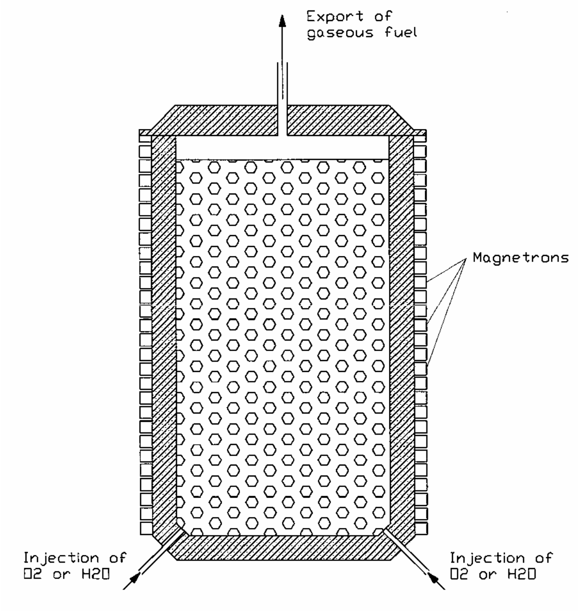

Figure 2.15. MW DRI reducing furnace and gaseous fuel generator

of this alternative are to 1) reduce iron ore at high energy efficiency and high productivity, and 2) generate and export high quality gaseous fuel. Figure 2.15 shows a schematic of this alternative.

We believe there are many good opportunities for microwave technology to be utilized in the steelmaking industry. The use of microwaves can help the industry advance its production technology to a new level.

Task 3. Evaluation of Equipment, Supplies, and Worker Environment

Equipment and Supplies

Information is provided for microwave and radio frequency equipment, along with data for electric arc furnaces.

Microwave Equipment

Microwave heating was discovered in 1950 and led to microwave ovens for home use in 1960. Today, microwave ovens are very popular and form a huge market after several decades of development. However, industrial microwave heating has a long way to go. At present, Cober Electronics, Microdry Inc., and Astex/Gerling Laboratories, Inc are the three major suppliers of industrial microwave heating equipment in the United States. Industrial microwave heating equipment includes more components than home microwave ovens, such as various sizes of generators, waveguides, circulator, monitoring instrumentation, applicators, and conveyors. Figure 3.1 illustrates an industrial MW heating system.

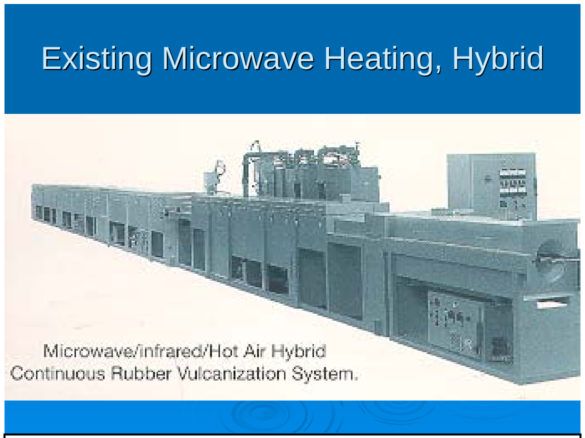

Figure 3.1. Industrial Microwave Heating System

Microwaves are generated from magnetrons. Currently, the largest single magnetron produced is 100 kW. However, large microwave systems do not necessarily have to have large magnetrons. Magnetrons can be connected in parallel to multiply the power output. Large microwave facilities such as 1000KW have been employed in many industries. In 1997, EMR Microwave Technology Corporation, a Canadian company, built a pilot plant microwave metallurgy system to calcine refractory gold ores and concentrates. The system, which can process 4-20 tons of concentrate per day, is shown in Figure 3.2. A larger plant capable of processing 1000 tons of concentrate per day is in the engineering design stage. Also, 100MW and 10GW high energy microwave systems are under development.

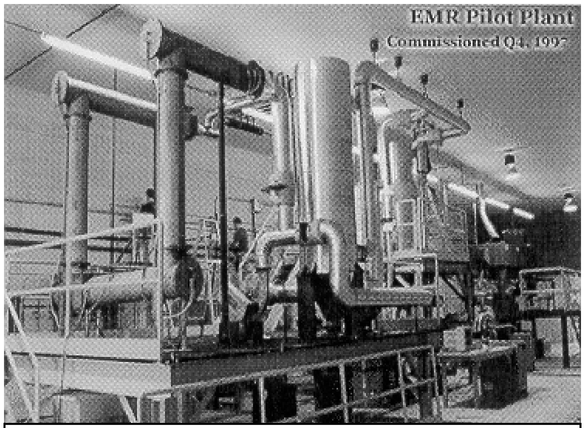

Figure 3.2. Microwave system to calcine refractory gold ores and concentrates

Microwave oven cost has decreased dramatically in recent years due to high volume production and technical progress. A 1 kW microwave oven for home use sells for about $50 while a 1 kW industrial microwave device costs about $1,000. The major progress in industrial microwave equipment is beginning in production of high power microwave generators. A single 100 kW microwave generator is on market. However, there is no expectation to lower the cost of industrial MW generators to the level of home use microwave ovens in the near future.

One strategy to deal with the situation is to develop MW assisted steelmaking facilities based on the use of small MW generators. The obvious advantage is low equipment cost. An 1 kW MW oven sells about $50 which include a metal box, a MW leakage free door, a rotating system, an electronic controller, a fan, a MW generator, a transformer, and a capacitor. To build a MW assisted facility for steelmaking, we only need to use the MW generator, the transformer and the capacitor. Figure 3.3 shows a 1 kW MW generator mounted on a MW digestion system we built in our lab. These three parts may only cost about $20. Another advantage is potentially more homogeneous distribution of MW energy in the materials to be heated. Many small MW generators will be mounted on the wall of a chamber. Microwaves are introduced into the chamber from each generator in all directions. The steelmaking raw material charge is an excellent MW absorber and placed in large quantity in the MW field. It is expected that this MW irradiation arrangement is more homogeneous than irradiation with microwaves introduced through a single waveguide. Figure 3.4 illustrates a schematic of a MW DRI furnace based on the use of multiple small MW generators. A 1 kW MW generator needs a space about 5” by 6”. A chamber 9 feet in diameter and 24 feet tall could house 3200 1 kW generators. Theoretically, current MW equipment manufacturing technology could be used to construct a large facility for steelmaking use.

Figure 3.3. Mounting of a 1 kW MW generator

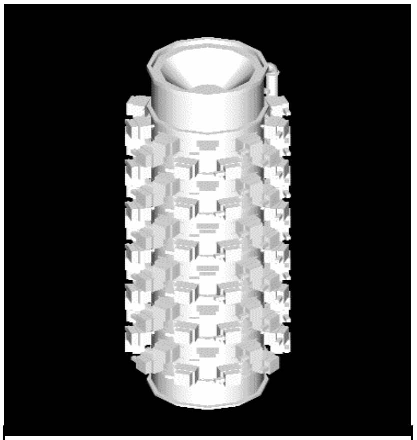

Figure 3.4. MW assisted furnace using multiple 1 kW MW generators

Radio Frequency Equipment

Radio frequency energy is another potential heating source to be utilized for steelmaking. An experiment done at a RF equipment manufacturer has shown that iron ore is a good absorber of RF irradiation. In comparison with microwave heating units, RF heating equipment is cheaper and higher power generators are available on the market. PSC Inc is the primary RF heating equipment manufacturer in the United States, manufacturing RF heating equipment for many industries as shown in Figure 3.5. Figures 3.6 and 3.7 present two RF units that PSC have built. PSC has the capabilities of manufacturing power ranges from kilowatts to megawatts and frequency ranging from kilohertz to megahertz.

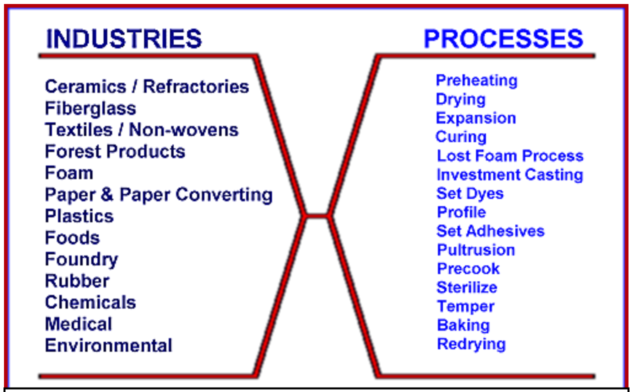

Figure 3.5. Industries and processes that utilize radio frequency heating

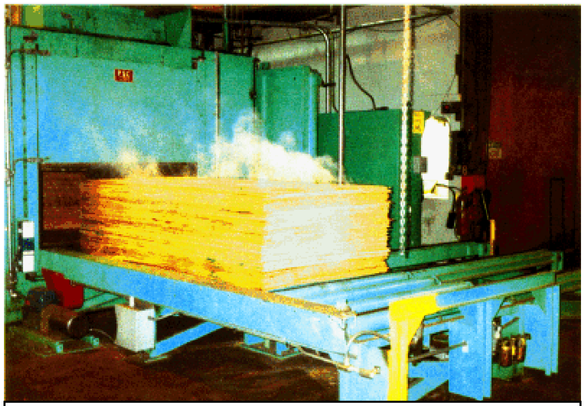

Figure 3.6. 350 kW plywood veneer redryer

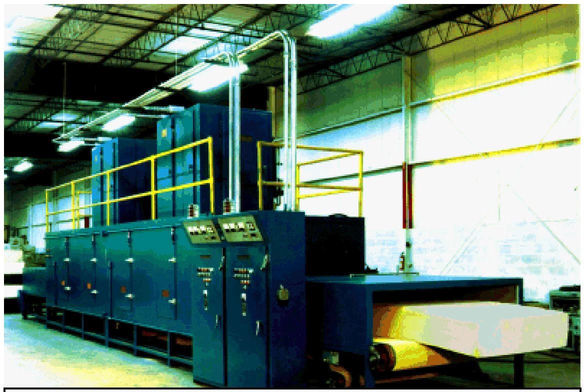

Figure 3.7. 200 kW Foam Dryer

EAF Manufacturers

There are two major EAF manufacturers in the United States, EMC International, Inc., a subsidiary of Midrex Enterprise, Inc., and Techint Technologies Inc. (who owns Lectromelt). This new steelmaking technology will require modification of the existing EAFs, or the design and manufacture of very different MW/EAF units. It is likely these companies will be involved in commercial equipment development.

Worker Environment

The workers in the new MW steelmaking plants will work in an environment similar to the current mini mills, with the additional concern of potential microwave leakage. Great attention should be given to worker safety by preventing microwave leaks. Online monitoring for microwave leakage, leak alarms, and emergency MW power shutdown systems should be designed and installed.

For microwave operations, the primary health effects of concern from electromagnetic radiation are thermal exposure or burns and contact shocks, although research is continuing to investigate non-thermal effects. OSHA has voluntary standards for workplace exposure to non-ionizing radiation (including microwaves). The recommended power density exposure limit is 10 milliwatt/cm^2 for periods of 0.1-hour or more. An energy density limit of 1 milliwatt-hour/cm^2 during any 0.1 hour period is also recommended. These standards have been ruled unenforceable. Some U.S. states with their own OSHA-type programs, however, are enforcing this or other exposure limits. The OSHA standard also specifies the design of a warning sign, although the inclusion and choice of warning information or precautionary instructions is discretionary. More information regarding these regulations is given in Task 7.

Task 4. Evaluation of Steel Company and Supplier Company Interaction and Logistics

Microwave assisted steelmaking seems very different from the traditional steelmaking and may lead to dramatic changes to the current steelmaking chain. The steelmaking chain consists of raw material supplies, logistics and steelmaking. Prediction of the technology impact on the current steelmaking chain will help to plan a technology implementation strategy.

Current interactions and logistics

Figure 4.1 shows the locations of steel plants in North America in the 1990's. This figure was prepared by American Iron and Steel Institute. Many of the plants shown did not survive the downturn of the U.S. steel industry during 1998-2002. They either declared bankruptcy or were acquired by other steelmakers, mostly by foreign steelmakers from Canada, Mexico, German, Brazil, Russia and China. The bankrupt companies included some large and well-known companies such as Bethlehem Steel Corporation, Geneva Steel, LTV Steel Company, National Steel Corporation, North Star Steel Company, Rouge Steel Company, and Weirton Steel Corporation.

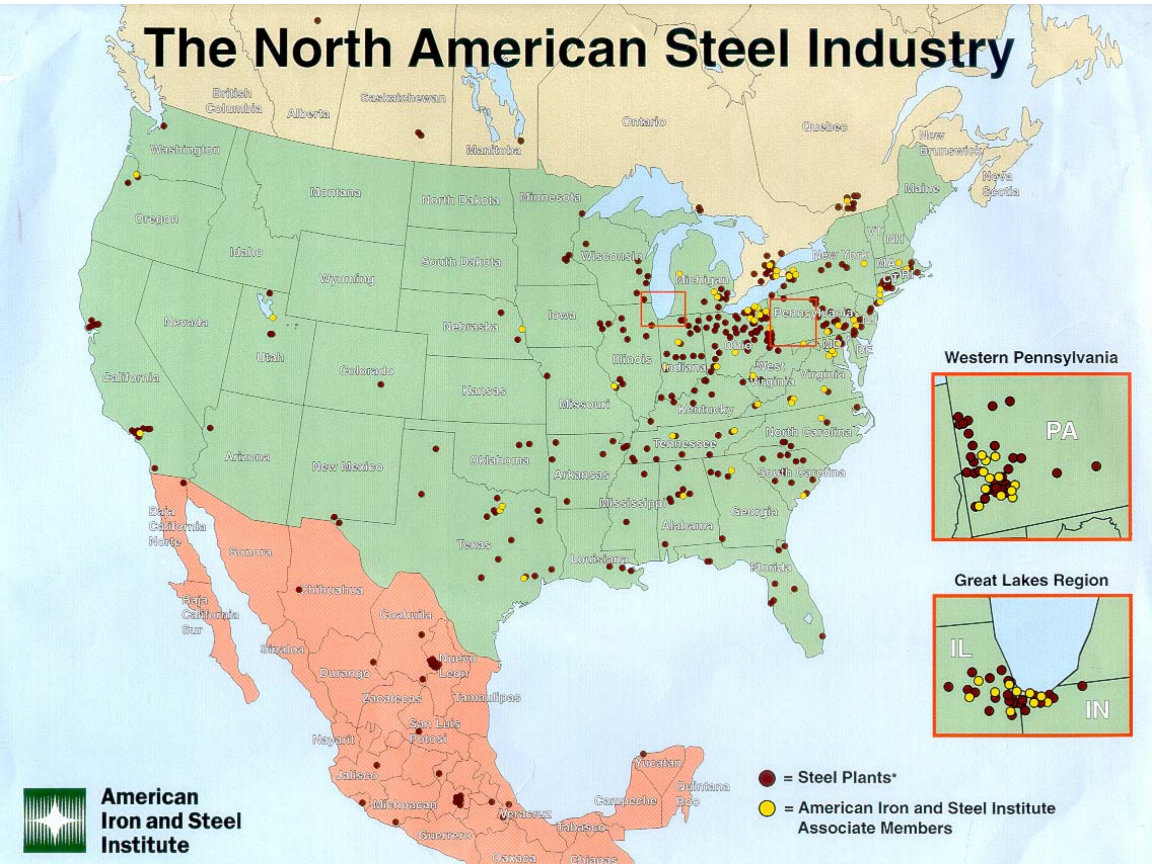

Figure 4.1. The North American steel industry.

Figure 4.1 includes facilities that do not make steel, such as cold rolling mills, pipe extrusion and electrolytic coating operations. MW assisted steelmaking may not have much effect on these downstream operations. To simplify the evaluation, only current steelmaking companies in the United States or the companies having a close supply relationship with steelmakers were studied. Table 4.1 gives their basic information.

Table 4.1. U.S. Steel Plants

COMPANY	WEB ADDRESS	OPERATION	MAIN LOCATIONS	ANNUAL SALES
A. Finkl & Sons Co.	www.finkl.com	EAF	IL	25-100 M
AK Steel Corp	www.aksteel.com	BF/BOF, EAF	OH, IN, KY	5.2 B
Algoma Steel Inc.	www.algoma.com	BF/BOF, coking	Ont.	1.3 B
Beta Steel Corp	www.betasteelcorp.com	EAF	IN	25-100 M
Charter Manufacturing Company, Inc.	www.chartermfg.com	EAF	WI	50-250 M
CitiSteel USA, Inc.	www.citisteel.com	EAF	DE	50-250 M
Cleveland-Cliffs Inc.	www.cleveland-cliffs.com	Iron ore pellets	MN, OH, Que	494 M
Gerdau Ameristeel	www.ameristeel.com	EAF, scrap	FL, GA, TN, NC, KY, NJ, Ont	3 B
Gallatin Steel Company	www.GallatinSteel.com	EAF	KY	250-500 M
IPSCO Inc.	www.ipsco.com	EAF, scrap	Saskatchewan	737 M
ISG	www.intlsteel.com	BF/BOF, EAF, coal, coking, iron ore, DRI, HBI	IN, OH, SC, IL, NY, NC, MD, PA, WV	9 B
Ispat Inland Inc.	www.inland.com	BF/BOF, iron ore	IL, IN, MN	2.38 B
Keystone Consolidated Industries, Inc.	www.keystonesteel.com	EAF	IL	370 M
Rouge Steel Company	www.rougesteel.com	BF/BOF	MI	1.16 B
Shenango Inc.	www.shencoke.com	Coking	PA	25-100 M
Steel Dynamics, Inc	www.steeldynamics.com	EAF	IN	2 B
The Timken Company	www.timken.com	EAF	OH, PA	882 M
Tuscaloosa Steel Corp	www.tsteel.com	EAF	AL	50-250 M
USX-US Steel Group	www.ussteel.com	BF, BOF, iron ore, coking	PA, AL, IN	11.4 B
Wheeling-Pittsburgh Steel Corp	www.wpsc.com	BF/BOF, coking	WV, OH	1.1 B

The current steelmakers can be divided into six categories:1) integrated mills operating BF/BOF and iron ore mining; 2) integrated mills operating BF/BOF; 3) mini mills operating EAF and scrap steel process; 4) mini mills operating EAF; 5) coke producer; and 6) iron ore mining and processing. The first category includes large organizations such as USX-US Steel Group and ISG. They operate not only BF/BOF facilities but also coking, iron ore mining and logistics directly. The second category includes entities that are relatively smaller in size, such as Ispat Inland and Rouge Steel. They may own some shares in iron ore suppliers, but generally speaking, they do not operate iron ore mines directly. Instead, they purchase iron ore pellets based on contracts with iron ore suppliers. The third category includes larger mini mills such as Gerdau Ameristeel and IPSCO. They have their own scrap steel collection, processing and transportation system. The fourth category includes smaller mini mills such as Beta Steel, CitiSteel, Gallatin Steel and Tuscaloosa Steel. They primarily rely on scrap suppliers to get their raw material. The fifth category is the independent coke producer, such as Shenango Inc. This company supplies coke to integrated mills. The sixth category includes iron ore processors such as Cleveland-Cliffs, Inc. This company operates iron ore mining and pelletizing facilities, and supplies iron ore pellets to integrated mills.

Now let's see more details of selected companies. Cleveland-Cliffs is a very typical iron ore supplier. CCI is the largest producer of iron ore pellets in North America. Cliffs sells the majority of its pellets to integrated mills in the United States and Canada. The Company operates six iron ore mines located in Michigan, Minnesota and Eastern Canada as shown in Figure 4.2. CCI-operated mines currently have the capacity to produce 37.7 million tons of iron ore pellets annually; Cliffs share represents approximately 28 percent of the total North American annual pellet capacity. The Company sells its share of iron ore production to integrated mills, generally pursuant to term supply agreements with various price adjustment provisions.

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Figure 4.2. CCI mine locations

The USX-US Steel Group is the largest U.S. integrated steelmaker. U.S. Steel itself supplies iron ore and coke. Iron ore is mined and processed by its Minnesota Ore Operations at Minntac in Mountain Iron and Keewatin Taconite in Keewatin, both on Minnesota's Mesabi iron range. After being extracted from the ground, the iron ore is crushed into a fine powder and separated from impurities with the use of magnets. The concentrated powder is then agglomerated into pellets and sintered. Coke is produced at the Gary Coke Plant in Gary, IN, Clairton Works outside Pittsburgh, PA, and Granite City Coke Plant near St. Louis, MO. U.S. Steel also sells iron ore pellets and coke to other steelmakers.

U.S. Steel had its own Logistics Services Department to provide the logistics services needed by U.S. Steel and other steelmakers. The U.S. Steel logistics services include transportation management, operations management, contract management, administrative services, packaging and loading services, and international services. In 2004, U.S. Steel sold its raw materials and transportation businesses including its coke operations at Clairton, PA and Gary, ID, its iron ore operations at Minnesota (Minntac), and its wholly owned transportation services subsidiary Transtar, Inc. (Transtar), to an entity formed by affiliates of Apollo Management, L.P. (Apollo) of New York City. The new company and U. S. Steel plan to enter into long-term contracts to supply U. S. Steel with its domestic iron ore and coke requirements and to provide U. S. Steel with transportation services.

ISG is the second largest steelmaking company in the United States. It was formed in 2002 by acquiring Bethlehem Steel, Weirton Steel, LTV Steel, and Georgetown Steel. It operates integrated steelmaking, EAF steelmaking, iron ore mining and processing, coking, scrap steel processing, DRI production, and logistics services. The logistics services consist of 1) eight short line railroads located in Pennsylvania, Maryland, New York, and Indiana; 2) lake shipping; and 3) trucking operations.

MW heating shows great advantages in decreasing iron ore reduction time. MW assisted direct reduced iron (DRI) production is a promising area of utilizing MW for steelmaking. DRI is replacement of scrap steel as EAF feed. Five DRI plants have been built in the United States as shown in Table 4.2. These DRI plants were originally independent operations supplying DRI to mini mills. Now, four of them are idle. Only Georgetown Steel is still in operation. Georgetown Steel was acquired by ISG in 2004.

Table 4.2. US Direct Reduction (DRI) Plants

Plant	Process	Location	Capacity, Mt/y	Start-up
Georgetown Steel	Midrex	Georgetown, SC	0.40	1971
Corus Mobile	Midrex	Mobile, AL	0.80	1997/1998
American Iron Reduction	Midrex	Convent, LA	1.20	1998
Qualitech	Iron Carbide	Corpus Christi, TX	0.66	1999
Iron Dynamics	Iron Dynamics	Butler, IN	0.50	1998

Generally speaking, many steelmaking plants are located by harbors, lake shores and rivers in Illinois, Indiana, Ohio, and Pennsylvania. The raw materials, iron ore and coke, are normally shipped by barges up rivers and lakes, or transported by railroad from iron ore mines and coking plants to steelmaking plants. Finished steel products are commonly transported by trucks.

Potential changes to interactions and logistics

Now let's discuss the potential changes to steel company and supplier company interaction and logistics assuming the MW assisted steelmaking technology is successfully developed and used by the steel industry. We see three potential scenarios.

Scenario 1. Deployment of MW assisted DRI production at mines.

Currently iron ore processors ship iron ore pellets as their end products to integrated steelmakers. The technology of MW assisted DRI production provides an opportunity for iron ore processors to produce DRI as their end product with much higher value. A change from making iron ore pellets to DRI will take time to accomplish simply because of the huge volume of material. The iron ore processors could start MW assisted DRI production on a small scale and gradually increase its share. In this scenario, the iron ore processors will not only supply iron ore pellets to integrated steelmakers but also supply DRI to mini mills. The iron ore processors could be independent entities which supply the raw material based on contracts. Or the iron ore processors could be wholly or partially owned by integrated steelmakers or mini mills. Logistics could be a part of the iron ore processor’s business or arranged with independent or partially owned logistics companies based on supply contracts.

The potential problems of this scenario are the electricity, coal and limestone supplies. The MW assisted DRI production requires new electricity, coal and limestone supplies, which may not be readily available at the current iron ore mining operations. Current pelletizing technology generally uses natural gas as the fuel to heat iron ore agglomerates to 2400ºF. These changes may create barriers for an iron ore processor to use this technology.

Scenario 2. Deployment of MW assisted DRI production by independent DRI producers.

The MW assisted DRI production technology could be utilized by independent DRI producers. It may happen when the technology is proven economically viable but the dramatic change is too risky for mini mills. In such circumstances, mini mills will be reluctant to deploy MW assisted DRI facilities at their sites. It is something like the current DRI plants in the United States. These DRI plants were originally built by independent entities. The mini mills need stronger reasons to get involved in direct DRI production.

In this scenario, independent DRI producers may be more flexible and emerge to take the initiative. The independent DRI producers will select locations convenient to an iron ore processor and a mini mill, and having abundant electricity. The independent DRI producers will purchase iron ore concentrate, coal and fluxing agent. The independent DRI producer may need to set up pelletizing facilities and do its own pelletizing. The independent DRI producer will sell DRI to mini mills at a competing price.

We can envision some potential barriers in this scenario. Shipping iron ore concentrate and setting up agglomeration facilities are not very desirable to an independent DRI producer. One solution would be for the iron ore processor to mix and agglomerate pellets using their current facilities and ship the green pellets to independent DRI producers. In such an arrangement, the independent DRI producer will focus on MW assisted DRI reduction and supply interaction with mini mills.

Scenario 3. Deployment of MW assisted DRI production or direct steelmaking at mini mills.

If this technology matures and demonstrates significant cost saving, or if scrap steel is in critical shortage, mini mills may have great interest in integrating MW assisted DRI production with EAF smelting or to deploy MW assisted direct steelmaking at their locations. In this circumstance, DRI will be produced separately and charged into EAFs directly or iron ore will be reduced and melted in a single MW/EAF. Either case will eliminate DRI cooling and further increase energy efficiency.

The required mixing and agglomeration operations of iron ore concentrate could be done either at an iron ore processor's site or at a mini mill site. The advantages of mixing and agglomeration at an iron ore processor's site will lower the investment and simplify the operation of the mini mill related to the DRI production. Mixing and agglomeration at a mini mill site may have the advantage of utilizing oxide scale as a part of feed.

Conclusion

Iron ore has the dominant quantity among steelmaking raw materials. In the current steelmaking operations, iron ore is mined and processed to produce pellets at mine sites using comparatively small amounts of electricity and large amounts of natural gas as fuel. The end product, iron ore pellets, are shipped to integrated mills by barge and rail with loading, unloading and storage facilities suitable for handling pellets. The changes caused by utilizing MW assisted steelmaking technology may either require shipping iron ore concentrate to locations away from mines or doing DRI production at mine sites. The first situation requires the adjustment of logistics from transportation and handling pellets to concentrates. The second situation requires establishment of additional electricity supply to the mine sites.

To avoid the above two situations, iron ore processors could conduct agglomeration of iron ore concentrates with additives of pulverized coal and limestone at mine sites and ship green pellets to independent DRI production sites or mini mills.

Task 5a - Energy Assessment

This chapter consists of four sections: general energy analysis, minimum theoretical energy requirement, experimental energy consumption, and energy consumption comparison between MW/EAF steelmaking process and conventional steelmaking processes.

5.1 General Energy Analysis

The general energy analysis is to analysis the energy consumption of MW/EAF process based on the raw materials used in the bench steelmaking tests described in Section 3 of Chapter 1.

Energy input into MW/EAF process includes electric energy used for microwave heating and electric arc heating and coal blended into the iron ore pellets. A part of energy in the coal is in the volatiles. The volatiles complete escape at a temperature lower than the temperature required for iron ore reduction. We assume no volatile participating in iron ore reduction in this analysis. The energy contained in the fixed carbon of the coal is consumed by iron oxide reduction, combustion with oxygen and remaining in the produced steel. Since the carbon content of steel is fairly low, we assume no carbon in the produced metal to simplify the energy analysis.

Actual iron ores may consist of magnetite (Fe_3O_4), hematite (Fe_2O_3) and wustite (FeO). This analysis only considers magnetite iron ore.

The heating sources of MW/EAF process include microwave heating, electric arc heating and exothermic reactions. The exothermic reactions include combustion of volatiles, combustion of fixed carbon with oxygen, and other carbon involved exothermic reactions.

Specific energy consumption (MJ/kg) indicates the amount of energy is consumed to produce a given amount of hot metal. Specific energy consumption is used in this chapter to compare the energy efficiency among steelmaking processes.

As the energy consumption of MW/EAF process can vary in a wide range with different pellet compositions and operation conditions, it is of practical interest to calculate theoretical energy consumption. From the calculation, the most important factors that have effects on the energy consumption of MW/EAF process will be included. Based on the analysis, the energy efficiency can be improved by selecting appropriate experimental settings.

Nomenclature

t_{MW}	Microwave heating time [second], otherwise specified
t_{EAF}	Electric arc heating time [second], otherwise specified
P_{MW}	Microwave output power [watt]
I	Electric current of electric arc heating [ampere]
V	Applied voltage of electric arc heating [volt]
W	Weight of pellet sample [gram]
W_{Fe}	Weight of produced steel [gram]
C_{cm}	Weight ratio of coal to magnetite ore with weight 100 in pellet sample

$C_{cm}^{\min}$	Minimum weight ratio of coal to magnetite with weight 100 in pellet sample for completely reducing magnetite
C_{bm}	Weight ratio of binder to magnetite ore with weight 100 in pellet sample
C_{lm}	Weight ratio of lime to magnetite ore with weight 100 in pellet sample
C_v	Volatile materials content of coal [wt %]
C_c	Fixed carbon content of coal [wt %]
C_m	Magnetite content of magnetite ore [wt %]
Y	Steel yield [%]
S_E	Specific energy consumption of steel produced [kJ/kg]
E	Energy [joules]
T	Temperature [K]
C_p	Heat capacity of materials [joules/mole K]
ΔH_{trans}	Molar heat of phase transformation [joules/mole]
ΔG	Free energy change of chemical reaction [joules/mole]

Temperature Change in MW/EAF Process

Assuming steelmaking is performed using a single MW/EAF furnace as we did in the bench steelmaking tests. The raw material pellets are made of coal, magnetite ore, lime and binder. The pellets are loaded into a crucible placed in MW/EAF furnace at room temperature. Microwave is introduced into the furnace for a while to heat the pellets. Electrical arcing is then turned on to heat the burden until steel is produced. The burden's temperature is a useful parameter to calculate the energy consumption. Exact temperature curve of the burden is not available due to limitation of measuring tools and difficulty of measurement under the tough environment of MW and EAF heating. However, the burden's temperatures at some critical points in MW/EAF process were measured. Based on these data at critical points, the relationship between the burden's temperature and time in the process is established as shown in Figure 5.1.

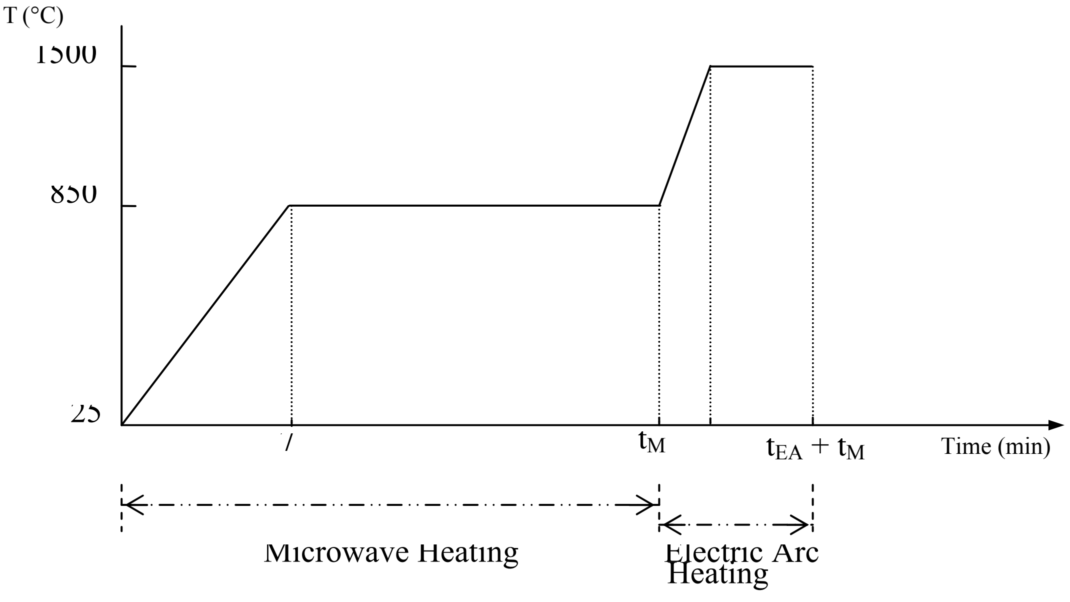

Figure 5.1 Variation of burden temperature in MW/EAF process

Thermodynamic Analysis of Chemical Reactions

To calculate the energy consumption of MW/EAF process, the thermodynamic data about the free-energy changes of the chemical reactions in MW/EAF process should be calculated first. The equation to calculate free energy change of chemical reaction is:

$$\Delta G = \Delta H_{298} + \int_{298}^{T} \Delta C_p dt - T\Delta S_{298} - T\int_{298}^{T} \frac{\Delta C_p}{t} dt \qquad (5\text{-}1)$$

Where ΔH_{298} and ΔS_{298} are the change of formation heats and entropies between products and reactants at ambient temperature respectively, ΔC_p is the change of heat capacities between products and reactants.

The main reactions and their free-energy change in MW/EAF process are [22]:

$$C_{(s)} + O_{2(g)} = CO_{2(g)} \qquad (5\text{-}2)$$

$$\Delta G = -394472.4 - 0.8375\ T$$

$$CO_{2(g)} + C_{(s)} = 2CO_{(g)} \qquad (5\text{-}3)$$

$$\Delta G = 170854.3 - 174.6\ T$$

$$Fe_3O_{4(s)} + 4CO_{(g)} = 3Fe_{(s)} + 4CO_{2(g)} \qquad (5\text{-}4)$$

$$\Delta G = -22822.45 + 26.13\ T$$

$$CH_{4(g)} + 2O_{2(g)} = CO_{2(g)} + 2H_2O_{(g)} \qquad (5\text{-}5)$$

$$\Delta G = -299384 + 59.9144T + 0.0145T^2 + 234240T^{-1} - 7.66T\ \ln(T)$$

$$Fe_3O_{4(s)} + 4C_{(s)} + 2O_{2(g)} = 3Fe_{(s)} + 4CO_{2(g)} \qquad (5\text{-}6)$$

$$\Delta G = -470058.6 - 324.79\ T$$

Carbon inside coal serves two functions in MW/EAF process. A part of carbon acts as reducing agent and the rest acts as fuel and produces heat. Fuel carbon reacts only with oxygen as indicated by chemical equation 5-2 and produces carbon dioxide which is released out of the furnace. Carbon as reductant participates in chemical reactions 5-2, 5-3 and 5-4, and reduces magnetite to iron. Chemical reactions 5-2, 5-3 and 5-4 can be considered as overall chemical reaction 5-6. Although “Boudouard” reaction 5-3 is endothermic and only proceeds at least above 400 °C, overall reaction 5-6 is an exothermic reaction, so carbon as reducing agent also produces heat.

Volatile materials inside coal can be represented by molecular formula $(CH_4)_m$. Due to the volatile characteristic of these materials, they stay in the early stage of MW/EAF process, while the inner temperature of furnace is not high. Volatile materials are oxidized as indicated by chemical equation 5-5 if oxygen is present.

The free-energy changes of chemical reactions 5-2 and 5-5 are dependent on the temperature at which the reactions proceed. Although the temperature change in MW/EAF process is established, the reaction rates of these reactions are unknown. We have to approximate the free-energy changes of those chemical reactions using some values at special temperature.

Chemical reaction 5-5 can occur at relatively low temperature. The free-energy change of chemical reaction 5-5 varies slightly with temperature, while temperature is below 1000 °C. The value of free energy change at 700 ºC is 277.6 kJ/mole.

The variation of free-energy change vs temperature of chemical reaction 5-2 is small in the temperature range of MW/EAF process, due to the small slope. The overall chemical reaction 5-6 proceeds rapidly at an elevated temperature. It is appropriate to calculate the free energy change of reaction 5-2 at temperature 700 ºC. The free energy change of the reaction is 395.8 kJ/mole, very significant. The chemical reaction 5-4 is exothermic at lower temperatures and becomes endothermic at higher temperatures. It absorbs 6.5 kJ/mole energy at 850 ºC.

Energy Balance

The energy balance of MW/EAF process can be expressed by equation 5-7. The heating energies to the process in the left side of the equation consist of electric energy and chemical energies released from coal. According to the analysis in section 5.1.2., all carbon and volatile materials in coal produce heat except "Boudouard" reaction 5-3 is endothermic.

$$E_{EAF} + E_{MW} + E_{exothermic} = E_{endothermic} + E_{vapor} + E_{magnetite} + E_{oarbon} + E_{slag} + E_{steel} + E_{offgas} + E_{losses} \tag{5-7}$$

The energies absorbed by the process in the right side of the equation include the energies required by the process and energy losses. The components in the raw materials and the end products are grouped into magnetite, carbon, slag and steel. The slag includes CaO, SiO_2 and their reaction product: $CaSiO_3$. $E_{magnetite}$ and E_{carbon} represent the energies absorbed by magnetite and fixed carbon to reach a temperature before reduction or a chemical reaction takes place.

E_{losses} include energies absorbed by the crucible and surrounding fireclay bricks as well as conversion losses from electricity to MW and from electricity to arcing. The energies absorbed by the furnace and surrounding environment are unnecessary to MW/EAF process. Although it is impossible to eliminate the energy consumption of refractory and surrounding environment, decreasing the ratio of this energy consumption can greatly improve the energy efficiency of the direct steelmaking technology.

Specific Energy Consumption

It is difficult to calculate the total energy consumption by considering all the energy-consuming factors due to heat loss to the surrounding environment. Based on the fact that the sum of input electric energy and released energy from exothermic reactions is equal to the total energy consumption in MW/EAF process, energy consumption can be formulated by considering input electric energy and exothermic heat.

Assume there is enough coal in the pellets to reduce the magnetite and the magnetite is completely reduced to iron.

The weight of iron in pellets W is $\frac{168*100*WC_m}{232*(100+C_{cm}+C_{lm}+C_{bm})}$.

Given steel yield Y, the weight of produced steel is $\frac{168*100*YWC_m}{232*(100+C_{cm}+C_{lm}+C_{bm})}$.

The molar number of volatile material in pellets is $\frac{WC_{cm}C_v}{16*(100+C_{cm}+C_{lm}+C_{bm})}$ mole. Combustion of volatile material in coal is represented by reaction 5-5, that is exothermic and the molar heat at temperature 700 ºC is 278399 joules/mole. The heat released from volatile materials combustion is $\frac{WC_{cm}C_v}{16*(100+C_{cm}+C_{lm}+C_{bm})}*278399$ joules.

If there is abundant fixed carbon in pellets, it will combust and release heat. The molar number of abundant carbon is $\frac{W}{100+C_{cm}+C_{lm}+C_{bm}}(\frac{C_{cm}C_c}{12}-\frac{2*100*C_m}{232})$ mole. The molar heat of reaction 5-2 at temperature 700 ºC is 395800 joules/mole, so the heat released from abundant fixed carbon combustion is

$$\frac{W}{100+C_{cm}+C_{lm}+C_{bm}}(\frac{C_{cm}C_c}{12}-\frac{2*100*C_m}{232})*395800 \text{ joules.}$$

The sum of energies released from exothermic reaction is

$$\frac{W}{100+C_{cm}+C_{lm}+C_{bm}}(\frac{395800*C_{cm}C_c}{12}+\frac{278399C_{cm}C_v}{16}) \text{ joules.}$$

The energies input through microwave heating and electric arc heating are $t_{MV}*P_{MV}$ joules and $t_{EAF}*I*V$ joules respectively.

The specific energy consumption in kJ/kg is:

$$\frac{\frac{t_{MV}P_{MV}+t_{EAF}I*V}{1000}+\frac{W}{100+C_{cm}+C_{lm}+C_{bm}}(\frac{395.8*C_{cm}C_c}{12}+\frac{278.40C_{cm}C_v}{16})}{\frac{168*100*YWC_m}{1000*232*(100+C_{cm}+C_{lm}+C_{bm})}}$$

Thus equation 5-8 represents the specific energy consumption of the new steal making process.

$$S_E = \frac{0.01381*(t_{MV}P_{MV} + t_{EAF}IV)(100 + C_{cm} + C_{lm} + C_{bm})}{YWC_m} + \frac{(455.5C_{cm}C_c + 239.65C_{cm}C_v)}{YC_m} \qquad (5\text{-}8)$$

Minimum Coal to Magnetite Ratio for Complete Reduction

In the above computation, we assume there is enough coal in pellets to completely reduce magnetite into iron. Though, what is the minimum ratio of coal to magnetite ore in pellets required for complete reduction? The minimum coal ratio is also a useful reference to increase the energy efficiency of MW/EAF process by decreasing the usage of coal.

Because volatile materials in coal can not reduce magnetite, if all the fixed carbon in coal serves as reducing agent, the amount of coal in pellets is the minimum ratio for complete reduction.

The molar number of magnetite in the pellets is $\frac{100WC_m}{232*(100+C_{cm}+C_{lm}+C_{bm})}$ mole.

The molar number of fixed carbon inside the pellets is $\frac{WC_{cm}C_c}{12*(100+C_{cm}+C_{lm}+C_{bm})}$ mole.

Although equation 5-6 indicates that one mole of carbon only can reduce 1/4 mole of magnetite, actually one mole of carbon can reduce 1/2 mole of magnetite if the production carbon dioxide from reaction 5-4 takes part in the "Boudouard" reaction. Thus $\frac{WC_{cm}C_c}{12*(100+C_{cm}+C_{lm}+C_{bm})}$ mole of fixed carbon in pellet sample can reduce $\frac{WC_{cm}C_c}{2*12*(100+C_{cm}+C_{lm}+C_{bm})}$ mole of magnetite.

Assume magnetite in pellets is completely reduced, we have the following equation:

$$\frac{100C_m}{232} = \frac{C_{cm}C_c}{2*12}.$$

Thus the minimum coal ratio in pellets is:

$$C_{cm}^{\min} = \frac{10.34C_m}{C_c} \qquad (5\text{-}9)$$

The minimum ratios of coals with different amount of fixed carbon are summarized in Table 5.1 as examples.

Table 5.1. Minimum ratios of different coals to magnetite ore with 81.2% magnetite

Fixed carbon of coal (%)	59.86	72.72	88.2
$C_{cm}^{\min}$	14.03	11.55	9.52

5.2 Minimum Theoretical Energy Consumption

Basic Assumption and Equations

The calculations performed are theoretical. The basic assumptions are given as following:

(1) Only energy directly used in MW/EAF process is considered.
(2) Energy and heat losses to furnace, refractory and electrical equipment are excluded.
(3) Energy credits in the offgas are excluded.
(4) Energy loss due to yield loss is not considered.
(5) Assume that yield is Y.
(6) Effects of steel composition on energy consumption are not considered.
(7) Heating temperature is a variable in MW/EAF process. Assume that final smelting temperature is 1700°C.
(8) Energy for reduction of silica and manganese oxide is excluded.
(9) Assume the coal content of pellets is the minimum coal required for complete reduction.
(11) Assume typical slag basicity is 1.2.
(12) Assume the energy balance is

$$E_{EAF} + E_{MW} + E_{exothermic} = E_{endothermic} + E_{vapor} + E_{slag} + E_{steel} + E_{offgas} \qquad (5\text{-}10)$$

Where E_{EAF} and E_{MW} are input energies through electric arc heating and microwave heating; $E_{exothermic}$ is heat released from exothermic chemical reactions; $E_{endothermic}$ is heat absorbed by endothermic chemical reactions; E_{vapor} and E_{offgas} are heat absorbed by water vapor and offgas; E_{slag} and E_{steel} are heat associated with slag and steel.

Changes in state functions do not depend on the details of a process but only on the initial and final states, so the methodology for calculating theoretical energy consumption is that all chemical reactions occur at ambient temperature (298°K) and products are heated to the temperature of final states. Therefore, the energies absorbed by magnetite and coal to their reaction temperatures are omitted.

The energy E for heating materials is given by:

$$E = \int_{T_1}^{T_2} nC_p dT \qquad (5\text{-}11)$$

Where C_p is heat capacity of materials depending on temperature, T_1 and T_2 are the initial and final temperature, n is the number of moles.

The energy E associated with phase transformation is given by:

$$E = n\Delta H_{trans} \qquad (5\text{-}12)$$

Where ΔH_{trans} is the molar heat of phase transformation, n is the number of moles.

Minimum Theoretical Energy Consumption Formulas

If there is abundant fixed carbon in coal, it will burn to carbon dioxide and release heat as fuel, as represented by reaction 5-2. The molar heat of reaction 5-2 at ambient temperature is 394722 joules/mole, so the heat released from abundant fixed carbon combustion is:

$$E_{carbon-combustion} = \frac{W(C_{cm} - C_{cm}^{\min})C_c}{12*(100 + C_{cm} + C_{lm} + C_{bm})} * 394722 \qquad (5\text{-}13)$$

The combustion of volatile material in coal is represented by reaction 5-5, which is exothermic. The molar heat at ambient temperature is 292460 joules/mole, so the heat released from volatile materials combustion is:

$$E_{volatile-combustion} = \frac{WC_{cm}C_v}{16*(100 + C_{cm} + C_{lm} + C_{bm})} * 292460 \qquad (5\text{-}14)$$

The specific heat of starch is 15.2 joules/g, so heat released from starch combustion is:

$$E_{starch-combustion} = \frac{WC_{bm}}{(100 + C_{cm} + C_{lm} + C_{bm})} * 15.2 \qquad (5\text{-}15)$$

Reaction 5-4 is exothermic at lower temperatures; the molar heat at ambient temperature is 15035 joules/mole. The heat released from magnetite reduction is:

$$E_{reduction} = \frac{100 * WC_m}{232*(100 + C_{cm} + C_{lm} + C_{bm})} * 15035 \qquad (5\text{-}16)$$

The total energy released from exothermic reactions is:

$$E_{exothermic} = E_{carbon-combustion} + E_{volatile-combustion} + E_{starch-combustion} + E_{reduction} \qquad (5\text{-}17)$$

The "Boudouard" reaction 5-3 is endothermic reaction and the molar heat at ambient temperature is 118817 joules/mole, so the heat required to produce carbon monoxide is:

$$E_{endothermic} = \frac{WC_{cm}^{\min}C_c}{12*(100 + C_{cm} + C_{lm} + C_{bm})} * 118817 \qquad (5\text{-}18)$$

The heat capacities of SiO_2 and CaO are $C_{P(SiO_2)} = 44.77$ joules/mole°K and $C_{P(CaO)} = 42$ joules/mole°K. Given W gram pellets, the theoretical energies used to heat the components of the slag from ambient temperature to temperature of T are:

$$E_{CaO} = n_{CaO}\int_{298}^{T} C_{p(CaO)}dT = \frac{100W(1 - C_m) + WC_{lm} + WC_{cm}(1 - C_v - C_c)}{1.83*56*(100 + C_{cm} + C_{lm} + C_{bm})} * 42(T - 298) \qquad (5\text{-}19)$$

$$E_{SiO_2} = n_{SiO_2}\int_{298}^{T} C_{p(SiO_2)}dT = \frac{100W(1-C_m)+WC_{lm}+WC_{cm}(1-C_v-C_c)}{2.2*60*(100+C_{cm}+C_{lm}+C_{bm})}*44.77(T-298) \tag{5-20}$$

The endothermic reaction forming slag is:

$$CaO + SiO_2 = CaSiO_3 \tag{5-21}$$

$$\Delta G = 92500 + 2.5\ T\ (J)$$

The heat associated with forming of the slag is:

$$E_{CaSiO_2} = \frac{100W(1-C_m)+WC_{lm}+WC_{cm}(1-C_v-C_c)}{2.2*60*(100+C_{cm}+C_{lm}+C_{bm})}*(92500+2.5T) \tag{5-22}$$

The total energy absorbed by slag is:

$$E_{slag} = E_{CaO} + E_{SiO_2} + E_{CaSiO_3} \tag{5-23}$$

The heat capacities of α-Fe and γ-Fe are $C_{P(\alpha-Fe)} = 17.5 + 24.8\times10^{-3}T$ joules/mole°K and $C_{P(\gamma-Fe)} = 7.7 + 19.5\times10^{-3}T$ joules/mole°K. The temperature of phase transformation from α-Fe to γ-Fe is 1181°K. The theoretical energies used to heat iron from ambient temperature to temperature of T are:

$$E_{\alpha-Fe} = n_{Fe}\int_{298}^{1181} C_{p(\alpha-Fe)}dT = \frac{3*100*WC_m}{232*(100+C_{cm}+C_{lm}+C_{bm})}*47840 \tag{5-24}$$

$$E_{\gamma-Fe} = n_{Fe}\int_{1181}^{T} C_{p(\alpha-Fe)}dT = \frac{3*100WC_m}{232*(100+C_{cm}+C_{lm}+C_{bm})}(7.7(T-1181)+19.5\frac{T^2-1181^2}{1000}) \tag{5-25}$$

The heat associated with solid phase transformation from α-Fe to γ-Fe is:

$$E_{\alpha\to\gamma} = \frac{3*100*WC_m}{232*(100+C_{cm}+C_{lm}+C_{bm})}*5940 \tag{5-26}$$

The heat associated with phase transformation from γ -Fe to liquid Fe is:

$$E_{\gamma\to l} = \frac{3*100*W*C_m}{232*(100+C_{cm}+C_{lm}+C_{bm})}*(13800+7.6*T) \tag{5-27}$$

$$E_l = \frac{3*100*W*C_m}{232*(100+C_{cm}+C_{lm}+C_{bm})}*41.88*(T_{discharge}-T) \tag{5-28}$$

The energy absorbed by steel is:

$$E_{steel} = E_{\alpha-Fe} + E_{\gamma-Fe} + E_{\alpha\to\gamma} + E_{\gamma\to l} + E_l \qquad (5\text{-}29)$$

Water vapor comes from the combustion of starch and volatile materials inside coal. Because one carbon atom usually binds with two hydrogen atoms on a long chain of atoms in organic materials such as starch, it is reasonable to represent starch by molecule formula $(CH_2)_m(OH)n$ (where n<<m). The volatile materials can be represented by CH_4.

The heat capacity of water vapor is $C_{p(H_2O)} = 30 + 10.7\times10^{-3}T + 0.33\times10^{5}T^{-2}$ joules/mole°K. The theoretical energies used to heat water vapor from ambient temperature to temperature of T is:

$$E_{H_2O} = n_{H_2O}\int_{298}^{T} C_{p(H_2O)}dT = \frac{W}{(100 + C_{cm} + C_{lm} + C_{bm})}*$$

$$(\frac{2C_{cm}C_v}{16} + \frac{C_{bm}}{14})(30(T-298) + 0.00107(T^2 - 298^2) + 0.33\times10^5(\frac{1}{T} - \frac{1}{298}))$$

(5-30)

The phase transformation of water is represented by following equation:

$$H_2O(liquid) \to H_2O(gas) \qquad (5\text{-}31)$$

$$\Delta G = 40650\ (J)$$

The heat associated with evaporation of water is:

$$E_{H_2O(l\to g)} = \frac{W}{(100 + C_{cm} + C_{lm} + C_{bm})} * (\frac{2*C_{cm}C_v}{16} + \frac{C_{bm}}{14})*40650 \qquad (5\text{-}32)$$

The total energy absorbed by water vapor is:

$$E_{vapor} = E_{H_2O} + E_{H_2O(l\to g)} \qquad (5\text{-}33)$$

The heat capacity of CO_2 is 36.62 joules/mole°K. The theoretical energies used to heat carbon dioxide from ambient temperature to temperature of T is:

$$E_{offgas} = n_{CO_2}\int_{298}^{T} C_{p(CO_2)}dT = \frac{36.62*W(T-298)}{(100 + C_{cm} + C_{lm} + C_{bm})}(\frac{C_{cm}C_v}{16} + \frac{C_{cm}C_c}{12} + \frac{C_{bm}}{14}) \qquad (5\text{-}34)$$

Equation 5-35 represents the steel weight produced from pellets of weight W, assuming that yield is Y. Specific energy consumption can be calculated through dividing energy consumption by steel weight.

$$W_{Fe} = \frac{168*100*WYC_m}{232*(100 + C_{cm} + C_{lm} + C_{bm})} \qquad (5\text{-}35)$$

Minimum Energy Consumption Computation

Table 5.2 and Table 5.3 summarize the theoretical energy consumption of two pellet samples with high volatile coal and low volatile coal respectively. Because the coal ratios in the pellet samples are minimum, the energy consumption of the two pellet samples are minimum theoretical energy consumptions. Table 5.2 and Table 5.3 indicate that about 45% of the total energy is consumed by steel, 22% to 28% is absorbed by water vapor and offgas. The percentage of energy consumed by water vapor and offgas in the total energy consumption is remarkable.

Total energy consumption significantly varies with the volatile content of coal. Pellet samples with high volatile coal need more energy to be reduced. The difference of total energy consumption between the two pellet samples mainly results from the energy absorbed by water vapor and offgas, because greater amounts high volatile coal are required for complete reduction and high volatile coal produces more water vapor.

Table 5.2 and Table 5.3 also indicate that the pellet sample with high volatile coal can release more heat due to combustion of volatile materials. For the two samples, the heats released from combustion of volatile materials are 504 kJ and 154 kJ.

Table 5.2. Minimum theoretical energy consumption using high volatile coal

Energy Type			Energy (kJ)			Energy/ Total (%)	
			Data	Sum	Total	Data	Sum
Input Energy	$E_{exothermic}$	$E_{carbon\text{-}combustion}$	0	−504.43		0	25.70
		$E_{volatile\text{-}combustion}$	−471.73			24.04	
		$E_{starch\text{-}combustion}$	−0.69			0.035	
		$E_{reduction}$	−32.01			1.63	
Absorbed Energy	$E_{endothermic}$	$E_{endothermic}$	505.65	505.65	1962.47	25.77	25.77
	E_{slag}	E_{CaO}	28.14	84.64		1.43	4.31
		E_{SiO2}	27.26			1.39	
		E_{CaSiO3}	29.24			1.49	
	E_{steel}	$E_{\alpha\text{-}Fe}$	305.53	818.06		15.57	41.68
		$E_{\gamma\text{-}Fe}$	246.90			12.58	
		$E_{\alpha \to \gamma}$	37.94			1.93	
		$E_{\gamma \to l}$	174.19			8.88	
		E_l	53.49			2.73	
	E_{vapor}	E_{H2O}	14.79	278.38		0.75	14.19
		$E_{H2O(l \to g)}$	263.59			13.43	
	E_{offgas}	E_{offgas}	275.74	275.74		14.05	14.05
Assume yield Y = 0.95, weight of produced steel is 354 g. Theoretical specific energy consumption is 5,543 kJ/kg.							
Data based on are: C_{cm} = 15.24, C_{lm} = 10, C_{bm} = 7.5, C_m = 81.2 %, C_c = 59.86 %, C_v = 30.25 %, vapor escape T = 100ºC, offgas escape T = 850ºC, steel melting and slag discharge T = 1500ºC, liquid steel discharge T = 1700ºC , W = 800 g.							

Table 5.3. Minimum theoretical energy consumption using low volatile coal							
Energy Type			Energy (kJ)			Energy/ Total (%)	
			Data	Sum	Total	Data	Sum
Input Energy	$E_{exothermic}$	$E_{carbon\text{-}combustion}$	0	−154.18		0	8.26
		$E_{volatile\text{-}combustion}$	−120.60			6.46	
		$E_{starch\text{-}combustion}$	−0.71			0.038	
		$E_{reduction}$	−32.87			1.73	
Absorbed Energy	$E_{endothermic}$	$E_{endothermic}$	519.33	519.33	1866.08	27.83	27.83
	E_{slag}	E_{CaO}	27.22	81.86		1.46	4.39
		E_{SiO2}	26.50			1.42	
		E_{CaSiO3}	28.13			1.51	
	E_{steel}	$E_{\alpha\text{-}Fe}$	313.80	840.19		16.82	45.02
		$E_{\gamma\text{-}Fe}$	253.58			13.59	
		$E_{\alpha \to \gamma}$	38.96			2.09	
		$E_{\gamma \to l}$	178.91			9.59	
		E_{l}	54.94			2.94	
	E_{vapor}	E_{H2O}	9.52	179.08		0.51	9.60
		$E_{H2O(l \to g)}$	169.56			9.09	
	E_{offgas}	E_{offgas}	245.61	245.61		13.16	13.16
Assume yield Y = 0.95, weight of produced steel is 358 g. Theoretical specific energy consumption is 5,213 kJ/kg.							
Data based on are: C_{cm} = 10.56, C_{lm} = 10, C_{bm} = 7.5, C_m = 81.2 %, C_c = 79.5 %, C_v = 10 %, vapor escape T = 100ºC, offgas escape T = 850ºC, steel melting and slag discharge T = 1500ºC, liquid steel discharge T = 1700ºC , W = 800 g.							

The theoretical specific energy consumption of two pellet samples at steel discharge temperature 1700°C are 5.543 MJ/kg and 5.213 MJ/kg respectively. The difference between the quantities of steel yielded from the two pellet samples is slight, so the notable difference of theoretical specific energy consumption between the two samples mainly results from the different total energy consumption. For a pellet sample with high volatile coal, the energies absorbed by water vapor and offgas are increased by 55% and 12.3% with respect to that of the pellet sample with low volatile coal.

5.3 Experimental Energy Consumption

Energy efficiency of an industrial steelmaking furnace capable of 50-250 T/h and energy efficiency of a bench scale steelmaking furnace capable of 3-6 kg/h are not in the same level of comparison. However, the energy consumption measured from the bench MW/EAF steelmaking tests is still useful information to indicate the energy efficiency to a certain degree. Energy consumption of future steel production using MW/EAF technology could be estimated with reference of the information.

We have conducted many steelmaking tests using the bench scale MW/EAF furnace. Steelmaking times were very different from test to test. It depended strongly on the operation skill of the furnace operator and the pellet composition. The best operation starts arcing immediately after the iron ore is reduced to the degree necessary for good electric conduction and has no bridging problems, otherwise a lengthy arcing time is required. A great amount of fine lime powder blended into the iron ore pellets is detrimental to early good conductivity of the reduced iron ore mass. Less lime addition is preferred to shorten steelmaking time.

Most steelmaking time varied from 15 to 30 minutes. The shortest test was 12 minutes. The experimental energy consumption was determined based on this best operation. Table 5.4 summarizes the experimental result, composition of pellet sample, and coal. Based on these data, the energy consumption of bench MW/EAF steelmaking is given in Table 5.5.

Table 5.4. Best Test experimental result and compositions of pellet sample & raw materials

Experimental result						**Pellet sample**				**Magnetite ore**	**Coal**	
t_M (s)	t_{EA} (s)	I (A)	V (V)	P_M (W)	Y (%)	C_{cm}	C_{lm}	C_{bm}	W (g)	C_m (%)	C_v (%)	C_c (%)
420	300	150	50	6000	94.8	15	5	5	800	81.2	18.78	71.92

Table 5.5. Specific energy consumption

		Microwave	**Electric Arc**	**Coal**	**Total**
Specific energy	(kJ/kg)	7063	6307	2521	15892
	Btu/kg	6679	5963	2384	15027
	kWh/kg	1.96	1.75	0.7	4.41
Percentage (%)		44.45	39.69	15.87	100

Energy consumption of a modern EAF furnace is 1440-1,800 KJ/kg, which includes the energy required to heat scrap steel from room temperature to 850ºC. Our bench scale MW/EAF furnace started arcing after the DRI had already reached 850ºC. It consumed 6,307 KJ/kg energy, 3.5-4.4 times higher than that of a modern EAF furnace. The large difference of arcing energy between an industrial furnace and a bench scale furnace tells that the experimental energy data derived from the operation of the bench scale furnace cannot be compared directly with the energy data of an industrial furnace.

However, it is crucial to know the energy efficiency of future industrial furnaces of MW/EAF steelmaking at the beginning of extensive research. Therefore, we will make some estimations. We assume 1) energy efficiency of future industrial furnace for MW iron ore reduction will be

20% higher than that of the present bench scale furnace; 2) the same amount of coal will be used; and 3) the energy consumption of acing hot DRI by future MW/EAF will be the energy consumption of the present industrial EAF minus the energy of heating scrap steel from room temperature to 850ºC. The theoretical energy of heating scrap steel from room temperature to 850ºC is 373 KJ/kg (specific heat of steel equal to 0.452 KJ/kgºC). Assuming 65% arcing efficiency of present EAF, the consumed energy will be 574 KJ/kg.

The total energy consumption of industrial MW/EAF furnace will be 5,650 KJ/kg + 2,521 KJ/kg + 1,440 KJ/kg - 574 KJ/kg = 9**,037 KJ/kg** to 5,650 KJ/kg + 2,521 KJ/kg + 1,800 KJ/kg - 574 KJ/kg = **9,397 KJ/kg**.

The MW/EAF steelmaking technology offers a possibility of utilizing a sealed MW DRI reducing furnace as shown in Figure 2.15. The furnace is also a gaseous fuel generator during the MW DRI production. The energy in the off-gas (246 KJ/kg as given in Table 5.3 and much more if more than theoretical minimum amount of coal is used) could be effectively utilized. The MW/EAF steelmaking energy could be further reduced.

5.4 Energy Consumption Comparison

Currently, two steelmaking routes are used by the steel industry. One is based on blast BF/BOF; the other is based on EAF. The charge of EAF is scrap steel and DRI. To make a comparison based on equal foot, the EAF steelmaking in this discussion uses DRI as the charge for total energy consumption calculation.

Table 5.6 shows the energy consumption of conventional steelmaking and the new direct steelmaking. All energy consumptions are collected from good practice. The energy consumption associated with manufacture of electrode, refractory, etc. are excluded, and energy credits in off gases are also excluded.

Table 5.6. Specific energy consumption comparisons

Conventional steelmaking				Direct steelmaking	
Process	Specific energy (MJ/kg)	Process	Specific energy (MJ/kg)	Process	Specific energy (MJ/kg)
Iron ore processing	2.5	Iron ore processing	2.5	Iron ore processing	2.5
Shipping	1.1	Shipping	0.94	Shipping	0.94
Pelletizing	1.9	Pelletizing	1.9	Pelletizing	1.9
Limestone calcination	1.1	Direct reduction*	14.9	Limestone calcination	0.5
Sintering	1.7	EAF	2.77	MW/EAF	9.04-9.40
Coke making	1.67				
BF	17.0				
BOF	0.95				
Total	**27.92**	**Total**	**23.01**	**Total**	**14.88-15.24**

* Midrex process.

The difference of shipping energy consumption comes from shipping less weight due to the elimination of coke shipping and less use of limestone. Sulfur in liquid iron produced by BF comes from the direct contact of liquid iron with coke. No coke in the new process reduces the need for limestone to remove sulfur. The energy difference of limestone calcination comes from limestone weight reduction in the new process.

Table 5.6 shows that conventional steelmaking requires about 27.92 MJ or 23.01 MJ to produce one kilogram of steel, while the new steelmaking requires about 15 MJ. It means a 46% or 35% energy saving in comparison with the two conventional steelmaking routes. The comparison indicates that MW/EAF steelmaking is more energy efficient than conventional steelmaking.

Replacing the combination of BF and BOF or the combination of Midrex and EAF with more efficient MW/EAF contributes the major proportion of energy saving for the new steelmaking process. Eliminating coke making and pellet sintering and reducing shipping weight and limestone requirements further increases the energy savings for the new process.

The energy consumption of MW/EAF steelmaking is 9.04-9.40 MJ/kg and its minimum theoretical energy consumption is 5.21 MJ/kg. The minimum theoretical energy consumption of BF/BOF is about 9.9 MJ/kg. The minimum theoretical energy consumption of Midrex and EAF is about 9.2 MJ/kg. These theoretical data indicates MW/EAF process is inherently more energy efficient and it mainly results from eliminating reduction of silica and manganese oxide in the MW/EAF process.

5.5 Summary

MW/EAF process is a more energy efficient steelmaking process than conventional steelmaking processes. It could achieve an energy saving of 46% over BF/EAF steelmaking and an energy saving of 35% over Midrex and EAF steelmaking.

The minimum theoretical energy consumption using low volatile coal is 5.21 MJ/kg in MW/EAF process, about 45% is consumed by steel and 22% to 28% is consumed by water vapor and offgas. Utilization of energy in offgas will play an important role to further increase energy efficiency. It is particularly important when high volatile coal is used as the reductant. MW/EAF steelmaking offers a good opportunity for controlling offgas composition. A combination of MW DRI furnace and gaseous fuel generator could be designed, fabricated and used.

The theoretical energy consumption of MW/EAF process varies with the volatile content of coal and the amount of coal in pellets. Pellets with high volatile coal or abundant amounts of coal have higher theoretical energy consumption.

Task 5b - Environmental Assessment

The iron and steel industry is crucial to the U.S. economy, however, it is associated with environmental issues. Current operations have raised significant concerns because of their 1) link to high energy consumption; 2) discharge of pollutants; 3) inherent demand for coke production; and 4) enormous amount of water consumption. The steel industry has invested over $6 billion over the last 25 years for environmental control, which represents approximately 15% of the total operating cost of the industry.

Although great efforts had been made, many steel operations were still shut down or moved to other countries due to difficulties or high cost of compliance with stringent environmental regulations. As the Steel Industry Technology Roadmap points out, the industry needs pollution prevention technologies to reduce costs, improve profitability, and facilitate compliance with changing Federal regulations. The steel industry's environmental goal is to avoid pollution rather than control and treat it. MW/EAF steelmaking technology will eliminate the operations of coking, sintering, BF steelmaking and BOF steelmaking, thus eliminating their associated environmental problems.

This environmental assessment consists of two studies: offgas emission analysis and estimation of environmental benefits. The objective of the offgas emission analysis is to identify potential emission problems, if any, associated with the new process. The estimation of environmental benefits is to calculate the possible benefits, assuming the technology is fully executed.

5.6. Offgas Emission Analysis

In MW/EAF process, offgas emission would contain CO_2, CO, SO_2, NO_x and VOCs, because these pollutants are combustion-related with coal as the reductant. NO_x is formed when nitrogen reacts with oxygen at appropriate conditions such as high temperature and arcing. SO_2 is produced from burning some of the sulfur in coal. Coal and iron ore contain organic compounds to some extent. When there is insufficient oxygen available for combustion, some of these organic compounds get into the offgas system, therefore VOCs can be burned off in the furnace by after-burning.

Assuming the volatile materials and fixed carbon in coal are completely oxidized, the amount of carbon dioxide emitted from a pellet sample with specific composition can be calculated by the following equation:

$$n_{CO_2} = \frac{W}{(100 + C_{cm} + C_{lm} + C_{bm})}\left(\frac{C_{cm}C_v}{16} + \frac{C_{cm}C_c}{12} + \frac{C_{bm}}{14}\right) \qquad (5\text{-}36)$$

Where C_{bm} is the weight ratio of binder to magnetite ore with weight 100 in pellet sample; C_{lm} is the weight ratio of lime to magnetite ore with weight 100 in pellet sample; C_{cm} is the weight ratio of coal to magnetite ore with weight 100 in pellet sample, C_v is the volatile materials content of coal, and C_c is the fixed carbon content of coal.

Using the measured offgas composition and the total amount of carbon dioxide emitted from pellet sample, the amount of other gases in offgas can be calculated. If the concentration of gas such as SO_2, NO_x and VOCs is too low to be detected by equipment, the possible maximum amount can be estimated by using the minimum measurable possible with the equipment.

Experimental Method

Apparatus

An offgas analysis system was set up to carry out this study. The constituent parts in the offgas analysis system are shown in Figure 5.2. Figure 5.3 is the schematic diagram of the offgas analysis system. In order to protect the gas analyzer, ceramic fibers were used as a filter to separate fine particulate from the gas emission. A vacuum pump was used to purge offgas flow. The main equipment and analysis instruments are listed as follows.

(1) Bench-scale microwave assisted electric arc furnace (MW/EAF) system

- Used for conducting direct steelmaking

(2) Quadrupole gas analyzer

- Used for analyzing offgas composition
- Manufacturer: AMETEK Thermox Instruments Division, USA
- Model: DYCOR^{TM} M100/M200
- Mass Range: 1 – 200
- Maximum Temperature: 350 °C
- Minimum Measurable Current: 1.0E –13 amps
- Maximum Measurable Current: 1.0E –5 amps
- Accuracy: 1% of signal from 1.0E –13 to 1.0E –8 amps

(3) Hydrogen sulfide monitor

- Used for detecting hydrogen sulfide concentration of offgas
- Manufacturer: GC Industries Incorporation, USA
- Model: GC–701
- Measurable Range: 0 – 100 ppm
- Accuracy: ± 3 ppm

(4) Carbon monoxide monitor

- Used for detecting carbon monoxide concentration of offgas
- Manufacturer: GC Industries Incorporation, USA
- Model: GC–401
- Measurable Range: 0 – 100 ppm
- Accuracy: ± 10 ppm

Figure 5.2 Photograph of constituent parts in offgas analysis system

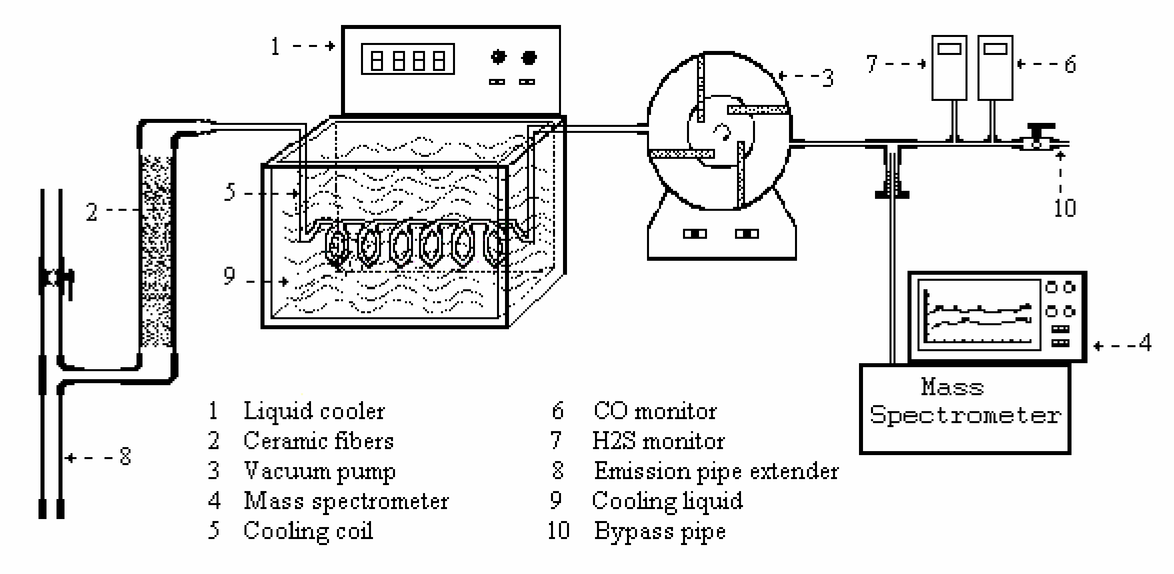

Figure 5.3. Schematic diagram of offgas analysis system

Materials and Procedures

Offgases from nine pellet samples with different composition were analyzed. The compositions of the pellet samples were listed in Table 1.7 and Table 1.8. The composition of raw materials was listed in Table 1.9.

For the purpose of comparison, offgas emitted from coal heated through microwave heating was also analyzed. The coal composition was listed in Table 1.10.

Direct steelmaking was carried out in the MW/EAF system, and the procedure for reduction of pellets is the same as Task 1.2. The parameters of these direct steelmaking experiments were summarized in Appendix B. Offgas was monitored in-situ from the beginning of MW/EAF process. The frequency of data collection is roughly one measurement every two minutes.

Results and Discussion

The compositions of offgases emitted from nine pellet samples and coal are listed in Appendix C. The major components of offgas are nitrogen, oxygen, argon, carbon dioxide, sulfur oxide, water vapor and carbon monoxide. NO_x and VOCs could not be detected by using the gas analyzer due to their lower concentrations.

The compositions of offgases emitted from pellets and coal during microwave heating illustrate the following: Carbon dioxide is generated soon after microwave heating is started. There is carbon monoxide in offgas during the early stage of microwave heating. The maximum concentration of carbon monoxide is 423 ppm. The carbon dioxide and water vapor content of offgas usually increases and the oxygen content of offgas decreases while microwave heating continues.

The composition of offgas emitted from the pellet sample during electric arc heating varies slightly with heating time. Because the temperature during electric arc heating varies slightly, the variation of offgas composition with time in MW/EAF process indicates that temperature has a determining influence on offgas composition.

Table 5.7 displays the average offgas composition over the entire process and its two stages respectively. The data about the content of carbon dioxide and sulfur dioxide indicates the following: The average carbon dioxide content of offgas emitted during electric arc heating is generally greater than during microwave heating. However, the average sulfur dioxide content of offgas emitted during electric arc heating is generally smaller than during microwave heating.

Table 5.8 illustrates that the average composition of offgas emitted from pellet sample during microwave heating is greatly different from the average composition of offgas emitted from microwave heated coal. The carbon dioxide content of the pellet sample's offgas is nearly 2.5 to 5 times that of coal's offgas, however the sulfur dioxide content of coal's offgas is nearly 3 to 11 times that of the pellet sample's offgas.

Table 5.7 Average composition of offgas from the MW/EAF process

	CO_2 (%)			N_2 (%)			O_2 (%)			SO_2 (%)			H_2O (%)			Ar (%)			CO (%)		
	MV	**EA**	**All**	**MV**	**EA**	**All**	**MV**	**EA**	**All**	**MV**	**EA**	**All**	**MV**	**EA**	**All**	**MV**	**EA**	**All**	**MV**	**EA**	**All**
#1	5.63	9.40	6.26	75.30	74.72	75.20	16.06	13.48	15.63	0.032	0.030	0.031	1.80	2.37	1.89	1.18	1.28	1.20	0.0048	0	0.0040
#2	5.19	8.80	5.79	78.44	78.92	78.52	13.57	9.29	12.86	0.024	0.007	0.021	1.61	1.80	1.64	1.17	1.19	1.17	0.0064	0	0.0053
#3	6.94	14.9	8.26	79.88	76.50	79.57	11.44	8.22	10.90	0.049	0.008	0.042	1.40	1.01	1.40	ND	ND	–	ND	ND	–
#4	7.40	9.88	7.85	77.48	78.35	77.64	14.50	9.88	13.66	0.024	0.007	0.021	0.60	1.85	0.82	ND	ND	–	ND	ND	–
#5	5.79	10.29	6.52	76.39	75.89	76.31	13.92	10.13	13.29	0.021	0.011	0.019	2.39	2.00	2.33	1.51	1.68	1.54	0.0024	0	0.0020
#6	10.01	9.92	9.99	75.99	77.15	76.2	12.30	10.35	11.95	0.036	0.006	0.031	1.69	2.59	1.85	ND	ND	–	ND	ND	–
#7	5.2	–	–	79.10	–	–	12.64	–	–	0.013	–	–	1.92	–	–	1.14	–	–	0.0045	0	–
#8	9.81	10.7	9.96	76.70	78.00	76.94	12.05	10.04	11.69	0.027	0.016	0.025	1.42	1.27	1.39	ND	ND	–	ND	ND	–
#9	6.68	10.56	7.33	77.83	78.87	78.00	13.94	8.08	12.97	0.024	0.024	0.024	1.53	2.48	1.69	1.26	1.23	1.26	0.0019	0	0.0016
Coal	2.03	–	–	79.71	–	–	16.31	–	–	0.145	–	0.145	1.79	–	–	ND	ND	–	ND	ND	–

MV: microwave heating, EA: electric arc heating, All: microwave and electric arc heating, ND: not detected, – : not applicable

Table 5.8. Estimated intensities of combustion-related pollutants from the MW/EAF process

Pollutant	SO_2	NO_x	**CO**	VOC_s	CO_2
Intensity (lbs/ton of steel)	≤ 23.15	≤ 0.01	≤ 1.86	≤ 0.015	3183

Rapid microwave heating rate of magnetite and magnetite reduction reaction in pellet samples are believed to contribute to the high carbon dioxide content of pellet sample's offgas. Compared with coal, pellet samples can be rapidly heated by microwave to an elevated temperature due to its magnetite constituent. The rates of coal combustion and magnetite reduction are greatly enhanced at higher temperature; therefore more carbon dioxide is emitted. Low sulfur dioxide content of pellet sample's offgas is contributed by the lime constituent of the pellet sample. The large proportion of sulfur in the pellet sample is retained in pellet sample due to reaction with lime, so lime in the pellet sample plays a very important role on reducing sulfur dioxide emission.

Table 5.8 lists the estimated intensities of combustion-related pollutants from pellet samples in the MW/EAF process. The intensity of carbon dioxide was estimated by using equation 5-36, and pellet samples with high volatile coal whose weight ratio was 35/100. The intensities of sulfur dioxide and carbon monoxide were estimated by using the intensity of carbon dioxide and measured maximum ratios. The intensities of NO_x and VOCs were estimated by using the intensity of carbon dioxide, measured carbon dioxide content of offgas, and the minimum measurable current of quadrupole gas analyzer.

Compared with the estimated intensity of combustion-related emissions from BF (blast furnace), offgas from the MW/EAF process contains less combustion-related pollutants.

The MW/EAF process can reduce carbon dioxide and sulfur dioxide emission by 34% and 26%, which is due to less coal used for one ton of steel. Coke is used as the major fuel in BF and the estimated intensity of carbon dioxide for BF is 2000 lbs per ton of iron. If carbon dioxide emission from coke making is taken into account, 4840 lbs carbon dioxide is released for producing one ton of pig iron.

MW/EAF process reduces carbon monoxide emission by 68% with respect to BF. VOCs and NO_x emission from MW/EAF process are almost insignificant (only 0.01 and 0.015 lbs per ton of steel). The low CO and VOCs emission in offgas indicate that almost all carbon monoxide and volatile organic compounds can be completely oxidized in the MW/EAF furnace before they get into the offgas system.

Summary

The major components of pellet sample's offgas are nitrogen, oxygen, argon, carbon dioxide, sulfur oxide, water vapor and carbon monoxide. The offgases emitted during the two stages of the MW/EAF process have different constituents and remarkably different composition; carbon monoxide is emitted during the early stage of microwave heating.

The average composition of offgas from the MW/EAF process by volume percent typically is 5% – 11% CO_2, 75% – 79% N_2, 10% – 16% O_2, 0.01% – 0.04% SO_2, 1% – 3% water vapor, 1.1% – 1.7% Ar and 0.002% – 0.005% CO. The maximum concentration of carbon monoxide measured in our investigation is 423 ppm (0.0423%).

Compared with conventional steelmaking, the MW/EAF process can greatly reduce combustion-related pollutants. With respect to BF, the MW/EAF process can reduce carbon monoxide and sulfur dioxide emission by 68% and 26%; and VOCs and NO_x emissions from the MW/EAF process are insignificant. The intensity of carbon dioxide emission from the MW/EAF process is 3183 lbs per ton of steel. With respect to coke making and BF, carbon dioxide emission is reduced by 34% because less coal is used in the MW/EAF process.

5.7 Estimation of Environmental Benefits

The environmental benefits will come from the elimination of cokemaking, pellet sintering, BF ironmaking, BOF steelmaking, and significant energy savings.

Sintering: Sinter plants emit particulate and CO, and discharge waste water. The emission rate of CO is about 0.47 lb/ton of sinter and the discharge rate of waste water is about 1,500 gallons/ton of sinter. The emissions and generation of waste water are due to combustion of fuel. Waste water is generated from scrubbers used for wet air pollution control. To produce one ton of steel by BF/BOF, about 1.35 tons of sinter is required. Currently, the United States produces about 46 million tons of steel by integrated mills. It translates into emission of 29.2 million pounds of CO and discharge of 93,150 million gallons of waste water annually in the United States.

BF Ironmaking: To produce one ton of liquid iron, BF operations generate 100 pounds of particulate, 2.5 to 3.5 tons of furnace gas, and 6,000 gallons of waste water. The furnace gas contains up to 40% CO and 6% H2. Nearly all of the waste water is direct contact water used in the gas coolers and wet scrubber of furnace dust. The generation of great amounts of particulate, furnace gas and waste waters are result of coke combustion in BF. The combustion requires great amount of air blown into the furnace. The United States produces about 46 million tons of iron at present. Therefore, the BF operations generate 4,600 million pounds of particulate, 115 to 161 million tons of furnace gas and 276,000 million gallons of waste water per year.

BOF Steelmaking: To produce one ton of steel, BOF operations generate approximately 10 kg of CO emissions, 8 pounds of dust, 62 pounds of sludge, and 1,100 gallons of waste water. The generation of these by-products is due to the high speed and high volume oxygen blown into the BOF to react with carbon in liquid iron. The United States generated 617,000 tons of CO emission in 1992 and 270,000 tons of dust and 1.3 million tons of sludge in 1996. Currently the United States produces about 46 million tons of steel by integrated mills. It translates into production of 50,600 million gallons of waste water annually.

Cokemaking: Cokemaking produces approximately 10,800 scf of coke oven gas per ton of coal charged. About 40% of the gas is used and the rest cause air emission problems. The emissions include ammonia, benzene-soluble organics, benzene, particulates, sulfur oxides, and volatile organic compounds. Cokemaking also generates approximately 100 gallons of waste water and 25 to 35 gallons of waste ammonia liquor per ton of coke produced. The waste water contains significant amounts of oil and grease, ammonia-nitrogen, cyanide, thiocyanates, phenols, benzenes, toluene, xylene, other aromatic volatile components, and polynuclear aromatic compounds. Waste water also contains trace amounts of the toxic metals antimony, arsenic, and selenium. To produce one ton of coke, about 1.4 tons of metallurgical coal is used. The United

States consumes about 27.6 million tons of coke each year for steelmaking. It converts to annual consumption of 38.64 million tons of metallurgical coal. In summary, the United States generates approximately 250,387 million scf of air emission, 2,760 million gallons of waste water, and 690 to 966 million gallons of waste ammonia liquor.

Energy Saving: MW/EAF steelmaking technology could save about 40% energy over BF/BOF steelmaking (40% x 27.92 GJ/t), which is equal 10.57 x 10^6 BTU per ton of liquid steel. Since coal is the dominant energy source for the iron and steel industry, the energy savings is equivalent to about 0.32 tons of coal for each ton of liquid steel. For about 45 million tons of steel produced by BF/BOF in the United States, it means a savings of 14.4 million tons of coal per year. Coal combustion means emissions of CO_2, SO_2, NO_x, trace elements, VOCs, fine particulates, and air toxics such as PAHs, fly ash, etc. The saving of 14.4 million tons of coal combustion will prevent the following emissions:

- 35 million tons of CO_2 (use 1.2 lb CO_2/MBTU)
- 87 thousand tons of SO_2 (use 0.3% sulfur) and 0.48 million tons of lime for scrubbing (for 2% sulfur in Midwest coal)
- 35 tons of mercury emissions (3 ppm Hg/ton coal)
- 1.5 million tons of fly ash
- Other emissions including NO_x and air toxins.

Slag Reduction: In conventional steelmaking, iron ore concentrate must be pelletized with bentonite as the binder and lime as a desulfurizer and fluxing agent before being charged into the blast furnace. The bentonite and limestone consume energy during iron and steelmaking, but also yield large tonnages of slag that must be disposed of. Since the new technology would use iron ore concentrate directly without additions of bentonite and, since sulfur contamination is present from western coal, only a small amount of lime is needed as a fluxing agent. Thus, slag generation is reduced and mining of bentonite and limestone can be reduced, respectively.

Task 6: Marketing and Economic Assessments

This chapter consists of two sections: marketing assessment and economic evaluation of MW assisted steelmaking process.

6.1. Marketing Assessment

This section discusses the marketing and economics of current steel and iron-making technologies to provide the basis for showing how the implementation of the microwave steel-making technology will improve the competitiveness of the US steel industry. The section is divided into three parts. The first part looks at the current technologies used in the steel and iron-making industries. The second part looks at the trends occurring in steel production and consumption for the world and the USA. From this information, the possible ways the microwave steel-making technology can be used to improve the competitiveness of US steel production are discussed. The third part looks at the cost of using the microwave steel-making technology and how it compares with existing technologies.

Current steel-making and iron-making technologies

Today, two technologies dominant the commercial production of steel worldwide: the Basic Oxygen Furnace (BOF) and the Electric Arc Furnace (EAF). The BOF technology accounts for about 60% of steel output in the world and 50% for the USA. This process is an indirect method that first produces iron (carbon content greater than 2.08%) and then converts it to steel (carbon content less than 2.08%). To make iron and steel, iron ore is ground to 500 mesh (22 mm) to liberate iron oxides from other minerals. The iron in the ground materials is concentrated by magnetic separation and froth flotation. The fine oxide particles cannot be fed to a smelter directly so they are pelletized with limestone and bentonite, sintered to make them strong, and then charged along with coke into the furnace. The raw materials are then subjected to a blast of very hot air. In the furnace, the iron oxide is reduced and melted and gains carbon and sulfur from the coke during melting. The carbon content in the iron must be lowered to make steel. This is commonly done in a Basic Oxygen Furnace, where pure oxygen is blown into the liquid iron at an ultra-sonic velocity to oxidize the excess carbon to form CO and CO_2. The gases are released to the atmosphere.

The EAF is the second major process for producing steel and accounts for about 40% of steel output in the world and 50% in the USA. Traditionally, 100% cold steel scrap is charged into an electric arc furnace and melted by intensive electric current between graphite electrodes and the electrically conductive raw materials. As an alternative to steel scrap, Directly Reduced Iron (DRI) has been developed and used to replace a percentage of steel scrap. Steel-making by the EAF process depends on the availability of scrap and the use of DRI, or pig iron produced by blast furnaces. DRI and pig iron usually contain fewer impurities than steel scrap and are preferred for the production of higher-grade steels. It is predicted that DRI will account for 25% to 50% of the EAF raw material charges by 2015.

Iron-making constitutes the process whereby iron oxides are chemically reduced to a metallic state by a reductant. The main iron-making technologies currently employed are the blast furnace technology (BF) and DRI. The BF technology as we recognize it today has been employed for approximately 150 years. The blast furnace is a vertical shaft furnace where raw materials are charged at the top and hot metallic iron and slag are topped from the bottom of the furnace. In the BF, iron ore, coke, and limestone are charged in layers at the top of the furnace. The charge direction is countercurrent to the gas flow in the stack. As the burden descends it comes in contact with hot gases that are rising in the stack. In the process, the coke is reheated as it descends so that when it arrives at the lower portion of the furnace, its contact with air from the hot blast makes it burn with intensity. With the high temperatures that exist, carbon dioxide is not stable because of the excess carbon present. The carbon dioxide reacts with the excess carbon to form carbon monoxide, the chemical reductant of the iron making process. As the iron ore and impurities work their way down through the stack they melt, forming liquid hot metal and slag. The liquid hot metal and slag are tapped from different locations periodically. The slag, the waste product of the process, is ladle transported, cooled, sized, and used as construction material. The hot metal proceeds by iron ladle to the refining process (primarily BOF) or is sent to the pig machine to be cast into solid ingots. Hot metal quality is typically 95% Fe, 3.5% C, and 1.5% other impurities.

In the subsequent refining operations, the hot metal is transferred to the BOF where it reacts with pure oxygen to burn out excess carbon and silicon. The liquid steel is then cast into billets or slabs for further processing by hot rolling and cold rolling. Steel made from ore in this manner is typically used for the highest quality applications. Approximately 45 million tons of steel per year are produced in the USA using this method.

On a worldwide basis DRI is a small but quickly growing source of metallic iron. DRI is a process to produce sponge iron or iron powder from iron ore using a gaseous or coal based reductant without a smelting process. Establishment of DRI plants can be traced to the early part of this century. Extensive direct reduction research however did not start until 1950s and several processes have been developed since such as Midrex, HyL, Fior, FINMET, Höganäs, Krupp-Renn, Iron Carbide, Circored, FASTMET, INMETCO, SL/RN, and Cicofer. Although a great deal of effort has been made, commercialization of these processes is very limited. DRI accounts for less than 10% of the input used in world steel production. This is up from the less than 3% in the 1980s. Approximately 5 million tons of DRI are imported into the USA per year, mainly to supplement scrap in EAF operations and to supplement iron units in the blast furnace.

The remaining iron-making technologies can be categorized by the type of reductant used - natural gas or coal. The resultant products are DRI, sponge iron, and, in one case, hot metal. In the USA, these types of processes account for less than one million tons per year of steel production. Where natural gas is used as the reductant, the gas is either used directly or cracked in a reformer chamber into hydrogen and carbon monoxide. Worldwide, gas based processes account for about 50 million tons per year of iron production, out of a world steel market of over 800 million tons per year. Gas is the reductant of choice where inexpensive natural gas is readily available, including countries like Malaysia, Bahrain, Mexico, Venezuela, Saudi Arabia, and Trinidad-Tobago. Gas based processes that are in commercial use or are being looked at for commercial development are the Midrex Shaft Furnace, HYL process, and various fluidized bed processes.

The Midrex Shaft Furnace is the most widely used process in the world for DRI production, generating 35 million tons per year of metallic iron. The feed to the process is fired pellets or lump ore and natural gas. A vertical shaft furnace is utilized, with the ore traveling down the stack countercurrent to the reducing gas. Natural gas goes through a reformer chamber where it is catalytically cracked into hydrogen and carbon monoxide prior to entering the furnace. The off gas is recovered at the top of the furnace, used to cool the DRI, and then recycled to the reformer with additional natural gas. The product is hot sponge iron that is directly charged into an EAF or briquetted and cooled for shipping.

The original HYL process was a batch version of the Midrex shaft furnace, where multiple shafts are charged with ore, reduced, and discharged. The process has since been modified into a continuous process similar to the Midrex Process. HYL plants are the second largest producer of DRI in the world, owned by Hylsa Steel of Mexico.

There are three commercialized fluidized bed processors; the Fimet process in Venezuela, the Iron Carbide, and Cliffs-Lurgi plants in Trinidad. In these processes, closely sized iron ore fines are suspended in a fluidized bed of reducing gases at high temperature. The processes produce grains of reduced iron at high temperature. In the Fimet and Cliffs-Lurgi processes, these grains are briquetted for shipment. In the Iron Carbide process, excess carbon is absorbed from the gas to produce iron carbide. These processes have the advantage of being able to use relatively coarse fine ore. The Fimet process is commercially used in Venezuela. The Cliffs-Lurgi plant in Trinidad is currently shut down. The Iron Carbide plant, built by Nucor, has been permanently shut down and is not considered a success. Feed for these plants is not readily available in the Great Lakes region, with the most likely source being crushed and sized pellets.

Coal is the reductant for most of the iron produced from ore in the world, whether as coal itself or made into coke as used in the blast furnace. Because of the significant tonnage of hot metal produced, the blast furnace was discussed previously, but is fundamentally part of this group of processes. The other coal based ironmaking processes that are in commercial use or being developed for commercial use are the Corex process, various rotary hearth processes, Hismelt and Ausmelt processes, and the ACCAR and Grate Car processes.

The Corex process has been commercialized in South Africa and Korea, and is designed as an alternative to blast furnace production of hot metal, which does not require metallurgical coke. It is basically a two-stage process with a direct reduction shaft furnace mounted on top of a high temperature oxygen blown melting furnace. The feed to the process is either pellets or lump ore and coal that is fed into the melting furnace with oxygen. The combustion of the coal in the lower melting furnace provides heat for melting and reduction furnaces along with an ascending off gas composed of various hydrocarbons and carbon monoxide working its way through the bed of the reducing furnace section. Iron and slag are periodically tapped from the furnace and the iron produced has essentially the same quality as hot metal from a blast furnace. This is a high-energy consumption process, at about 16 million BTU per ton of hot metal after credit for off gas energy use.

Several rotary hearth ironmaking processes have been proposed over the years, starting with the Surface Combustion Heat Fast process of the early 1960's. In the typical rotary hearth process, a layer of green balls, dried green balls, or pellets made of fine iron ore concentrate, pulverized coal, and a binder are placed in a thin layer on the surface of an annular rotary hearth. As the hearth revolves through its cycle, the feed is heated by radiant heat from the hood over the hearth and supplemental burners in the hood, reducing the carbon in the coal to carbon monoxide for reduction of the iron oxides. The resulting product is sponge iron in the form of pellet or briquette or nodules of pig iron. The sponge iron can either be compressed and cooled or charged directly into an EAF or BOF. In the sponge iron processes, a relatively impure iron product is produced because any slag in the ore or coal and most of the sulfur in both stay with the iron for later removal.

A typical sponge iron product would be approximately 94% metallic iron and 6% carbon-slag. It should be noted that a sponge iron product carries roughly a 10% penalty in value due to impurities. Commercial names for sponge iron processes include Inmetco/Demag, Fastmet/Midrex, Dryiron/Maumec, Iron Dynamics and others. Commercial plants have been installed for iron ore in Indiana, and for steel mill waste recycling in Pennsylvania, Michigan, Alabama, and Japan. In addition, two new processes under development independently by Kobe Steel and Kawasaki Steel use the rotary hearth to produce drops or nuggets of pig iron. The major difference is that the rotary hearth is run at a high temperature and the sponge iron pellets or briquettes melt to droplets of molten pig iron, with slag residing on the surface of the droplet, which can be easily separated by mechanical means. Nugget composition is similar to pig iron. These processes have only been run in pilot plants in Japan. A pilot plant is being assembled to test the Kobe process in Minnesota and a 50,000 tons per year (1/20 scale) demonstration plant for the Kobe process is under development for Cleveland Cliffs' Northshore site in Minnesota.

The Hismelt and Ausmelt processes are similar independently developed processes from Australia. Hismelt has been successfully demonstrated and Ausmelt is currently starting up a demonstration plant. Both processes start with a heel of molten metal in the bottom of the vessel similar to an empty blast furnace. A mixture of fine iron ore, pulverized coal, pulverized lime, preheated air and supplemental oxygen are blown at the surface of the hot metal. This ignites the coal, producing carbon monoxide and reducing the iron ore to metallic iron. The metallic iron is similar to pig iron quality. The capacity of the process is limited by the size of the combustion ball that can be maintained in the furnace.

The only other coal based processes that have shown commercial success are the ACCAR and Grate Car processes developed by Allis Mineral Systems (now Metso Minerals). In both processes, the feed to the system is fired pellets or lump ore and lump coal with pulverized coal added to the rotary kiln, where the mixture is tumbled in a reducing atmosphere. This process produces a product that is less sensitive to impurities in the coal, but still requires high quality iron oxide feed stock. The product is sponge iron pellets or briquetted sponge iron.

The Global and USA Markets

During 1975-2002, the annual world consumption of steel has been cyclical with the consumption levels of 1975 and 2002 being similar (around 750 million metric tons). The regional consumption patterns for steel, however, have been changing over this time period. Asia is the region of strongest growth in steel consumption-largely driven by China as the largest consumer of steel in the world. The other major consuming regions are the European Union (EU) and North American Free Trade Agreement (NAFTA). Within the EU, growth in consumption is being driven by Spain, Italy, and the smaller consuming nations. The larger consuming nations of the EU-France, Germany, and UK-have had a flat consumption trend. The USA is the dominant consumer in NAFTA, and its steel consumption has been increasing at an average annual rate of nearly 1% during1975-2002. Much of the growth in consumption occurred in the mid-to-late 1990s. Annual steel consumption is very cyclical and varied from 70 to 120 million metric tons during 1975-2002. Annual steel consumption in 2002 was a relatively high 107 million metric tons. The US market for steel is one of the largest in the world and is not fragmented into smaller national segments like in the EU and other parts of the world that must be added together to equal it. Alone, the USA accounted for nearly 15% of total annual world steel consumption. This is up from 11% in 1975. The major buyers of steel in the USA are warehouses and steel service centers, automobile industry, construction, and cans and containers.

US steel consumption can be largely explained with its level of industrial production and the changing nature of the US economy. An ordinary least-squares model using annual data for 1975-2002 with the explanatory variables of indexed industrial production and a yearly time variable explains about 80% of the observed annual variation in consumption. The variables are highly significant: the Indexed industrial Production variable's t-statistic is 6.9 and the t-statistic for the time variable is –5.0 (A t-statistic value greater than 2.5 is significantly different from zero at the 99 percent level of confidence.). There is a small but significant trend over time for the USA of less steel being consumed each year with all else being constant. The annual per capita consumption of steel in the USA (around 376 kilos in 2001) has remained fairly constant since 1975 despite the significant economic growth that has occurred. A similar trend can be observed for the wealthiest countries of the EU and Japan.

One theory used to explain this observed behavior is the Intensity-of-Use Hypothesis. It is argued that wealthy nations will emphasize service goods over manufactured goods over time. One implication is that service goods require less material like steel over time as compared with manufactured goods. Another implication is that countries still in the process of becoming wealthy (like China and Spain) should show increasing consumption of materials like steel. The steel industry statistics do not contradict this view. However, the large level of consumption by the wealthiest nations relative to other nations will maintain their key importance to the market trends for the foreseeable future. The key exception is China with its already large level of steel consumption despite its lower average income level.

Steel production occurs throughout the world, but it is centered in EU, NAFTA, and East Asia. Annual steel production in 2002 was 870 million metric tons. This compares to 644 million metric tons in 1975. World output tends to be less cyclical than the output from individual countries. The countries will the largest levels of steel production include China, Japan, USA, Russia, Germany, and Korea. Most of the world's production capacity is privately owned, and approximately 40% of the world's steel production is traded internationally. World steel production during 1975-2002 has been growing at an average annual rate of just under one percent. On average throughout the time period, 60% of the steel production was done with the BOF technology with the remainder being produced mainly with the EAF technology. A surplus of production capacity relative to steel consumption has led to the current market trend of producer consolidation to reduce capacity. This consolidation trend is also helping to create steel producers with global capacity (in an industry where transportation costs are important) that can offset home markets that are too small to achieve full production economies-of-scale and can match key consumers like the automobile industry that are becoming more global in their demand.

Steel is produced in the USA at 140 sites by 90 companies (the number varies from year-to-year). The focus for production is around the Midwest with Indiana, Ohio, Illinois, and

Pennsylvania being the leading producing states. Despite a period of increased production during the 1990s, the USA has had a decline in steel production during 1975-2002 that has been offset by increased imports. This decline has been centered on the production of steel with the BOF technology. The production of steel by the EAF technology has been rising over the same time period. In 1975, the BOF technology accounted for 65% of the annual US steel production with the EAF technology accounting for another 21%. By 2002, the USA's annual production share of steel by the BOF and EAF technologies were about equal with the EAF technology output being a little greater. US producers are less interested in global alliances than other producers because they have adequate demand at home in a market they understand well. US iron ore production is also unattractive for the globalization trend because of its geographic isolation. The large US market attracts world producers who are seeking export markets. A competitive US producers' price can have no premium beyond the $40-50/ton transportation costs of the low-cost foreign producers to the US market (except under tariff protection).

Use of Microwave Technology to Improve Competitiveness

BOF production in the USA is under pressure from production both domestically and abroad. Domestically, expanding, regional EAF producers have used their relatively lower production costs to take over the lower-valued steel markets from BOF producers. In the past, EAF producers have been limited by the quality of their feed material for production to lower-valued steel markets. Current efforts to improve the quality of feed material for EAF production have placed BOF higher-valued steel markets at risk as well. Lower cost imports from foreign BOF producers have also reduced the demand for domestic BOF production. Worldwide, the market for BOF steel is characterized by overcapacity and low prices. This is a difficult situation for US producers with their high legacy costs (benefits for retired workers) and older facilities. The long period of limited profits has made BOF producers unable and unwilling to put financial resources into capital investment and innovation. Overall, R & D spending is low at only 0.5% of sales revenues (as compared to 4% on average for manufacturing industries). The microwave technology is not a probable good fit with the BOF producers and their situation to improve competitiveness.

Today, EAF producers are the major providers of wire rods, wire, bars, and structural shapes. EAF producers are also starting to move into the production of higher-value products that have been the main business of BOF producers. EAF production success in these higher-valued steel markets depends on the availability of low electricity costs and adequate quantities of high-quality scrap and other iron feed inputs. EAF producers have more of a regional focus and are less concentrated in the Midwest as compared to BOF producers. This gives the EAF producers the ability to follow their customers as they shift location and keep transportation costs down. Overall, EAF operations have lower operating and capital costs than BOF operations and, correspondingly, stronger profits. The future growth of EAF production, however, depends on moving into higher quality steels. This makes the availability and price of high quality scrap a concern.

The microwave technology is an excellent fit with the EAF producers for improving competitiveness. EAF producers are very competitive in the steel industry and are gaining production share in the USA. Their move into the higher quality steels requires the availability of affordable, higher-quality scrap or suitable alternative. The EAF operators have more ability to fund capital investment and innovation. The ability of the EAF operators to use an alternative iron ore feed in place of scrap would improve their flexibility and competitiveness.

Existing alternative iron production methods like DRI have not made significant gains in production share in the USA so far. The problems with the current DRI processes include low productivity, low energy efficiency and relatively high production cost. These problems are caused by the fundamental fact that gas/solid or solid/solid reduction reactions take place at relatively low temperature with the assistance of inefficient external heating. The heat transfer rate, chemical reaction rate, and mass transport rate are low in these processes. For instance, Midrex and HyL, two major DRI processes, require 5 to 6 hours for complete reduction of iron ore. In addition, these two processes require pelletized iron ore, high capital costs, and production scales of at least one million tons per year to be economical. The microwave technology provides another low cost alternative iron production option that avoids these problems. An EAF producer can use the microwave technology as a supplement to its existing operations by allowing it to use iron ore feed as well as steel scrap. The cost of the addition of the microwave technology to existing EAF operations would be lower than stand-alone facilities because of the ability to use the existing capital and workforce already in place.

Another possible role for the microwave technology is as stand-alone facilities. These facilities could play a role as regional producers in a similar manner as EAF producers. These facilities could make use of excess US iron ore production that becomes available as US BOF production continues to decline. The isolation of US iron ore production makes it unlikely for it to be used by foreign producers given the ready availability of iron ore in the world. The microwave technology can provide a competitive alternative. The microwave facilities can also be located as to take advantage of savings in transportation costs between iron ore producers and steel markets.

In a global economy that is becoming more competitive, the U.S. steel industry needs technology that is responsive to changing market demands. This proposed technology will offer the steel industry flexibility in production capabilities, providing a means to explore products with new properties to meet new demands, yet capable of maintaining current product lines without penalty of additional capital investment. This flexibility is envisioned to come from a broader spectrum of feedstocks to be used, the combination of two energy input systems, and the simplification of mill equipment layouts. As this technology develops, it will be those companies who can create new operating methods and recipes to meet new demands that will establish market share. As exhibited by the spectrum of the project’s industrial participants, there is strong interest in this technology and a desire to understand how their current position in the industry will be affected.

6.2. Economic Evaluation

Noramco Engineering was invited to conduct an independent economic evaluation of the MW assisted steelmaking process based on production of 500,000 tons of steel per year. Noramco Engineering Corporation is a Minnesota-based major engineering firm serving the iron and steel industry (www.noramcoeng.com). Noramco sent an engineer to Michigan Tech to observe a steelmaking demonstration and collect basic technical data. The company then developed a conceptual design of a MW assisted steelmaking system as shown in Figure 2.5. Noramco's economic evaluation was based on this design. Noramco also compared the capital and operating costs of this new technology with those of existing DRI or ironmaking processes, as shown in Table 6.1. The new microwave assisted steelmaking process compares very favorably with any of the existing processes in both capital and operating costs. The details of Noramco's economic evaluation of the MW assisted steelmaking technology are given in Appendix D, Tables D.1 and D.2.

Table 6.1. Comparison of Direct Reduction Processes

Process	Ore Source	Reductant	Capital* per Annual Ton	Cash Operating Cost** per Ton	End Product
Gas Based Processes					
Midrex	Fired Pellet or Lump	Natural Gas	$200	$130	DRI
HYL	Fired Pellet or Lump	Natural Gas	$200	$130	DRI
Fluidized Bad	Screened Fines	Natural Gas	$200	$150	DRI
Coal Based Processes					
Blast Furnace	Pellets, Lump or Sinter	Coke	$1750	$120	Liquid Iron
Corex	Pellets, Lump	Coal	$400	$140	Liquid Iron
Rotary Hearth	Green Balls	Pulv. Coal	$270	$90	DRI
Rotary Hearth Nuggets	Green Balls	Pulv. Coal	$300	$100	Iron Nuggets
Hismelt, Ausmelt	Fine Concentrate	Pulv. Coal	$200	$100	Liquid Iron
ACCAR, Grate Car	Green Balls	Pulv. Coal, Gas	$250	$100	DRI
Microwave Assisted Hot Metal Production	Green Balls or Iron Ore Concentrate	Pulv. Coal or Gas	$48	$68	Liquid Steel

*Purchased raw materials basis, 500,000 to 1,000,000 tons per year annual capacity, adjacent to an existing mine or steel mill.
**Does not include indirect costs such as depreciation, debt service, and profit.

6.3. Economic Feasibility of a 500,000 T/y Plant

This section uses standard discounted cash flow analysis to estimate the potential profitability of the microwave steel making process. The basic procedure is to estimate the various costs and revenues that would be expected if the process be constructed into a full scale operation. These estimates are used in a standard cash flow statement to calculate the net cash flow, which is then used to compute the net present value using an appropriate discount rate. Other measures of profitability such as rate of return can also be computed from the cash flows, but net present value method will be the measure of profitability to be used here.

There are several possible applications for the microwave steel-making technology, and each of these will be analyzed as a different scenario.

Any measure of profitability of a project such as this relies entirely on estimates about costs, prices, and economic conditions in the future. It is of course impossible to know today exactly what these conditions will be, thus it is necessary to make forecasts and estimates. There are many different forecasting procedures, but almost all of them rely on using information from the past to choose values for the future. In other words, the past is usually used as a guide for the future. This may or may not lead to “good” forecasts of the future, but it is typically better than making completely uniformed guesses and there is usually no other procedure. The problem of estimating these future values is especially difficult when projecting out 15 or 20 years, as is necessary in this case because major capital plant investments must be for the long term.

Basic Assumptions

Applications to be analyzed

The two applications of microwave steel-making technology to be analyzed are:

A) Using the microwave technology to make hot metal for an existing mini-mill. This new technology would provide additional steel to the existing casting, rolling, and fabrication facilities. The purpose would be to provide another source of iron produced from iron ore to augment the existing electric arc furnace and its reliance on iron from scrap. In this scenario, the product from the microwave process would be hot metal, and the economic evaluation is for only the production of hot metal, without considering the fabrication facilities.

B) Constructing a stand-alone facility that would produce finished steel ingots that would compete against other steel in the semi-finished market. This scenario includes not only the microwave steel making furnace, but also the steel making and casting operations.

Figure 6.1 shows the basic inputs and materials flow for these two situations. Application A would only include the hot metal operations, whereas Application B would include hot metal, steel making and casting operations. In both cases, the analysis is based on producing ½ million tones per year of hot metal from the microwave steel-making process. For the complete process of application B, the addition of other inputs such as some scrap and other steel-making ingredients results in the final production of 0.585 million tones per year of steel slabs.

Figure 6.1. Material Flows in Microwave Steel Making

Hot Metal Operations:

		Million Tonnes per year	
Iron Ore			
1.35	Tonnes concentrate per tonne metal	0.675	Tonnes Iron Ore
Coal			
0.32	Tonnes coal per tonne metal	0.160	Tonnes Coal
Electricity			
667,233	Kwhr per tonne metal	333,617	Kwhr Electricity
	Yields	**0.500**	Tonnes Hot Metal Produced per year

Steel Making:

Hot Metal			
0.83	Tonnes hot metal per tonne steel	0.500	Tonnes Hot Metal
Scrap			
0.21	Tonnes scrap per tonne steel	0.127	Tonnes Scrap Metal
	Yelds	**0.602**	Tonnes Steel Produced per year

Casting:

Liquid Steel			
1.03	Tonnes liquid steel per tonne slabs	**0.585**	Tonnes Steel Slabs Produced per year

Technical parameters

The microwave steel making technology has been described elsewhere in this report, and Figure 6.1 shows the relevant technical parameters that are needed to estimate the costs and revenues from each scenario. Figure 6.1 shows the physical materials and energy flows for the process developed by this research. Table D.3A (in Appendix D) uses this information to develop the basic costs and revenues for the hot metal only operation of application A. Table D.3B (in Appendix D) uses the same information but extends the estimates to include the steel making and casting operations of application B.

All of this information applies to the first year of operation. The cash flow analysis will be extended out for an assumed plant life of 10 years. Many of these basic parameters will remain unchanged over the 10 years, such as the output of ½ million tones per year of hot metal and the energy and other input requirements. However, many of the economic factors will change over time due to inflation or other anticipated economic fluctuations.

The data presented in Tables D.3A and D.3B represent the base case scenario since this is believed to be the most likely plant configuration and operating characteristics for the two applications. However, sensitivity analysis will be performed by varying some of the more important of these basic assumptions to determine how sensitive the overall profitability is to these assumptions.

Economic and cost assumptions

This section discusses the key economic assumptions and describes the sources for the data.

Economic Parameters for producing hot metal: Table D.3A

Steel product selling price: This is the value per tone that is expected to be earned from producing hot metal. Since this replaces other sources of hot metal in the mini-mill, its value is the cost of obtaining hot metal via other means, such as melting of scrap. From source we estimate this value to be $300 per tone.

Steel price escalation rate: This is the expected percentage change per year (the rate of change) in the product price. This is like an inflation rate except that it is specific to the price of the final product, and therefore is more properly referred to as the escalation in price. For much of the past, materials prices such as steel and metals have not increased at the same rate as the general rate of inflation, thus it is appropriate to use a different escalation rate for this than the general rate of inflation that is used for the other cost items.

Royalty rate: We are assuming that a royalty will be paid to the owners of the intellectual property rights of this process. We are assuming 1% of the gross revenue will be paid as royalties.

Cost inflation rate: This is the general rate of inflation that will occur over the life of the project, in percent per year. This rate of inflation applies to the costs of inputs, salaries and wages, and the various other expenses of the operation. We are using 2% per year, based on the inflation experienced in the US economy over the last few years.

Iron ore cost per tonne: This is the cost of purchasing iron ore concentrates as feedstock for the microwave furnace. This is obtained as an approximate average of recent iron ore prices as published in Skilling's Mining Review in the spring of 2003. These published prices need some translation, since they are published in terms of cents per natural iron unit and need to be converted into dollars per tone, based on the typical iron units per ton for the specific type of ore listed. These conversions were made for several major ore types which were then averaged together and rounded to $40.00 per tonne.

Electricity cost per kWhr: This is the typical price per kilowatt-hour of electricity for a very large industrial customer using long term contracts. We found that some such customers were obtaining electricity at about 3.5 cents per kilowatt-hour in the spring of 2003.

Coal price per tonne: Coal prices were obtained from information published by Energy Publishing, Llc. In their "Coal & Energy Price Report" from the spring of 2003. Since these prices vary somewhat depending upon the terms of delivery, quality and type of coal, and the market cycle, $20.00 per tonne is used as a typical value.

Labor wage rate: The US Department of Labor publishes surveys of wages paid to workers in the iron and steel industries in the US and these show that the average wage for workers is about $25.00 per hour.

Employee overhead rate: The same Department of Labor studies show that most industries of this type incur costs of about 55% of salaries and wages for additional employee expenses such as unemployment insurance, heath insurance, retirement expenses, various kinds of employment taxes, and a variety of other costs associated with employing people.

Base Case Analysis

Table D.4 in Appendix D uses the base case assumptions for all the technical, cost, and economic parameters to compute the net cash flow for the two alternative situations. A project life of 10 years is assumed. Table D.4A shows the cash flow results and net present value results for producing only hot metal that would be used as feed material for an existing electric arc steel making operation. Table D.4B shows the corresponding analysis for a stand alone operation that would use the microwave process along with other facilities to produce cast steel slabs as the final product.

The results of each economic evaluation are summarized at the bottom of each table. The most important single number is the net present value: $262 million in the case of producing only hot metal and $316 million for producing steel slabs. Both of these are positive indicating that the projects are acceptable, given the assumptions used. More details about the specific cost items are shown below, and all of these estimates include the effects of the time value of money (cost of capital).

Sensitivity Analysis

All of these results are of course critically dependent upon the assumptions used. In order to determine which of the specific assumptions are most critical towards affecting the profitability, sensitivity analysis was performed. Each critical assumption was varied by plus or minus 1% from the base case estimate, resulting in a new net present value. The percentage change in the net present value that resulted from this 1% change in the underlying parameter was then computed. This is the elasticity of net present value with respect to the given parameter. For example, if the cost of electricity were to increase by 1%, this changes the net present value by -0.16%, where a negative indicates a reduction in net present value.

Table 6.2 shows the elasticities for the key parameters and assumptions, where Table D.5A in Appendix D shows the results for producing only hot metal and Table D.5B shows the results for producing steel slabs. Other parameters and assumptions are even less important than these, thus they are not shown in this table. Clearly, the product selling price is by far the most critical factor for both alternative production strategies and the metal production rate is the second most important factor. For all of the other parameters and assumptions, a 1% change results in less than a 1% change in final profitability.

Table 6.2: Sensitivity analysis

	for producing only hot metal	for producing steel slabs
Factor:	**Elasticity:**	**Elasticity:**
Hot metal production rate	1.07	1.12
Steel product selling price	2.23	2.88
Iron ore cost per tonne	-0.42	-0.35
Electricity cost per kwhr	-0.19	-0.16
Coal cost per tonne	-0.06	-0.05
Labor wage rate	-0.04	-0.08
Scrap cost		-0.19
Capital cost per tonne hot metal	-0.50	-0.40
Capital cost per tonne steel		-0.19
Capital cost per tonne slab		-0.19
Cost of Capital: MARR	-0.69	-0.82

Task 7. Evaluation of Policies, Regulations, and Affected Agencies

The steel sector is a heavily-regulated industry that must abide by policies and rules of three federal agencies and their delegated state authorities: U.S. Environmental Protection Agency (EPA), Occupational Safety & Health Administration (OSHA), and U.S. Department of Transportation (DOT). The major regulations of the EPA are the most comprehensive, covering air pollution, water pollution and waste disposal, and the Agency also spent much of the 1990s focusing on regulatory reform and reinvention activities. OSHA has a voluntary standard for occupational exposure to non-ionizing radiation, including microwaves. OSHA's primary regulations affecting this industry are its general safety and health regulations and its control of occupational exposure to cadmium. The DOT regulates the transportation of hazardous waste. While several other regulations apply to the steel industry, it should be noted that since microwave steel making technology has not yet been commercialized there are no specific, enforceable regulations for it. Consequently, we will discuss the primary regulations and policies affecting the electric arc furnace in the steel industry and speculate about the applicability of a few other regulations to microwaves. In most cases our proposed novel direct steel-making technology will be much more energy-efficient with substantially lower emissions and wastes than existing technology and have an easier time in meeting the applicable regulations.

U.S. Environmental Protection Agency (EPA)

The EPA's regulatory framework is generally organized around individual environmental media, i.e. air, water and land (for solid and hazardous wastes), and operates under more than a dozen statutes addressing these and other problems. Thus industrial sectors such as iron and steel must comply with a wide range of regulations as its operations affect multiple media. While coke ovens have traditionally been the largest environmental problem of this industry (the majority of environmental compliance costs are for air pollution control), environmental regulations affect it throughout all stages of manufacturing and product forming processes. Nonetheless, steel mills are primarily affected by four major environmental laws: the Clean Air Act (CAA), Clean Water Act (CWA), Resource Conservation and Recovery Act (RCRA), and the Emergency Planning and Community Right-to-Know Act (EPCRA). Other environmental statutes, such as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Safe Drinking Water Act (SDWA) affect only a limited number of existing or former steel mills and will not be reviewed here (EPA, 1995). In addition, greenhouse gas emissions such as carbon dioxide (CO_2), while important, have yet to be regulated in the U.S. and thus steel mills do not face mandatory controls.

Clean Air Act

The Clean Air Act of 1970, as amended in 1977 and 1990 (CAA), has required substantial capital investments to be made by the steel industry. While overall environmental control accounts for about 15% of total capital investment expenditures for the electric arc furnace industry, clean air requirements have accounted for more than three-fourths of the total in this sector (Wrona and Julien, 1997). Especially critical have been the state implementation plans (SIPs) to meet the National Ambient Air Quality Standards (NAAQS), particularly for nitrogen oxides (NO_x), lead, and particulate matter. For steel mills with basic oxygen furnaces the largest challenge has been in keeping coke ovens in compliance with EPA standards, though dust control from electric arc furnaces is also critical.

The EPA promulgated two new NAAQS in 1997, for ozone (O_3) and particulate matter of 2.5 microns in diameter ($PM_{2.5}$) that are relevant to the steel industry. While controversial, the new standards were subjected to lawsuits but upheld by the U.S. Supreme Court on February 27, 2001. These NAAQS are expected to result in an increased number of areas in the country being designated with non-attainment (NA) status, once all the requisite rules are implemented and the monitoring equipment is in place and working properly (Brownell and Goldberg, 2001). The new standard will be an 8-hour average of 0.08 ppm for O_3, an annual $PM_{2.5}$ NAAQS of 15 ug/m^3, and a daily $PM_{2.5}$ NAAQS of 65 ug/m^3. The preexisting O_3 standard has been 0.12 ppm averaged over 1 hour, while the $PM_{2.5}$ standard is new (the preexisting coarse particulates standard, or PM_{10}, of 50 ug/m^3 and 150 ug/m^3 for a year and daily, respectively, will continue to be in effect). While the NAAQS do not directly regulate stationary sources such as steel mills, if geographic areas are in NA status further restrictions on these sources may be required.

Title V of the CAA sets the permit requirements for major stationary sources of air pollution such as steel mills. A permit is required for facility construction, as well as its operation (for new, modified or existing sources). A Title V operating permit includes all CAA control requirements for a source in a single document and is legally enforceable by the EPA or a state air pollution control agency (40 **CFR** 70 and 71). These rules also establish a federal permitting program for use where state air agencies fail to establish or implement an adequate program, though most states are running their own air permitting program (since they meet the minimum EPA standards). Nevertheless, only about 6,000 operating permits have been issued thus far as compared to nearly 20,000 that are needed.

The control requirements for the criteria air pollutants regulated by the NAAQS for a major stationary source such as a steel mill vary depending on whether the facility is an existing, new, expanded or modified source, and whether it is located in a NA area or a geographic area in compliance. Existing facilities located in NA areas would have to install reasonably available control technology (RACT) as determined by the state authority, while no such requirements are imposed in the cleaner areas.

New Source Review (NSR) requirements under the CAA apply to major sources of the criteria air pollutants with new facilities, expansions or major process modifications (40 **CFR** 52.21(b)(1)(I)(a)-(b)), and is currently under review by the EPA. At the present time, a NSR for a facility in a NA area would by done by the state agency in most cases, and would require the facility to meet the lowest achievable emission rate (LAER) standard and acquire tradeable emission offsets of the same pollutant from other sources in the NA area in slightly greater amounts than the emission level of the new source (EPA, 1995).

A new steel mill to be located in an area meeting the NAAQS would be subject to a prevention of significant deterioration (PSD) review and would be required to install the best available control technology (BACT). BACT is the strictest possible technology standard required under the CAA, and is often equivalent to the LAER in practice. In addition, the owner or operator of the new source is required to conduct continuous on-site air quality monitoring in the area for a year prior to commissioning the new source to determine its effects on ambient air quality (EPA, 1995). To avoid this delay in startup in these clean areas, some mills have attempted to be reclassified as a “synthetic minor” source, which would require an even tighter restriction on total emissions allowed on the air permit, but thereby avoiding the lengthy and expensive PSD review.

The minimum standards for the LAER and BACT for iron and steel mills were set in 1975 by the EPA (40 **CFR** 60, Subpart AA), and last amended in 1999. The New Source Performance Standards (NSPS) for electric arc furnaces are described in 40 **CFR** 60.270, which regulates the particulate matter and opacity in any gases discharged from dust-handling equipment. The standard for particulate matter is 12 mg/dscm, which is usually controlled with a baghouse. The shop opacity (the arithmetic average of 24 or more opacity observations of emissions from the shop taken in accordance with EPA Reference Method 9) limit is under 6% during melting and refining, 20% during charging, and 40% during tapping. A continuous emission monitoring system is required for the measurement of opacity.

The EPA has issued several Maximum Achievable Control Technology Standard (MACT) standards for emissions of hazardous air pollutants (HAPs) that affect the steel industry, which sometimes is also called National Emission Standards for Hazardous Air Pollutants (NESHAPs) under Title III of the CAA. The MACT treatment standard is defined as a technology that will result in the maximum degree of reductions achievable subject to economic, energy and environmental considerations. Such standards have been set for coke oven batteries; benzene emissions from coke by-product recovery plants; halogenated solvent cleaning; chromium-industrial process cooling towers; steel pickling facilities that use hydrochloric acid; and have been proposed for integrated iron and steel manufacturing facilities with blast furnaces and basic oxygen process furnaces. While the EPA had once also considered establishing a MACT standard for electric arc furnaces (EAF), it decided to de-list this category on June 4, 1996 (61 **FR** 28197). This was done because the EPA believes that there are no major EAF sources that emit more than 10 tons per year of a single HAP, or 25 tons per year of the sum of all HAPs emitted per year. In addition, the EPA does not believe that the EAF technology poses a significant risk warranting a standard that would affect area sources.

The CAA required the EPA to promulgate regulations to prevent accidental releases of regulated substances and to reduce the severity of those releases that do occur. Pursuant to this requirement, under section 112(r)(7) of the CAA (“Accident Prevention”) stationary sources with processes that contain more than a threshold quantity of a regulated substance have been required to prepare and implement a Risk Management Plan (RMP). The EPA issued its list of 77 regulated toxic substances and 63 flammable substances and threshold quantities on January 31, 1994, which affects many steel mills including mini-mills such as Nucor. The regulation for risk management programs and the RMP was issued on June 20, 1996, and facility RMPs were required to be filed and registered with the EPA by June 21, 1999. About 15,000 RMPs were received by the EPA across all sectors. The RMPs also were required to be submitted to the five member Chemical Safety and Hazard Investigation Board, and be available to state and local authorities, and the general public (40 **CFR** 68).

Processes are divided into three program categories, based on the potential for offsite consequences associated with a worst-case accident release; no offsite accident history; or compliance with the prevention requirements under OSHA's Process Safety Management (PSM) Standard (29 **CFR** 1926). Processes that have no potential impact on the public in the case of an accident release have minimal requirements. For other processes, sources must implement a risk management program that includes more detailed requirements for hazard assessment, prevention, and emergency response. Processes in industry categories with a history of accidental releases and processes already complying with OSHA's PSM Standard are subject to a prevention program identical to parallel elements of the OSHA Standard. All other processes are subject to a streamlined prevention requirement. All sources, however, must prepare offsite consequence analyses for a worst-case release scenario.

An RMP must include the following information:

- a 5-year history of accidental releases of substances subject to the RMP regulation that have resulted in injury or death to humans, off-site evacuations, or property or environmental damage;
- a hazard assessment of worst-case releases of toxic or flammable substances and, for some sources, alternative release scenarios;
- a summary of the facility's emergency response program, including procedures for notifying the public of a release, and schedules for drills completed and planned;
- the contact person for emergencies;
- the date of the last safety inspection and the agency that performed it; and
- a general description of the company's accident prevention plan.

Some sources also need to include pertinent details of any incident investigation, management of change procedures, operating procedures, pre-startup reviews, maintenance activities, compliance audits, process safety training information, and process hazard analyses.

Clean Water Act

The Clean Water Act of 1972, as amended in 1977 and 1987 (CWA), set up the National Pollution Discharge Elimination System (NPDES) for permitting and controlling effluents from point sources of water pollution. Most NPDES permitting programs are implemented by state environmental agencies. Since the iron and steel manufacturing industry is a major water user, the EPA established effluent limitations guidelines and standards for it in a 1974 regulation, revised in 1982 and amended in 1984, for both new and existing facilities (40 **CFR** 420). These guidelines and standards are implemented through the NPDES permit program and through state and local pretreatment programs. Whereas part 420 limits in the EPA regulations are production-based, steel mills with higher levels of output receive higher effluent discharge allowances in their permits. Subpart D, in particular, covers steelmaking including electric arc furnaces (EPA, 1995). These point sources of water pollution are required to install best practicable technology currently available (BPT) or best available technology economically achievable (BAT).

Revisions to the effluent limitations guidelines and pretreatment standards for wastewater discharges were proposed by the EPA in August, 2002 (EPA, 2000). Among the proposed changes would be a zero discharge standard as the NSPS at non-integrated steel mills, and elimination of effluent trading for oil & grease (see the discussion on effluent trading below).

The water pollutants covered by these regulations fall into three categories:

1. Conventional pollutants: total suspended solids, oil & grease, pH;
2. Nonconventional pollutants: ammonia, phenols; and
3. Priority (toxic) pollutants: cyanide, chromium (total and hexavalent), lead, nickel, zinc, benzene, benzo(a)pyrene, napthalene, tretachlorethylene.

The EPA has worked with steel companies to try and reduce the volume and toxicity of wastewater effluents discharged from their mills. Water pollution from the steel industry has also been the subject of several court challenges by environmental groups. Wastewater effluent is often recycled at steel mills to reduce the volume of such discharges. In addition, the process wastewater is typically filtered or clarified on-site before it is discharged. The oil and greases are removed from the process wastewater by either skimming, filtration or air flotation, and are often used as lubricants or for preservation coatings. Some waste iron and organic chemicals will remain in the sludge, which can be recovered and reclaimed through sintering and pelletizing operations (EPA, 1995).

To increase the flexibility and cost-effectiveness of effluent control at steel mills, the EPA has allowed intra-plant effluent trading at Sparrows Point, Maryland and at about 10 other iron and steel mills in Michigan and Indiana since 1983, although most of the trades are no longer active (Podar and Kashmanian, 1998). This permitting option resulted from a negotiated settlement between the Natural Resources Defense Council and the iron and steel industry. Trading has been permitted for conventional pollutants (total suspended solids and oil & grease) as well as toxic pollutants (zinc and lead). To have intra-plant trading approved, the steel mills have had to reduce their conventional pollutants by at least 15% and the toxic pollutants by at least 10% below the BPT or BAT limits, although the net water quality effects of such trading have not been clear (Kashmanian et al., 1995).

The storm water rule under the CWA (40 **CFR** 122.6(b)(14), subparts (i, ii)) requires the capture and treatment of storm water at primary metals manufacturing facilities, including iron and steel plants. The management of storm water reduces the discharge of total suspended solids, biological oxygen demand (BOD), oil & grease, and some metals (EPA, 1995).

Resource Conservation and Recovery Act

Under Subtitle C of the Resource Conservation and Recovery Act of 1976 (RCRA), as amended in 1984 (40 **CFR** 261), generators of hazardous wastes are responsible for keeping track of the wastes they generate and where they go for treatment, storage or disposal. Electric arc furnace emission control dust and sludge are identified by the RCRA as process K061, although 90% of these wastes are managed for metal recycling or recovery (EPA, 1995). The metals targeted for recovery are iron, zinc, nickel alloys, lead, and cadmium. This statute requires “cradle to grave” waste management and restricts land disposal at landfills and includes waste accumulation, manifesting, and record keeping standards. Consequently any hazardous wastes shipped off-site must be accompanied by a hazardous waste form or manifest at all times, to ensure that the transportation and disposal of the wastes is done in an environmentally sound manner. Forty-six of the 50 state environmental agencies implement the RCRA provisions.

Several technical options exist for the disposition of the metals in the dust and sludge that are not recycled. These include stabilization, use as an ingredient in fertilizer, cement production, or in glass grit for abrasive blast, glass ceramic or ceramic glaze, roofing shingles, and use as an ingredient in the production of special aggregates.

The EPA proposed a conditional exclusion from the definition of solid waste for hazardous secondary materials that are recycled to make zinc fertilizers or their ingredients (65 **Federal Register** 70954, November 28, 2000). A generator of zinc waste would no longer be subject to hazardous waste management regulations as long as it meets the specified conditions relating to accumulation, storage, transportation, reporting and record-keeping requirements of excluded materials. This proposal included a second conditional exclusion for zinc fertilizers made from hazardous wastes or excluded hazardous secondary materials (p. 70967). Manufacturers would be required to meet the proposed technology-based contaminant limits, and maintain analytical data and analyses demonstrating compliance.

The EPA also is pursuing a Hazardous Waste Identification Rule exemption, which would exempt listed hazardous wastes that meet chemical-specific exemption levels from the definition of hazardous wastes. While this rule was originally planned to be issued in April 2001, its release has been delayed because of complexities involved in the risk assessment using the Multi-media, Multi-pathway and Multi-receptor risk assessment (3MRA) Model. This rule would be intended to better align the costs of RCRA regulation with the risks being controlled.

Emergency Planning and Community Right-to-Know Act

Under Section 313 of the Emergency Planning and Community Right-to-Know Act (EPCRA), a steel mill is subject to the annual reporting requirements if it has 10 or more full-time employees and it manufactures, imports, processes or otherwise uses any of the EPCRA section 313 chemicals an amounts greater than threshold quantities. There are currently more than 650 chemicals and chemical categories on this list. Examples of target chemicals at steel mills with electric arc furnaces are cadmium, lead, zinc, and hexavalent chromium. The threshold reporting quantities are usually 25,000 pounds per chemical per year for target chemicals that are manufactured or processed at the facility, and 10,000 pounds per chemical per year for target chemicals that are otherwise used at the facility. *De minimus* reporting exemptions are allowed when these chemicals are less than 0.1 percent or 1 percent (depending on the chemical in question) in mixtures.

While most (if not all) steel mills with electric arc furnaces operate below the reporting thresholds of the EPCRA these facilities should still be familiar with the reporting requirements. The information requested under section 313 of the EPCRA must be filed on Form R, available from the EPA, for each of the Toxic Release Inventory (TRI) chemicals above the threshold and *de minimus* quantities listed by the EPA. The EPA consolidates these reports on its annual TRI report. Each company must report the following:

- the name and location of the facility;
- the identity of the EPCRA section 313 chemical;
- whether it manufactures, imports, processes, or otherwise uses the chemical;
- the maximum quantity of the chemical on-site at any time during the year;
- the total quantity of the chemical released during the year (separately for on-site releases to air, water, land and injected underground; and transfers for off-site disposal;
- the total quantity of the EPCRA section 313 chemical otherwise managed as waste during the year (separately for on-site treatment, on-site combustion for energy recovery, on-site recycling, transfers for off-site treatment, transfers for off-site energy recovery, and transfers for off-site recycling):
- off-site locations that were shipped wastes containing the EPCRA section 313 chemical and the quantity of that chemical sent to those locations for recycling, energy recovery, treatment, or disposal;
- on-site recycling, energy recovery, or treatment methods used for wastes containing the EPCRA section 313 chemical, and estimates of the treatment efficiency for each chemical;
- source reduction activities involving the EPCRA section 313 chemical.

Common Sense Initiative

The Common Sense Initiative (CSI) was an innovative experiment conducted from 1994-98 to encourage “cleaner, cheaper, and smarter” sector-based approaches to protecting the environment and human health. It was a primary component of the EPA’s regulatory reinvention efforts in the 1990s. The EPA addressed six sectors in this initiative; iron and steel was one of them. The Iron and Steel Subcommittee included more than 20 representatives from industry, environmental justice organizations, labor and environmental groups, and federal, state and local governments. This Subcommittee met several times between January 1995 and May 1998. Using a consensus approach to decision making intended to avoid costly delays and litigation, the subcommittee considered a variety of topics including regulation, permits and public participation, compliance, reporting, Brownfields, pollution prevention and environmental technology. The CSI Council presented 28 formal recommendations from all subcommittees to the EPA at the end of 1998, few of which have been implemented thus far (GAO, 1997).

Several projects were conducted by the CSI Iron and Steel Subcommittee, with mixed results. For example, state/EPA multi-media (air, water, wastes) permit information was identified that can be consolidated into electronically submitted reporting for a mini-mill. The Subcommittee also developed a pseudo, non-enforceable multi-media permit. The consolidated report can potentially reduce duplication, minimize errors, yield significant cost savings and provide affected communities with usable environmental information. This project has already been integrated into Utah’s “One Stop” reporting initiative. General permitting issues were also considered. Two recommendations resulted in an improved NSPS regulation for electric arc furnace monitoring (issued on March 2, 1999), and consolidated guidance on witnessing certain air testing, respectively. Another important project resulted in the establishment of an iron and steel (among other sectors) liaison at the EPA. This liaison is currently Robert S. Benson, director of the Sector Strategies Division in the Office of Policy, Economics and Innovation.

While the CSI formally ended in 1998, important follow-up work is being done as part of the EPA's sector programs.

Occupational Safety & Health Administration (OSHA)

The safety and occupational health of workers in steel mill is regulated under the Occupational Safety and Health Act of 1970. This Act encourages safe and healthful working conditions, and authorizes the Secretary of Labor to set mandatory occupational safety and health standards and enforce them through OSHA. OSHA has established permissible exposure limits (PELs) for about 430 chemical substances that are considered occupational air contaminants, which are listed in 29 **CFR** 1910.1000. The PELs include time-weighted average (TWA) limits, short term exposure limits, ceiling limits and, in some cases, skin designations.

OSHA promulgated a standard for occupational exposure to cadmium, which took effect in December 1992 (29 **CFR** 1910.1027). Cadmium is part of the hazardous waste stream contained in the dust produced by the operation of an electric arc furnace in a steel mill. Employees exposed to excess amounts of cadmium face a significant health risk in the form of lung and prostate cancers, and serious kidney dysfunction. OSHA's standard is an 8-hour time TWA PEL of 5 micrograms of cadmium per cubic meter (ug/m^3) of air, which includes exposure through fume and dust. Employers are required to comply with this PEL primarily by means of engineering and work practice controls.

For microwave operations, the primary health effects of concern from electromagnetic radiation are thermal exposure or burns and contact shocks, although research is continuing to investigate non-thermal effects. OSHA has voluntary standards for workplace exposure to non-ionizing radiation (including microwaves) that can be found in 29 **CFR** Section 1910.97, which were approved in 1996. The recommended power density exposure limit is 10 milliwatt/cm^2 for periods of 0.1-hour or more. An energy density limit of 1 milliwatt-hour/cm^2 during any 0.1 hour period is also recommended. These standards have been ruled unenforceable. Some U.S. states with their own OSHA-type programs, however, are enforcing this or other exposure limits. For instance, while Michigan follows the OSHA guidelines the New Jersey Department of Environmental Protection has an exposure limit of 5 milliwatt/cm^2. The guideline is also half the OSHA level in Ontario, Canada (Ontario Ministry of Labour, 2002). The OSHA standard also specifies the design of a warning sign, although the inclusion and choice of warning information or precautionary instructions is discretionary.

U.S. Department of Transportation (DOT)

Electric arc furnace dust typically contains 1-2% of the charge in the form of zinc, lead, cadmium, chromium and smaller amounts of other hazardous materials. While there is a modest but growing market for recovery and use of these hazardous wastes by-products, especially zinc, their shipment is subject to the regulations under the Federal Hazardous Materials Transportation Law (49 **CFR** 171-180). These regulations are issued by the Research and Special Programs Administration of the U.S. Department of Transportation (DOT). The rules and regulations govern the safe transportation of hazardous materials from all sources; authorize approvals and exemptions for specific activities; require the receipt and maintenance of records of cylinder test reports, manufacturer certifications, and incident reports; normally preempt state, local and tribal hazardous materials transportation requirements; and provide for civil and criminal penalties for violations.

ACCOMPLISHMENTS

After three years of effort, the bench scale study has been successfully completed and the technical feasibility of microwave steelmaking has been verified. Energy efficiency, cost savings, and environmental benefits of the revolutionary steelmaking technology has indicated a potential savings of 45% of the energy and a 40% reduction in steel production costs. Environmental benefits are significant, including the reduction of particulates, CO_2, SO_2, NOx, VOCs, CO emissions, and slag generation.

U.P. Steel has licensed this technology for commercialization. This is a private company created in 2001. The founders of the company have extensive experience in mining, mineral processing and steelmaking, and identified microwave steelmaking as the most important and promising technology for the future of the industry. U.P Steel has filed world wide patent applications and extensively marketed the process with $100,000 of current investment.

Cleveland Cliffs Iron Company is the largest domestic iron ore company and operates iron ore mines in Michigan. CCI participated in this microwave steelmaking project by providing iron ore for steelmaking tests and assistance in evaluating test results and economics. CCI has closely watched the progress of the microwave steelmaking technology since 2001 and is actively involved in the proposed pilot plant planning and cost sharing.

Several presentations were made during the project:

Potential Application of Microwaves in Steelmaking
Third World Congress on Microwave and RF Applications
Microwave Working Group, September 22 - 26, 2002, Sydney, Australia
Authors: **S. X. Huang**, J. Y. Hwang, S. Shi, R. C. Greenlund, T. Xu, and A. M. Hein

Microwave Assisted Direct Steelmaking
Upper Peninsula Section of SME, Annual Technical and Business Meeting
Michigan Technological University, Houghton, MI
April 16, 2003
X. Huang

Microwave Production of Steels
Structural Engineers Association of Texas, 2004 State Conference
Lakeway, TX,
October 21-23, 2004
J.Y. Hwang, X. Huang

Contributing investigator, Michigan Tech Associate Professor Barry Solomon (Social Sciences) presented a paper, "**A Market Transformation Strategy for Highly Efficient Steel Meeting**," at the 2003 Summer Study on Energy Efficiency in Industry of the American Council for an Energy-Efficient Economy, which was held from July 29-Aug. 1, 2003 in Rye Brook, New York.

One PhD dissertation was completed during the project period: “**Microwave Application and Modelling in Direct Reduction of Iron Oxide**” by Shaolong Qu, in partial fulfillment of the requirements for a degree of Doctor of Philosophy in the field of Chemical Engineering, Michigan Technological University, 2004.

Demonstrations to at least ten sets of visitors interested in the microwave steelmaking technology were given over the course of the project, including Noramco, US Steel, Steel Dynamics, Cober Electronics, CCI, Michigan State government Representatives, automobile foundries, and foreign industries.

PROJECT GENERAL CONCLUSIONS

From the conclusions made in each task, we have the following general conclusions for this Phase I project.

- MW/EAF steelmaking is a validated technology. Its technical feasibility was proven by a previous concept study and has been proven again by the newly developed bench scale equipment and the bench scale study. Evaluation of the produced steels showed that steel containing 0.2% carbon and less than 0.01% sulfur can be produced. Steel yield above 95% can be easily obtained.

- MW/EAF steelmaking is a much more environmental friendly process than current technologies. Environmental benefits are significant, including the reduction of particulates, CO_2, SO_2, NOx, VOCs, CO emissions, and slag generation. The process reduces the environmental impact of steelmaking by preventing pollutant generation rather than relying on end-of-the-pipe pollution treatment.

- MW/EAF steelmaking is a more energy efficient process than current steelmaking processes using iron ore as the feed material. Results indicate a potential savings of 45% of the energy and a 40% reduction in steel production costs. In addition, iron ore reduction time is dramatically reduced.

- The inherent flexibility of the technology allows it to be used with various feedstocks and process sizes. This facilitates the integration of MW/EAF steelmaking with the current steelmaking plants and creates less disorder in the industry.

- MW/EAF steelmaking requires much lower capital cost and operation cost in comparison with current steelmaking processes. It is economically feasible and will provide more profit to the steel industry if it is implemented.

- MW/EAF steelmaking can be scaled up to the current high volume industry production using currently available manufacturing techniques to build the required new steelmaking equipment.

RECOMMENDATIONS

While many of the scale-up and integration questions have been answered, there is still work to do to bring microwave steelmaking technology to commercial readiness. Larger scale testing and integration studies should continue. We propose to design, build and test a 500 kg/h MW DRI column with the feature of exporting gaseous fuel and associated material charge and discharge mechanisms. We also propose to study the integration of the MW DRI columns with an EAF through a conveyer system and define the plant layout.

The goal of the proposed Phase II study is to develop the key equipment for the MW/EAF steelmaking technology and make it ready for commercialization activities.

The objectives associated with the goal are to a) design and fabricate a 500 kg/h MW DRI furnace with the feature of exporting gaseous fuel; b) test and evaluate its performance; c) generate a solid base of technical and economic data for the next phase of development; e) assess energy efficiency and environmental impact of the 500 kg/h MW DRI furnace and overall MW/EAF steelmaking based on the test data; f) define industrial implementation of MW/EAF steelmaking process; and g) demonstrate the pilot equipment performance to potential investors to promote an early industrial implementation.

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APPENDIX A

Design for Experiment of Direct Microwave Steel-making (Phase 2)-1

Iron ore type: Magnetite May 2002

Sample No.	Iron ore %	Coal (%)	Lime (%)	Binder ratio		Compact State	Time (min)	KW & C^0
				Type	%			
a. Change the Ratio of Iron Ore and Coal, Using Bentonite as Binder								
M80-C15-L5-B2	80	15	5	Bentonite	2	Tight (3000 psi)	7	1.6
M75-C20-L5-B2	75	20						
M70-C25-L5-B2	70	25						
b. Change the Ratio of Iron Ore and Coal, Using Starch as Binder								
M80-C15-L5-S2	80	15	5	Starch	2	Tight (3000 psi)	7	1.6
M75-C20-L5-S2	75	20						
M70-C25-L5-S2	70	25						
c. Change the Compact States 1 with half pressure								
M80-C15-L5-S2-O1	80	15	5	Starch	2	Loose 1 (1500 psi)	7	1.6
M75-C20-L5-S2-O1	75	20						
M70-C25-L5-S2-O1	70	25						
d. Change the Compact States 2 without pressure								
M80-C15-L5-S0-O0	80	15	5	Non	0	Loose2 (Ground)	7	1.6
M75-C20-L5-S0-O0	75	20						
M70-C25-L5-S0-O0	70	25						
e. Change the Heating Power (Temperature)								
M75-C20-L5-S2-P1.0	75	20	5	Starch	2	Tight (3000 psi)	7	1.0
M75-C20-L5-S2-P1.3								1.3
M75-C20-L5-S2-P1.9								1.9
f. Change the Heating Time								
M75-C20-L5-S2-T3	75	20	5	Starch	2	Tight (3000 psi)	3	1.6
M75-C20-L5-S2-T5							5	
M75-C20-L5-S2-T9							9	

Continued from “Design for Experiment of Direct Microwave Steel-making (Phase 2)-1”

Sample No.	Iron ore %	Coal (%)	Lime (%)	Binder ratio		Compact State	Time (min)	KW & C^0
g. Change the Lime Ratio								
M73-C20-L7-S2	73	20	7	Starch	2	Tight (3000 psi)	7	1.6
M70-C20-L10-S2	70		10					
M65-C20-L15-S2	65		15					
h. Change the Reducing Agent: Replace Coal with Coal-S (High S)								
M80-Cs15-L5-S2	80	15	5	Starch	2	Tight (3000 psi)	7	1.6
M75-Cs20-L5-S2	75	20						
M70-Cs25-L5-S2	70	25						
i. Change the Reducing Agent: Replace Coal with Graphite								
M80-G15-L5-S2	80	15	5	Starch	2	Tight (3000 psi)	7	1.6
M75-G20-L5-S2	75	20						
M70-G25-L5-S2	70	25						
j. Replace Starch with Molasses								
M80-C15-L5-m4	80	15	5	molasses	4	Tight (3000 psi)	7	1.6
M75-C20-L5-m4	75	20						
M70-C25-L5-m4	70	25						
k. Change the Ratio of Binders 1								
M80-C15-L5-S5	80	15	5	Starch	5	Tight (3000 psi)	7	1.6
M70-C25-L5-S5	70	25						
l. Change the Compact States 1 of Binder 1								
M80-C15-L5-S5-O1	80	15	5	Starch	5	Loose 1 (1500 psi)	7	1.6
M70-C25-L5-S5-O1	70	25						

Sample Preparation for Microwave Steel-making (Phase 2)-1

Magnetite June 2002

Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
a. Change the Ratio of Iron Ore and Coal, Using Bentonite as Binder							
M80-C15-L5-B2	Ma1-1	18.26	5.60	22.01			
	Ma1-2	18.45	5.50	22.10		1.69	
	Ma1-3	18.79	5.59	22.49	1.98	1.72	61.15
M75-C20-L5-B2	Ma2-1	18.26	5.42	21.42			
	Ma2-2	18.58	5.42	21.75		2.33	
	Ma2-3	18.3	5.29	21.35	.83	2.22	88.96
M70-C25-L5-B2	Ma3-1	18.91	5.34	21.76			
	Ma3-2	18.11	5.08	20.87		1.74	
	Ma3-3	18.53	5.24	21.32	.55	2.24	97.09
b. Change the Ratio of Iron Ore and Coal, Using Starch as Binder							
M80-C15-L5-S2	Mb1-1	18.37	5.71	22.12			
	Mb1-2	18.07	5.66	21.79		1.65	
	Mb1-3	18.49	5.49	22.09	1.96	1.64	59.37
M75-C20-L5-S2	Mb2-1	18.61	5.57	21.81			
	Mb2-2	18.48	5.62	21.64		2.43	
	Mb2-3	18.36	5.95	21.76	.85	2.55	90.85
M70-C25-L5-S2	Mb3-1	18.28	5.18	21.09			
	Mb3-2	18.11	5.05	20.92	0.60	2.21	99.39
	Mb3-3	18.89	5.29	21.77	.55	2.33	100.03
c. Change the Compact States 1 with half Pressure							
M80-C15-L5-S2-O1	Mc1-1	18.34	5.41	21.85			
	Mc1-2	18.47	5.64	22.20		1.68	
	Mc1-3	18.62	5.56	22.31	2.08	1.61	57.55
M75-C20-L5-S2-O1	Mc2-1	18.53	5.22	21.62			
	Mc2-2	18.47	5.41	21.69		2.10	
	Mc2-3	18.40	5.26	21.47	.90	2.17	87.45

Continued from “Sample Preparation for Microwave Steel-making (Phase 2)-1”

Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
M70-C25-L5-S2-O1	Mc3-1	18.55	5.15	21.38			
	Mc3-2	18.31	4.73	21.96		2.10	
	Mc3-3	18.24	5.17	21.06	.55	2.27	99.72
d. Change the Compact States 2 without Press							
M80-C15-L5-S0-O0	Md1-1	18.23	6.69	22.12			
	Md1-2	18.26	5.97	22.20		1.44	
	Md1-3	24.66	5.72	28.71	2.92	1.13	39.26
M75-C20-L5-S0-O0	Md2-1	24.41	5.44	27.6			
	Md2-2	23.83	5.58	26.63		1.75	
	Md2-3	23.59	5.41	26.56	.93	2.04	79.93
M70-C25-L5-S0-O0	Md3-1	23.60	5.76	26.36			
	Md3-2	24.63	5.30	26.74		1.28	
	Md3-3	23.01	5.67	25.57	.82	1.74	69.70
e. Change the Heating Power							
M75-C20-L5-S2-P1.0	Me1-1	18.05	5.11	20.97			
	Me1-2	18.17	5.20	21.2			
	Me1-3						LOOSE
M75-C20-L5-S2-P1.3	Me2-1	18.77	5.50	21.92			
	Me2-2	18.67	5.60	21.87		2.44	
	Me2-3	18.14	5.66	21.37	.77	2.46	92.13
M75-C20-L5-S2-P1.9	Me3-1	18.54	5.72	21.74			
	Me3-2	18.16	5.74	21.38		2.53	
	Me3-3	18.83	5.39	21.86	.66	2.37	93.21
f. Change the Heating Time							
M75-C20-L5-S2-T3	Mf1-1	18.57	5.77	21.85			
	Mf1-2	18.07	5.76	21.40		2.54	
	Mf1-3	18.77	6.05	22.23	.84	2.62	91.8
M75-C20-L5-S2-T5	Mf2-1	18.54	5.72	21.81			
	Mf2-2	18.74	5.96	22.14		2.57	
	Mf2-3	18.72	5.77	22.02	.79	2.51	92.21

Continued from “Sample Preparation for Microwave Steel-making (Phase 2)-1”

Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
M75-C20-L5-S2-T9	Mf3-1	18.22	5.63	21.44			
	Mf3-2	18.80	5.55	22.00		2.40	
	Mf3-3	18.86	5.70	22.13	.78	2.49	92.60
g. Change the Lime Ratio							
M73-C20-L7-S2	Mg1-1	18.48	5.59	21.70			
	Mg1-2	18.21	5.55	21.36		2.36	
	Mg1-3	18.58	5.51	21.73	.83	2.32	91.7
M70-C20-L10-S2	Mg2-1	17.89	5.21	20.83			
	Mg2-2	18.53	5.26	21.51		2.14	
	Mg2-3	17.85	5.15	20.78	.85	2.08	91.73
M65-C20-L15-S2	Mg3-1	18.51	5.05	21.37			
	Mg3-2	18.44	5.41	21.49		2.12	
	Mg3-3	18.02	5.19	20.95	.89	2.04	96.14
h. Change the Reducing Agent: Replace Coal with Coal-S (High S)							
M80-Cs15-L5-S2	Mh1-1	18.24	6.24	22.63			
	Mh1-2	18.42	5.94	22.55		1.08	
	Mh1-3	18.56	5.93	22.66	3.00	1.10	36.86
M75-Cs20-L5-S2	Mh2-1	18.26	5.37	21.63			
	Mh2-2	18.14	5.54	21.66		1.64	
	Mh2-3	18.51	5.6	22.05	1.81	1.73	65.49
M70-Cs25-L5-S2	Mh3-1	18.72	4.94	21.51			
	Mh3-2	18.42	5.06	21.28		2.11	
	Mh3-3	18.41	5.38	21.45	.84	2.20	92.87
i. Change the Reducing Agent: Replace Coal with Graphite							
M81-G14-L5-S2	Mi0-1	18.44	5.00	21.41	0.52	2.43	95.4
	Mi0-2	18.33	5.00	21.28	0.52	2.43	95.4
	Mi0-3	18.19	5.61	21.48	0.71	2.58	90.3
M80-G15-L5-S2	Mi1-1	17.61	5.25	20.69			
	Mi1-2	18.30	5.35	21.43		2.50	
	Mi1-3	18.77	5.19	21.81	.56	2.48	94.96

Continued from “Sample Preparation for Microwave Steel-making (Phase 2)-1”

Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
M75-G20-L5-S2	Mi2-1	18.61	4.92	21.49			
	Mi2-2	18.78	4.76	21.55			
	Mi2-3	18.49	4.68	21.18			LOOSE
M70-G25-L5-S2	Mi3-1	18.71	4.44	21.08			
	Mi3-2	18.74	4.54	21.45			
	Mi3-3	18.31	4.49	20.86			LOOSE
j. Replace Starch with Molasses							
M80-C15-L5-m4	Mj1-1	18.57	6.22	22.48			
	Mj1-2	18.82	5.54	22.31		1.87	
	Mj1-3	17.80	6.01	21.59	1.72	2.07	68.45
M75-C20-L5-m4	Mj2-1	18.38	5.66	21.60			
	Mj2-2	18.29	5.55	21.47		2.46	
	Mj2-3	18.48	5.74	21.73	.75	2.5	92.32
M70-C25-L5-m4	Mj3-1	18.29	5.42	21.17			
	Mj3-2	18.36	5.29	21.36		1.58	
	Mj3-3	18.60	5.37	21.43	.62	2.21	93.47
k. Change the Ratio of Binders 1: Starch							
M80-C15-L5-S5	Mk1-1	19.15	5.63	22.76			
	Mk1-2	18.09	5.39	21.57		1.38	
	Mk1-3	18.12	5.64	21.75	2.06	1.57	55.32
M70-C25-L5-S5	Mk3-1	18.47	5.16	20.91			
	Mk3-2	18.34	5.17	21.01		2.22	
	Mk3-3	18.29	4.84	21.27	.96	2.02	94.79
l. Change the Compact States 1 of Binder 1: Starch							
M80-C15-L5-S5-O1	Ml1-1	18.53	5.24	21.76			
	Ml1-2	18.97	5.63	22.48		1.76	
	Ml1-3	18.88	5.44	22.27	1.67	1.72	62.83
M70-C25-L5-S5-O1	Ml3-1	18.3	4.91	20.8			
	Ml3-2	18.44	4.99	21.04		2.11	
	Ml3-3	18.63	5.04	21.19	.40	2.16	97.34

Continued from "Sample Preparation for Microwave Steel-making (Phase 2)-1"							
Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
b. Change the Ratio of Iron Ore and Coal, Using Starch as Binder							
M80-C15-L5-S2	Mb1-1	18.37	5.71	22.12			
	Mb1-2	18.07	5.66	21.79		1.65	
	Mb1-3	18.49	5.49	22.09	1.96	1.64	59.37
M75-C20-L5-S2	Mb2-1	18.61	5.57	21.81			
	Mb2-2	18.48	5.62	21.64		2.43	
	Mb2-3	18.36	5.95	21.76	.85	2.55	90.85
M72-C23-L5-S2	Mb4-1	17.98	5.15	20.90			
	Mb4-2	18.72	4.99	21.53		2.19	
	Mb4-3	18.16	5.25	21.12		2.29	96.31
M71-C24-L5-S2	Mb5-1	18.78	5.29	21.66			
	Mb5-2	18.55	5.30	21.33		2.32	
	Mb5-3	18.27	5.27	21.16		2.26	96.03
M70-C25-L5-S2	Mb3-1	18.28	5.18	21.09			
	Mb3-2	18.11	5.05	20.92	0.60	2.21	99.39
	Mb3-3	18.89	5.29	21.77	.55	2.33	100.03
M69-C26-L5-S2	Mb6-1	18.69	5.28	21.54			
	Mb6-2	18.62	5.32	21.61		1.83	79.26
	Mb6-3	18.70	5.29	21.64		1.82	79.27
M68-C27-L5-S2	Mb7-1	18.44	4.93	21.14		1.66	78.73
	Mb7-2						
	Mb7-3						
M65-C30-L5-S2	Mb8-1	18.43	4.91	21.19		0.95	47.32
	Mb8-2						
	Mb8-3						
M62-C33-L5-S2	Mb9-1	18.00	4.73	20.51			loose
	Mb9-2						
	Mb9-3						

h. Change the Reducing Agent: Replace Coal with Coal-S (High S)							
M80-Cs15-L5-S2	Mh1-1	18.24	6.24	22.63			
	Mh1-2	18.42	5.94	22.55			
	Mh1-3	18.56	5.93	22.66	3.00	1.10	36.86
M75-Cs20-L5-S2	Mh2-1	18.26	5.37	21.63			
	Mh2-2	18.14	5.54	21.66			
	Mh2-3	18.51	5.6	22.05	1.81	1.73	65.49
M70-Cs25-L5-S2	Mh3-1	18.72	4.94	21.51			
	Mh3-2	18.42	5.06	21.28			
	Mh3-3	18.41	5.38	21.45	.84	2.20	92.87
M68-Cs27-L5-S2	Mh4-1	18.45	5.23	21.10			
	Mh4-2	18.42	5.19	21.13		2.21	
	Mh4-3	18.47	5.22	21.17		2.20	98.54
M65-Cs30-L5-S2	Mh5-1	18.46	5.06	21.08			
	Mh5-2	18.51	4.84	20.93		1.91	
	Mh5-3	18.59	4.92	21.11		1.93	95.95
M62-Cs33-L5-S2	Mh6-1	18.10	4.91	20.68			
	Mh6-2	18.91	5.00	21.37			
	Mh6-3	18.34	4.71	20.78		1.50	81.66
i. Change the Reducing Agent: Replace Coal with Graphite							
M81-G14-L5-S2	Mi0-1	18.44	5.00	21.41	0.52	2.43	95.4
	Mi0-2	18.33	5.00	21.28	0.52	2.43	95.4
	Mi0-3	18.19	5.61	21.48	0.71	2.58	90.3
M80-G15-L5-S2	Mi1-1	17.61	5.25	20.69			
	Mi1-2	18.30	5.35	21.43			
	Mi1-3	18.77	5.19	21.81	.56	2.48	94.96
M79-G16-L5-S2	Mi4-1	18.25	5.11	21.24			loose
	Mi4-2	18.52	5.00	21.46			loose
	Mi4-3						
M78-G17-L5-S2	Mi5-1	18.02	4.90	20.89			loose
	Mi5-2	18.98	5.01	21.86			loose

	Mi5-3	18.67	5.01	21.61		1.66	loose
M77-G18-L5-S2	Mi6-1	18.54	4.94	21.40			loose
	Mi6-2	18.08	4.62	20.76			loose
	Mi6-3						
M76-G19-L5-S2	Mi7-1	18.77	4.81	21.56			loose
	Mi7-2	18.16	4.87	20.90			loose
	Mi7-3						

Design for Experiment of Direct Microwave Steel-making (Phase 2)-H

Iron ore type: Hematite July 2002

Sample No.	Iron ore %	Coal (%)	Lime (%)	Binder ratio		Compact State	Time (min)	KW & C^0
				Type	%			
a. Change the Ratio of Iron Ore and Coal, Using Bentonite as Binder								
H-C20-L5-B2	75	20	5	Bent-onite	2	Tight (3000 psi)	7	1.6
H-C23-L5-B2	72	23						
H-C24.5-L5-B2	70.5	24.5						
b. Change the Ratio of Iron Ore and Coal, Using Molasses as Binder								
H-C20-L5-m4	75	20	5	Mola-sses	2	Tight (3000 psi)	7	1.6
H-C23-L5-m4	72	23						
H-C24.5-L5-m4	70.5	24.5						
c. Change the Ratio of Iron Ore and Coal, Using Starch as Binder								
H-C20-L5-S2	75	20	5	Starch	2	Tight (3000 psi)	7	1.6
H-C23-L5-S2	72	23						
H-C24-L5-S2	71	24						
H-C24.5-L5-S2	70.5	24.5						
H-C25-L5-S2	70	25						
H-C27-L5-S2	68	27						
d. Change the Compact States 1 with half pressure								
H-C20-L5-S2-O1	75	20	5	Starch	2	Loose 1 (1500 psi)	7	1.6
H-C23-L5-S2-O1	72	23						
H-C24.5-L5-S2-O1	70.5	24.5						
e. Change the Heating Power (Temperature)								
H-C24.5-L5-S2-P1.0	70.5	24.5	5	Starch	2	Tight (3000 psi)	7	1.0
H-C24.5-L5-S2-P1.3								1.3
H-C24.5-L5-S2-P1.9								1.9

Continued from “Design for Experiment of Direct Microwave Steel-making (Phase 2)-1”								
Sample No.	Iron ore %	Coal (%)	Lime (%)	Binder ratio		Compact State	Time (min)	KW & C^0
f. Change the Heating Time								
H-C24.5-L5-S2-T3	70.5	24.5	5	Starch	2	Tight (3000 psi)	3	1.6
H-C24.5-L5-S2-T5							5	
H-C24.5-L5-S2-T9							9	
g. Change the Lime Ratio								
H-C25.1-L7-S2	71.9	25.1	3	Starch	2	Tight (3000 psi)	7	1.6
H-C23.3-L10-S2	66.7	23.3	10					
H-C22.0-L15-S2	63.0	22.0	15					
h. Change the Reducing Agent: Replace Coal with High Sulfur Coal-Cs (Eastern Coal)								
H-Cs20-L5-S2	75	20	5	Starch	2	Tight (3000 psi)	7	1.6
H-Cs25-L5-S2	70	25						
H-Cs27-L5-S2	68	27						
H-Cs30-L5-S2	65	30						
i. Change the Reducing Agent: Replace Coal with Graphite								
H-G12-L5-S2	83	12	5	Starch	2	Tight (3000 psi)	7	1.6
H-G13-L5-S2	82	13						
H-G14-L5-S2	81	14						
H-G15-L5-S2	80	15						
H-G16-L5-S2	79	16						

Sample Preparation for Microwave Steel-making (Phase 2)-1

Hematite June 2002

Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
a. Change the Ratio of Iron Ore and Coal, Using Bentonite as Binder							
H75-C20-L5-B2	Ha1-1	18.37	5.21	21.36		2.09	
	Ha1-2	18.17	5.01	20.99		1.92	
	Ha1-3	18.64	5.28	21.62	0.85	2.13	88.5
H72-C23-L5-B2	Ha2-1	18.33	5.13	21.15			
	Ha2-2	18.56	4.98	21.30		1.89	
	Ha2-3	18.41	5.15	21.22	0.95	1.86	82.5
H70.5-C24.5-L5-B2	Ha3-1	18.60	4.93	21.27			
	Ha3-2	17.94	4.79	20.51		1.81	
	Ha3-3	18.00	5.16	20.75	0.70	2.05	92.7
b. Change the Ratio of Iron Ore and Coal, Using Molasses as Binder							
H75-C20-L5-m4	Hb1-1	18.50	5.27	21.45			
	Hb1-2	17.96	5.26	20.88		2.17	
	Hb1-3	18.77	5.22	21.59	0.96	2.22	91.5
H72-C23-L5-m4	Hb2-1	18.41	4.78	20.89			
	Hb2-2	18.68	4.87	21.26		2.06	
	Hb2-3	18.27	5.16	20.99	0.52	2.20	95.5
H70.5-C24.5-L5-m4	Hb3-1	18.73	5.21	21.43			
	Hb3-2	18.50	4.91	21.02		2.07	
	Hb3-3	18.47	5.12	21.05	0.42	2.16	96.5
c. Change the Ratio of Iron Ore and Coal, Using Starch as Binder							
H75-C20-L5-S2	Hc1-1	18.44	5.61	21.62			
	Hc1-2	18.44	5.71	21.67		2.41	
	Hc1-3	18.43	5.32	21.45	0.77	2.25	92.77
H72-C23-L5-S2	Hc2-1	18.00	5.51	20.98			
	Hc2-2	18.38	5.40	21.34		2.33	
	Hc2-3	18.30	5.51	21.37	0.70	2.37	98.28

Continued from “Sample Preparation for Microwave Steel-making (Phase 2)-1”

Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
H71-C24-L5-S2	Hc3-1	18.62	5.62	21.68			
	Hc3-2	18.31	5.58	21.36		2.40	
	Hc3-3	18.04	5.77	21.17	0.64	2.49	99.99
H70.5-C24.5-L5-S2	Hc4-1	17.81	4.77	20.19			
	Hc4-2	18.85	5.10	21.29		2.10	
	Hc4-3	18.25	5.06	20.79	0.65	1.89	87.2
H70-C25-L5-S2	Hc5-1	18.30	5.34	21.25			
	Hc5-2	18.57	5.35	21.45		2.31	
	Hc5-3	18.69	5.58	21.75	0.66	2.40	101.08
H69-C26-L5-S2	Hc6-1	18.59	5.35	21.50			
	Hc6-2	17.97	5.48	20.99		2.33	
	Hc6-3	18.78	5.42	21.77	0.94	2.05	91.50
H68-C27-L5-S2	Hc7-1	18.25	4.74	20.72			
	Hc7-2	18.71	4.80	21.25		2.00	
	Hc7-3	18.48	4.97	21.06	0.54	2.04	99.3
d. Change the Compact States 1 with half Pressure							
H75-C20-L5-S2-O1	Hd1-1	18.19	4.86	20.85			
	Hd1-2	17.59	4.78	20.24		1.99	
	Hd1-3	18.88	4.98	21.59	0.63	2.08	91.6
H72-C23-L5-S2-O1	Hd2-1	18.46	4.49	20.85			
	Hd2-2	18.19	4.73	20.72		1.95	
	Hd2-3	18.38	4.73	20.93	0.61	1.94	93.7
H70.5-C24.5-L5-S2-O1	Hd3-1	18.74	4.41	20.73			
	Hd3-2	18.82	4.65			1.42	
	Hd3-3	18.59	4.60	20.76	0.44	1.73	87.8
e. Change the Heating Power							
H70.5-C24.5-L5-S2-P1.0	He1-1	18.22	4.90	20.87			
	He1-2	18.33	5.04	21.10		2.00	
	He1-3	18.65	5.04	21.41	0.74	2.02	93.5

Continued from "Sample Preparation for Microwave Steel-making (Phase 2)-1"							
Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
H70.5-C24.5-L5-S2-P1.3	He2-1	18.19	4.91	20.86			
	He2-2	18.97	5.17	21.75		2.12	
	He2-3	18.97	5.06	21.66	0.68	2.01	92.7
H70.5-C24.5-L5-S2-P1.9	He3-1	18.29	4.88	20.61			
	He3-2	18.47	4.95	20.90		1.91	
	He3-3	17.67	5.03	20.13	0.46	2.00	92.8
f. Change the Heating Time							
H70.5-C24.5-L5-S2-T3	Hf1-1	18.12	4.96	20.51			
	Hf1-2	18.74	5.03	21.23		2.03	
	Hf1-3	18.44	5.01	20.98	0.63	1.91	89.0
H70.5-C24.5-L5-S2-T5	Hf2-1	18.39	4.93	20.90			
	Hf2-2	18.20	5.10	20.85		2.08	
	Hf2-3	18.21	5.10	20.66	0.37	2.08	95.2
H70.5-C24.5-L5-S2-T9	Hf3-1	17.69	4.97	20.30			
	Hf3-2	17.82	5.05	20.36		2.04	
	Hf3-3	18.62	5.05	21.22	0.49	2.11	97.5
g. Change the Lime Ratio							
H71.9-C25.1-L3-S2	Hg1-1	17.82	4.89	20.41			
	Hg1-2	17.94	4.91	20.53		2.07	
	Hg1-3	18.15	4.87	20.67	0.44	2.08	97.7
H66.7-C23.3-L10-S2	Hg2-1	18.61	4.60	21.02			
	Hg2-2	18.15	4.38	20.46		1.78	
	Hg2-3	19.08	4.66	21.39	0.38	1.93	102.2
H63-C22-L15-S2	Hg3-1	18.32	4.41	20.64			
	Hg3-2	18.54	4.59	20.96		1.79	
	Hg3-3	18.15	4.72	20.65	0.68	1.82	100.7
h. Change the Reducing Agent: Replace Coal with Coal-S (High S)							
H75-Cs20-L5-S2	Hh1-1	18.55	4.90	21.37			
	Hh1-2	18.57	5.04	21.54		1.69	
	Hh1-3	18.66	4.90	21.50	1.21	1.63	73.0

Continued from “Sample Preparation for Microwave Steel-making (Phase 2)-1”							
Sample	**No.**	**Before Heating (g)**		**After Heating (g)**			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
H70-Cs25-L5-S2	Hh2-1	18.65	4.74	21.10			
	Hh2-2	18.51	4.63	20.96		1.93	
	Hh2-3	18.32	5.07	21.01	0.57	2.12	98.3
H68-Cs27-L5-S2	Hh3-1	18.50	4.77	20.97			
	Hh3-2	18.58	4.79	21.08		1.96	
	Hh3-3	18.56	4.89	21.09	0.51	2.02	99.9
H65-Cs30-L5-S2	Hh4-1	18.54	4.25	20.50			
	Hh4-2	18.08	4.58	20.27		1.85	
	Hh4-3	18.50	4.51	20.59	0.24	1.85	103.8
i. Change the Reducing Agent: Replace Coal with Graphite							
H83-G12-L5-S2	Hi1-1	18.67	5.10	21.58			
	Hi1-2	18.57	5.05	21.44		2.16	
	Hi1-3	18.33	5.05	21.21	0.77	2.11	82.8
H82-G13-L5-S2	Hi2-1	18.40	5.00	21.32			
	Hi2-2	18.30	5.05	21.67			
	Hi2-3	19.02	5.04	21.94	0.64	2.28	90.76
H81-G14-L5-S2	Hi3-1	18.28	5.05	21.21			
	Hi3-2	18.02	5.04	20.92			
	Hi3-3	18.70	5.04	21.62	0.64	2.28	91.88
	Hi3-4	17.79	5.04	20.70	0.76	2.15	86.64
H80-G15-L5-S2	Hi1-1	18.27	5.00	21.12			
	Hi1-2	17.87	4.92	20.69	0.67	2.15	89.87
	Hi1-3	17.87	4.92	20.65	0.54	2.25	94.05
H79-G16-L5-S2	Hi2-1						
	Hi2-2						
	Hi2-3						
j. Using Dried Warehouse Coal as Reducing Agent.							
-Cw24.5-L5-S2	Hj3-1	17.98	5.03	21.15			
	Hj3-2	18.67	5.03	21.88			
	Hj3-3	18.50	5.00	21.65	2.19	0.96	44.8

Design for Experiment of Direct Microwave Steel-making (Phase 2)-H

Iron ore Hematite July 2002

Sample No.	Iron ore %	Coal (%)	Lime (%)	Binder ratio		Compact State	Time (min)	KW & C^0
				Type	%			
k. Change the Reducing Agent: Western Coal + Graphite								
H-C22G1-L5-S2	72	22+1	5	Starch	2	Tight (3000 psi)	7	1.6
H-C19G3-L5-S2	73	19+3						
H-C16G5-L5-S2	74	16+5						
H-C10G9-L5-S2	76	10+9						
H-C8G10-L5-S2	77	8+10						
H-C6.5G11-L5-S2	77.5	6.5+11						
H-C5G12-L5-S2	78	5+12						
H-C3.5G13-L5-S2	78.5	3.5+13						
l. Mix a certain amount of Polyvinyl Alcohol (99-100% hydrolyzed) in Hc4 + Graphite								
H-C24.5-L5-S2-h8	70.5	24.5	5	Starch	2	Tight (3000 psi)	7	H8
H-C24.5-L5-S2-h4		24.5						H4
H-C20G3-L5-S2-h4		20+3						
H-C20G2-L5-S2-h4		20+2						
H-C20G1-L5-S2-h4		20+1						
m. Reducing Agent: Western Coal; Binder: Wheat Flour + Yeast; Pellet: No pressure								
H75-C20-L5-W5	75	20	5	Flour + Yeast	5	Loose	7	1.6
H75-C20-L5-W10					10			
H75-C20-L5-W15					15			
H75-C20-L5-W20					20			
n. Reducing Agent: Carbon from Fly-ash								
H-C20-L5-S2	75	20	5	Starch	2	Tight (3000 psi)	7	1.6
H-C23-L5-S2	72	23						
H-C25-L5-S2	70	25						
H-C27-L5-S2	68	27						
nr. Reducing Agent: Carbon from Fly-ash + Rice								
H-C19-L5-R4.75	71.5	19			4.75			

H-C18-L5-R9.5	67.5	18	5	Rice	9.5	Tight (3000 psi)	7	1.6
H-C17-L5-R14.5	63.75	17			14.25			
H-C16-L5-R19	60	16			19			
br. Add 10% Rice in Mb1 and Mc1								
M80-C15-L5-S2 +10% Rice	80	15	5	Rice 10%	Bentonite 2%	Tight (3000 psi)	7	1.6
M80-C15-L5-S2 +10% Rice	67.5	18			Starch 2%			

Sample Preparation for Microwave Steel-making (Phase 2)-1

Hematite June 2002

Sample	No.	Before Heating (g)		After Heating (g)			
		Crucible	Sample	Total wt	Slag	Steel	Yield %
k. Change the Reducing Agent: Western Coal + Graphite							
H72-C22G1-L5-S2	Hk1-1	18.66	4.77	21.10	0.44	1.996	95.6
	Hk1-2	17.88	4.30	20.16	0.44	1.837	97.6
H73-C19G3-L5-S2	Hk2-1	18.53	4.67	20.92	0.36	2.034	98.2
	Hk2-2	18.44	4.54	20.75	0.36	1.948	96.7
H74-C16G5-L5-S2	Hk3-1	17.95	4.49	20.29	0.38	1.963	97.2
	Hk3-2	18.08	4.44	20.38	0.39	1.913	95.8
H76-C10G9-L5-S2	Hk4-1	18.13	4.57	20.59	0.52	1.941	91.9
	Hk4-2	18.98	4.44	21.41	0.68	1.752	85.4
H77-C8G10-L5-S2	Hk5-1	18.16	4.31	20.47	0.29	2.015	99.9
	Hk5-2	18.24	4.24	20.49	0.30	1.947	96.5
H77.5-C6.5G11-L5-S2	Hk6-1	18.39	4.38	20.72	0.37	1.961	95.0
	Hk6-2	18.53	4.5	20.94	0.30	2.108	99.4
H78-C5G12-L5-S2	Hk7-1	18.77	4.61	21.27	0.36	2.136	97.7
	Hk7-2	18.82	4.54	21.29	0.32	2.147	99.7
H78.5-C3.5G13-L5-S2	Hk8-1	18.71	4.70	21.28	0.42	2.148	95.8
	Hk8-2	18.78	4.58	21.33	0.78	1.771	81.0
H77-C6G7.5-L5-S2	Hk9-1	18.74	5.15	21.68	0.66	2.285	90.6
	Hk9-2	18.63	4.57	21.25	0.67	1.949	87.1
H77-C4G5-L5-S2	Hk10-1	18.86	4.73	21.98	1.86	1.260	51.9
	Hk10-2	18.34	5.13	21.71	1.91	1.459	55.4
H77-C8G10-L5-S2 6 min	Hk51-1	18.36	4.26	20.68	0.42	1.899	95.2
	Hk51-2	18.00	4.28	20.29	0.35	1.941	96.9
H77-C8G10-L5-S2 5 min	Hk52-1	18.48	4.43	20.87	0.40	1.997	96.3
	Hk52-2	18.45	4.43	20.82	0.33	2.038	98.3
H77-C8G10-L5-S2 4 min	Hk53-1	18.42	4.58	20.93	0.59	1.922	89.7
	Hk53-2	18.12	4.46	20.59	0.64	1.830	87.7
l. Mix a certain amount of Polyvinyl Alcohol (99-100% hydrolyzed) in Hc4							
	Hl1-1	19.34	4.00	20.20	0.45	1.412	88.8

H-C24.5-L5-S2-h8	Hl1-2	18.76	4.16	20.63	0.61	1.261	74.9
H-C24.5-L5-S2-h4	Hl2-1	18.72	4.30	20.74	0.19	1.831	103.3
	Hl2-2	18.19	4.16	20.24	0.32	1.727	100.7
H-C20G3-L5-S2-h4	Hl3-1	18.28	4.07	20.31	0.42	1.609	94.5
	Hl3-2	17.91	4.22	19.91	0.26	1.742	98.7
H-C20G2-L5-S2-h4	Hl4-1	18.36	3.94	20.23	0.46	1.414	85.0
	Hl4-2	18.59	4.10	20.62	0.36	1.672	95.9
H-C20G1-L5-S2-h4	Hl5-1	18.48	4.12	20.62	0.49	1.651	94.0
	Hl5-2	18.25	3.90	20.26	0.46	1.550	93.2
gc. Change the Lime Ratio (coated crucible)							
H71.9-C25.1-L3-S2	Hgc1-1	18.47	4.75	20.78	0.33	1.979	94.9
	Hgc1-2	18.51	4.54	20.60	0.20	1.885	95.0
H70.5-C24.5-L5-S2	Hcc4-1	18.73	4.40	20.84	0.26	1.85	98.1
	Hcc4-2	18.57	4.63	20.75	0.28	1.90	95.8
H66.7-C23.3-L10-S2	Hgc2-1	18.54	4.28	20.57	0.29	1.742	100.4
	Hgc2-2	18.61	4.33	20.66	0.38	1.669	95.1
H63-C22-L15-S2	Hgc3-1	18.61	4.19	20.61	0.44	1.561	97.3
	Hgc3-2	18.89	4.34	21.17	0.60	1.683	101.3
m. Reducing Agent: Western Coal; Binder: Wheat Flour + Yeast; Pellet: No pressure							
H75-C20-L5-W5	Hm1-1	17.97	3.98	20.09	0.50	1.620	91.9
	Hm1-2	18.90	4.11	21.09	0.56	1.633	89.7
H75-C20-L5-W10	Hm2-1	18.21	4.01	20.25	0.44	1.600	94.4
	Hm2-2	18.60	3.90	20.57	0.42	1.548	93.9
H75-C20-L5-W15	Hm3-1	18.32	3.85	20.198	0.38	1.492	95.8
	Hm3-2	18.05	3.68	19.81	0.35	1.415	95.1
H75-C20-L5-W20	Hm4-1	18.69	3.63	20.36	0.38	1.289	91.6
	Hm4-2	18.56	3.72	20.30	0.32	1.416	98.2
	Hm4-3	18.19	5.33	20.63	0.39	2.049	99.2
	Hm4-4	18.41	6.00	21.03	0.36	2.263	97.3
	Hm4-5	18.63	5.86				
	Hm4-6	18.28	6.66-				
	Hm4-7	8.45	4.97	20.84	0.53	1.862	96.7
H75-C20G1-L5-W5	Hm5-1	18.49	6.18	21.72	0.64	2.595	95.7

WHOLE	Hm5-2	18.46	5.51	21.30	0.42	2.419	100.0
n. Using carbon from fly-ash as reducing agent							
H75-C20-L5-S2	Hn1-1	18.09	4.64	20.50	0.70	1.716	81.1
	Hn1-2	19.19	4.56	21.60	0.67	1.737	83.6
H72-C23-L5-S2	Hn2-1	18.33	4.27	20.28	0.66	1.161	62.1
	Hn2-2	18.84	4.33	21.05	0.67	1.538	81.2
H70-C25-L5-S2	Hn3-1	18.56	4.33	20.77	0.53	1.683	91.3
	Hn3-2	18.14	4.18	20.23	0.49	1.600	90.0
nr. Reducing agent: Fly-ash Carbon + Rice							
H71.25 -C19-L5-R4.75	Hnr1-1	18.20	4.015	20.08	0.51	1.370	77.2
	Hnr1-2	18.32	4.055	20.26	0.64	1.296	72.3
H67.5-C18-L5-R9.5	Hnr2-1	18.24	3.74	20.08	0.48	1.360	86.9
	Hnr2-2	18.72	3.98	20.77	0.43	1.614	96.9
	Hnr2-3	18.58	4.08	20.50	0.44	1.485	87.0
H71.25 -C19-L5-R4.75-S2	Hnr1-1s	18.72	4.21	20.92	0.52	1.677	92.0
	Hnr1-2s	18.37	4.39	20.69	0.47	1.849	97.3
H67.5-C18-L5-R9.5-S2	Hnr2-1s	18.38	3.97	20.42	0.46	1.579	96.9
	Hnr2-2s	18.25	4.04	20.31	0.41	1.647	99.4
br. Add 10% Rice in Mb1 and Mc1 under the pellets							
M80-C15-L5-S2 +10% Rice	Mbr1-4	18.43+0.5	4.47			1.71	77.5
	Mbr1-5	18.52+0.5	4.40			1.599	73.7
M80-C15-L5-S2 +10% Rice	Mcr1-4	18.35+0.5	4.36	21.13		1.543	71.7
	Mcr1-5						

Steel carbon and sulfur analysis results

Sample ID	**C%**	**S%**
Ha1-3	0.0763	0.522
Ha2-3	0.412	0.559
Ha3-3	2.21	0.575
Hb1-3	0.577	0.484
Hb2-3	2.29	0.419
Hb3-3	2.22	0.405
Hc1-3	0.0632	0.457
Hc2-3	1.95	0.413
Hc3-3	2.31	0.467
Hc4-3	2.91	0.313
Hc5-3	2.87	0.417
Hc6-3	2.77	0.328
Hc7-3	2.52	0.43
Hd1-3	0.385	0.501
Hd2-3	2.44	0.498
Hd3-3	2.86	0.089

Steel carbon and sulfur analysis results

Sample ID	**C%**	**S%**
He1-3	2	0.499
He2-3	2.29	0.477
He3-3	1.86	0.46
Hf1-3	2.54	0.455
Hf2-3	1.83	0.494
Hf3-3	1.75	0.45
Hg1-3	2.05	0.505
Hg2-3	3.01	0.263
Hg3-3	3.66	0.161
Hh1-3	0.026	1.14
Hh2-3	0.804	1.45
Hh3-3	0.82	1.57
Hh4-3	0.872	1.24
Hi1-3	0.0335	0.037
Hi2-3	0.739	0.027
Hi3-3	1.03	0.029
Hi4-3	2.28	0.029

Steel sample chemical analysis results

Sample	**Ha1-3**	**Ha2-3**	**Ha3-3**	**Hb1-3**	**Hb2-3**	**Hb3-3**	**Hc1-3**	**Hc2-3**	**Hc3-3**	**Hc4-3**	**Hc5-3**	**Hc6-3**	**Hc7-3**
Cr	0.075%	0.054%	0.065%	0.060%	0.060%	0.059%	0.061%	0.064%	0.058%	0.061%	0.068%	0.062%	0.063%
P	0.105%	0.130%	0.131%	0.131%	0.134%	0.141%	0.098%	0.117%	0.125%	0.140%	0.127%	0.133%	0.129%
Zn	0.015%	0.008%	0.009%	0.009%	0.009%	0.010%	0.009%	0.009%	0.010%	0.010%	0.011%	0.011%	0.011%
Si	0.478%	0.164%	0.432%	0.282%	0.198%	0.191%	0.118%	0.393%	0.182%	0.338%	0.197%	0.316%	0.347%
Mn	0.038%	0.014%	0.053%	0.042%	0.098%	0.124%	0.020%	0.083%	0.111%	0.221%	0.127%	0.132%	0.103%
Fe	98.62%	98.57%	96.44%	98.33%	96.71%	96.74%	99.10%	96.90%	96.65%	95.91%	96.09%	96.14%	96.31%
Mg	0.001%	0.003%	0.002%	0.002%	0.002%	0.002%	0.002%	0.001%	0.002%	0.004%	0.002%	0.002%	0.002%
V	0.011%	0.013%	0.015%	0.017%	0.018%	0.018%	0.017%	0.022%	0.016%	0.024%	0.020%	0.016%	0.007%
Al	0.031%	0.047%	0.040%	0.043%	0.033%	0.044%	0.032%	0.033%	0.033%	0.047%	0.055%	0.056%	0.051%

Steel sample chemical analysis results

Sample #	**Hd1-3**	**Hd2-3**	**Hd3-3**	**He1-3**	**He2-3**	**He3-3**	**Hf1-3**	**Hf2-3**	**Hf3-3**	**Hg1-3**	**Hg2-3**	**Hg3-3**
Cr	0.074%	0.070%	0.064%	0.077%	0.074%	0.077%	0.071%	0.063%	0.072%	0.075%	0.089%	0.082%
P	0.134%	0.125%	0.143%	0.128%	0.132%	0.156%	0.116%	0.140%	0.127%	0.144%	0.178%	0.193%
Zn	0.012%	0.011%	0.013%	0.011%	0.012%	0.011%	0.011%	0.012%	0.012%	0.011%	0.011%	0.012%
Si	0.339%	0.349%	0.275%	0.178%	0.374%	0.200%	0.252%	0.382%	0.229%	0.106%	0.174%	0.477%
Mn	0.038%	0.072%	0.280%	0.028%	0.067%	0.089%	0.123%	0.080%	0.098%	0.097%	0.168%	0.136%
Fe	98.412%	96.335%	96.144%	96.754%	96.124%	96.942%	96.312%	96.903%	97.001%	96.901%	96.000%	95.002%
Mg	0.002%	0.002%	0.010%	0.002%	0.002%	0.002%	0.005%	0.002%	0.002%	0.002%	0.003%	0.002%
V	0.018%	0.019%	0.021%	0.016%	0.013%	0.016%	0.009%	0.013%	0.000%	0.002%	0.001%	0.013%
Al	0.058%	0.052%	0.064%	0.055%	0.073%	0.069%	0.063%	0.057%	0.058%	0.050%	0.060%	0.056%
Sample #	**Hh1-3**	**Hh2-3**	**Hh3-3**	**Hh4-3**	**Hi1-3**	**Hi2-3**	**Hi3-3**	**Hi4-3**				
Cr	0.062%	0.071%	0.084%	0.080%	0.070%	0.08%	0.09%	0.081%				
P	0.138%	0.144%	0.164%	0.146%	0.119%	0.15%	0.15%	0.143%				
Zn	0.011%	0.012%	0.012%	0.012%	0.012%	0.01%	0.01%	0.011%				
Si	0.080%	0.301%	0.228%	0.158%	0.122%	0.20%	0.20%	0.311%				
Mn	0.009%	0.095%	0.110%	0.149%	0.019%	0.11%	0.07%	0.097%				
Fe	98.413%	97.001%	96.903%	97.242%	99.500%	98.56%	98.30%	96.904%				
Mg	0.003%	0.003%	0.004%	0.002%	0.002%	0.00%	0.00%	0.003%				
V	0.001%	0.015%	0.000%	0.002%	0.012%	0.03%	0.03%	0.009%				
Al	0.063%	0.064%	0.072%	0.053%	0.048%	0.06%	0.07%	0.065%				

Slag sample chemical analysis results

Oxides	Ma1	Ma2	Ma3	Mb1	Mb2	Mb3	Mb4	Mb5	Mc1	Mc2	Mc3	Md1
P2O5	0.340%	0.390%	0.184%	0.480%	0.465%	0.357%	0.129%	0.156%	0.279%	0.124%	0.164%	0.207%
SiO2	53.085%	61.853%	65.260%	53.528%	66.101%	67.291%	61.864%	62.961%	51.656%	63.031%	66.958%	49.075%
MnO	0.195%	0.300%	0.205%	0.181%	0.353%	0.224%	0.293%	0.329%	0.201%	0.318%	0.234%	0.154%
FeO	27.840%	6.385%	1.410%	28.954%	4.131%	1.239%	7.294%	1.568%	29.832%	10.055%	2.129%	35.203%
MgO	2.103%	3.618%	3.739%	1.856%	4.224%	3.313%	3.614%	4.428%	2.015%	3.224%	3.672%	1.645%
Al2O3	7.443%	9.346%	12.249%	7.365%	10.547%	11.248%	9.371%	10.593%	7.644%	9.433%	10.346%	7.057%
TiO2	0.173%	0.245%	0.306%	0.172%	0.248%	0.249%	0.245%	0.271%	0.155%	0.216%	0.251%	0.144%
CaO	8.678%	17.669%	16.156%	7.255%	13.739%	15.813%	16.960%	19.084%	8.080%	13.442%	15.911%	6.356%
C	0.075%	0.120%	0.252%	0.143%	0.114%	0.125%	0.127%	0.453%	0.111%	0.105%	0.187%	0.087%
S	0.068%	0.073%	0.238%	0.067%	0.077%	0.141%	0.102%	0.157%	0.028%	0.052%	0.146%	0.074%

Slag sample chemical analysis results

Oxides	Md2	Md3	Me2	Me3	Mf1	Mf2	Mf3	Mg1	Mg2	Mg3	Mh1	Mh2
P2O5	0.248%	0.287%	0.193%	0.171%	0.165%	0.283%	0.403%	0.343%	0.258%	0.276%	0.334%	0.347%
SiO2	61.030%	59.578%	61.324%	67.215%	61.600%	63.572%	63.795%	61.196%	59.129%	62.430%	45.716%	49.868%
MnO	0.272%	0.235%	0.364%	0.272%	0.339%	0.333%	0.342%	0.282%	0.268%	0.207%	0.140%	0.201%
FeO	13.727%	13.545%	2.170%	2.084%	5.690%	2.613%	3.042%	6.583%	3.608%	0.982%	38.618%	30.153%
MgO	2.388%	3.422%	4.691%	3.876%	4.332%	4.383%	4.476%	3.764%	3.314%	2.679%	1.587%	2.207%
Al2O3	8.662%	8.620%	8.739%	11.295%	9.139%	9.247%	9.276%	8.808%	8.933%	9.411%	6.301%	7.647%
TiO2	0.215%	0.238%	0.277%	0.255%	0.259%	0.277%	0.241%	0.226%	0.196%	0.197%	0.134%	0.156%
CaO	13.262%	13.828%	21.805%	14.663%	18.261%	19.062%	18.149%	18.506%	23.969%	23.475%	6.756%	9.057%
C	0.132%	0.131%	0.280%	0.107%	0.123%	0.124%	0.174%	0.138%	0.130%	0.136%	0.074%	0.096%
S	0.064%	0.116%	0.157%	0.064%	0.091%	0.106%	0.103%	0.153%	0.194%	0.206%	0.340%	0.268%

Slag sample chemical analysis results

Oxides	Mh3	Mh4	Mh5	Mi0	Mi1	Mj1	Mj2	Mj3	Mk1	Mk3	Ml1	Ml3
P2O5	0.288%	0.179%	0.171%	0.013%	0.075%	0.056%	0.199%	0.016%	0.081%	0.261%	0.261%	0.071%
SiO2	60.116%	61.023%	48.388%	61.132%	61.064%	53.227%	57.537%	63.293%	51.550%	53.350%	52.302%	65.792%
MnO	0.375%	0.191%	0.149%	0.383%	0.312%	0.221%	0.374%	0.175%	0.184%	0.262%	0.214%	0.169%
FeO	5.660%	2.436%	9.329%	1.781%	1.171%	25.125%	8.310%	3.276%	30.980%	11.288%	28.476%	2.593%
MgO	4.208%	3.319%	2.807%	5.122%	4.694%	2.399%	4.148%	3.604%	1.923%	3.793%	2.172%	3.268%
Al2O3	8.795%	12.160%	9.195%	8.252%	9.485%	8.098%	8.664%	12.329%	7.254%	8.716%	7.322%	11.589%
TiO2	0.225%	0.287%	0.246%	0.213%	0.196%	0.178%	0.248%	0.254%	0.134%	0.245%	0.146%	0.281%
CaO	19.999%	17.392%	14.510%	22.946%	22.824%	10.544%	20.234%	15.901%	7.750%	18.248%	8.913%	15.664%
C	0.119%	2.630%	14.500%	0.127%	0.147%	0.085%	0.117%	0.807%	0.079%	3.490%	0.085%	0.301%
S	0.216%	0.383%	0.705%	0.029%	0.032%	0.067%	0.169%	0.345%	0.064%	0.348%	0.110%	0.272%

APPENDIX B: Summary of MW/EAF steelmaking results

No	Pellet		Crucible & Lining		Time			Initializing arcing	Concurrent heating	Iron weight (g)	Yield (%)	Sample names for slag, iron & gas analysis		
	No	Weight (g)	Crucible	Lining	Total time (minute)	MV time (minute)	EA time (minute)					Slag	Iron	Gas
1	#3	800	Fireclay	No	23	23	3	Yes	Yes	271.32	88.6	-	-	-
2	#3	800	Fireclay	No	16	12	4	Yes	No	243.23	79.5	-	-	-
3	#3	800	Fireclay	No	16.5	16.5	4.5	Yes	Yes	213.26	69.7	-	-	-
4	#3	800	Fireclay	No	15	10	5	Yes	No	290	94.8	-	-	-
5	#3	800	Fireclay	No	13	10	3	Yes	No	163.48	53.4	-	-	-
6	#3	800	Fireclay	No	14	14	4	Yes	Yes	226	73.9	-	-	-
7	#3	800	Fireclay	No	13	13	3	Yes	Yes	172	56.2	-	-	-
8	#3	800	Fireclay	No	12	12	5	Yes	Yes	263	86.0	-	-	-
9	#3	800	Fireclay	No	11.5	11.5	4.5	Yes	Yes	257.8	84.2	-	-	-
10	#3	800	Fireclay	No	10	7	3	Yes	No	215.09	70.3	-	-	-
11	#3	800	Fireclay	No	6	6	-	No	-	-	-	-	-	-
12	#3	800	Fireclay	No	7	7	-	No	-	-	-	-	-	-
13	#3	800	Fireclay	No	9	9	-	No	-	-	-	-	-	-
14	#1	800	Fireclay	No	25	25	5	Yes	Yes	272.21	89.0	-	-	-
15	#3	800	Fireclay	No	25	20	5	Yes	No	294	95	-	-	-
16	#3	800	Fireclay	No	25	20	5	Yes	No	276	89.2	-	-	-

Appendix B Continued

No	Pellet		Crucible & Lining		Time			Initializing arcing	Concurrent heating	Iron weight (g)	Yield (%)	Sample names for slag, iron & gas analysis		
	No	Weight (g)	Crucible	Lining	Total time (minute)	MV time (minute)	EA time (minute)					Slag	Iron	Gas
17	#3	800	Fireclay	No	26	20	6	Yes	No	297	95.9	-	-	-
18	#3	800	Fireclay	No	26	20	6	Yes	No	290	93.7	-	-	-
19	#3	800	Fireclay	No	25	20	5	Yes	No	297	95.9	-	-	-
20	#3	800	Fireclay	No	26	20	6	Yes	No	250	80.75	-	-	-
21	#3	800	Fireclay	No	25	20	5	Yes	No	297.1	96	sf1	tt1	-
22	#3	800	Fireclay	No	26	20	6	Yes	No	252	80	sf2	tt2	-
23	#3	800	Fireclay	No	24	20	4	Yes	No	261	85.6	-	-	-
24	#3	800	Fireclay	No	24	20	4	Yes	No	267	86.3	sf3	tt3	-
25	#3	800	Fireclay	No	25	20	5	Yes	No	289	93.4	-	-	gf3
26	#4	800	Fireclay	No	26	20	6	Yes	No	285	79.8	-	-	-
27	#4	800	Fireclay	No	23	20	3	Yes	No	241	70	sf4	tt4	-
28	#4	800	Fireclay	No	24.5	20	4.5	Yes	No	244	71	sf5	tt5	-
29	#4	800	Fireclay	No	25	20	5	Yes	No	281	78.5	sf6	tt6	gf1
30	#5	800	Fireclay	No	24.5	20	4.5	Yes	No	200	55.2	sf7	tt7	-
31	#5	800	Fireclay	No	25	20	5	Yes	No	226	62.4	sf8	tt8	
32	#5	800	Fireclay	No	26	20	6	Yes	No	273	75.4	-	-	gf7
33	#6	800	Fireclay	No	26	20	6	Yes	No	288	100.2	sf11	tt11	-
34	#6	800	Fireclay	No	25	20	5	Yes	No	226	78.6	-	-	gf4

Appendix B Continued

No	Pellet		Crucible & Lining		Time			Initializing arcing	Concurrent heating	Iron weight (g)	Yield (%)	Sample names for slag, iron & gas analysis		
	No	Weight (g)	Crucible	Lining	Total time (minute)	MV time (minute)	EA time (minute)					Slag	Iron	Gas
35	#7	800	Fireclay	No	27	20	7	Yes	No	261	95.1	sf9	tt9	-
36	#7	800	Fireclay	No	20	20	-	No	-	-	-	-	-	gf5
37	#8	800	Fireclay	No	20	20	-	No	-	-	-	-	-	-
38	#8	800	Fireclay	No	25	20	5	Yes	No	255	93.7	sf10	tt10	gf2
39	#2	800	Fireclay	No	25	20	5	Yes	No	268	81.4	-	-	gf6
40	#1	800	Fireclay	No	25	20	5	Yes	No	260	68.8	-	-	gf8
41	#9	800	Fireclay	No	26	20	6	Yes	No	302	96.2	-	-	gf9
42	#3	600	MgO	No	26	20	6	Yes	No	167.7	72.3	sd1	td1	-
43	#3	600	MgO	No	26	20	6	Yes	No	152	65.5	-	-	-
44	#3	600	MgO	Cao	26	20	6	Yes	No	211	91.0	sd3	td3	-
45	#3	600	Fireclay	No	26	20	6	Yes	No	210	90.5	sd4	td4	-
46	#9	600	MgO	No	26	20	6	Yes	No	177	75.2	sd5	td5	-
47	#9	600	MgO	Cao	26	20	6	Yes	No	220	93.4	sd6	td6	-
48	#9	600	Fireclay	Cao	26	20	6	Yes	No	240	101	sd7	td7	-
49	#10	600	Fireclay	Cao	26	20	6	Yes	No	218	95.4	sd8	td8	-
50	#9	600	Fireclay	MgO	26	20	6	Yes	No	227	96.4	sd9	td9	-
51	#10	600	Fireclay	MgO	26	20	6	Yes	No	232	101.5	sd10	td10	-

APPENDIX C: Composition of Offgases in the MW/EAF Process

Gas sample: gf1					
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %
	Microwave Heating (total time 20 min)				
2 min	76.1	7.07	16.4	0.0390	0.312
4 min	76.7	7.07	15.9	0.0209	0.309
6 min	76.6	6.75	16.3	0.0212	0.326
8 min	76.6	6.68	16.0	0.0208	0.719
10 min	77.2	7.06	15.3	0.0121	0.483
12 min	79.6	7.44	12.4	0.0207	0.498
15 min	78.3	8.24	12.8	0.0256	0.681
18 min	78.1	8.30	12.7	0.0289	0.849
20 min	78.1	7.96	12.7	0.0255	1.19
	Electric Arc Heating (total time 5 min)				
2 min	78.3	10.3	9.46	0.0138	1.89
4 min	78.4	9.46	10.3	0.00	1.80

Gas sample: gf2					
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %
	Microwave Heating (total time 20 min)				
1 min	75.5	3.80	20.0	0.0661	0.614
3 min	76.9	3.05	19.2	0.0231	0.829
5 min	78.9	10.7	9.32	0.0215	1.06
7 min	78.2	9.93	10.7	0.0434	1.19
9 min	76.8	12.5	9.07	0.0426	1.59
12 min	76.1	13.1	8.99	0.0104	1.78
15 min	75.0	12.9	10.2	0.00	1.89
17 min	76.5	11.5	10.2	0.0191	1.83
20 min	76.4	10.8	10.8	0.0191	1.96
	Electric Arc Heating (total time 5 min)				
2 min	78.2	10.7	9.87	0.00	1.23
4 min	77.8	10.6	10.2	0.0320	1.31

Appendix C continued

Gas sample: gf3					
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %
	Microwave Heating (total time 20 min)				
1 min	83.9	5.89	7.34	2.90	0.000
3 min	81.5	9.49	8.14	0.1120	0.815
5 min	79.8	9.41	9.42	0.0689	1.31
7 min	79.8	8.68	10.1	0.0334	1.38
9 min	78.4	7.35	12.5	0.0243	1.65
11 min	80.5	6.10	11.9	0.0421	1.46
13 min	78.2	6.44	13.5	0.0323	1.77
15 min	78.7	5.85	13.6	0.0483	1.78
17 min	78.7	5.47	14.0	0.0496	1.83
19 min	79.3	4.68	13.9	0.0815	2.04
	Electric Arc Heating (total time 5 min)				
2 min	76.5	15.5	7.19	0.0166	0.832
4 min	75.3	14.2	9.25	0.0000	1.19

Gas sample: gf4					
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %
	Microwave Heating (total time 20 min)				
2 min	75.5	12.6	11.1	0.0189	0.910
5 min	77.9	10.2	10.3	0.308	1.32
7 min	76.2	10.5	11.8	0.00	1.53
9 min	76.0	9.68	12.7	0.00	1.71
11 min	74.7	9.87	13.7	0.00	1.71
13 min	74.8	9.75	13.5	0.00	1.90
15 min	74.9	9.55	13.5	0.00	2.00
17 min	76.0	9.36	12.7	0.00	2.03
19 min	77.9	8.59	11.4	0.00	2.10
	Electric Arc Heating (total time 5 min)				
2 min	77.1	10.1	10.2	0.004	2.63
4 min	77.2	9.73	10.5	0.007	2.55

Appendix C continued

Gas sample: gf5							
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %	Ar %	CO %
	Microwave Heating (total time 20 min)						
2 min	78.12	4.50	15.09	0.0373	1.03	1.23	0.0321
4 min	76.85	6.24	14.47	0.0280	1.33	1.09	0.0133
6 min	77.99	7.46	11.85	0.0323	1.57	1.10	0
8 min	79.93	5.52	11.52	0.0170	1.87	1.14	0
10 min	80.02	4.97	11.85	0.0028	2.00	1.15	0
12 min	79.37	5.29	12.17	0.0027	2.03	1.14	0
14 min	79.75	4.42	12.44	0.0028	2.25	1.13	0
16 min	79.63	4.43	12.53	0.0027	2.29	1.13	0
18 min	79.58	4.60	12.34	0.0027	2.35	1.13	0
20 min	79.73	4.60	12.09	0.0030	2.44	1.13	0

Gas sample: gf6							
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %	Ar %	CO %
	Microwave Heating (total time 20 min)						
2 min	78.67	1.85	17.34	0.0135	0.92	1.20	0.0423
4 min	76.68	5.22	15.70	0.0264	1.22	1.15	0.0215
6 min	76.40	5.10	16.16	0.0265	1.17	1.15	0
8 min	75.95	5.85	15.53	0.0397	1.51	1.12	0
10 min	80.05	4.86	12.07	0.0419	1.81	1.17	0
12 min	78.90	6.78	11.35	0.0131	1.79	1.16	0
14 min	79.81	6.10	11.13	0.0001	1.80	1.16	0
16 min	79.22	4.98	12.68	0.0265	1.91	1.18	0
18 min	78.96	5.46	12.36	0.0133	1.98	1.22	0
20 min	79.73	5.65	11.39	0.0404	1.98	1.21	0
	Electric Arc Heating (total time 5 min)						
2 min	79.28	8.45	9.32	0.0021	1.80	1.14	0
4 min	78.56	9.14	9.26	0.0112	1.79	1.23	0

Appendix C continued

Gas sample: gf7							
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %	Ar %	CO %
	Microwave Heating (total time 20 min)						
2 min	77.01	0.59	19.14	0.0226	1.68	1.56	0.0105
4 min	76.25	3.82	16.48	0.0230	1.96	1.46	0.0132
6 min	75.20	6.66	13.94	0.0102	2.63	1.56	0
8 min	75.73	7.39	12.70	0.0353	2.64	1.51	0
10 min	75.45	7.26	13.20	0.0168	2.53	1.54	0
12 min	77.24	6.53	12.25	0.0117	2.46	1.50	0
14 min	76.37	6.10	13.63	0.0266	2.41	1.47	0
16 min	76.31	6.58	12.99	0.0246	2.57	1.53	0
18 min	76.93	6.29	12.58	0.0203	2.69	1.49	0
20 min	77.42	6.38	12.31	0.0169	2.37	1.50	0
	Electric Arc Heating (total time 6 min)						
2 min	75.86	10.23	10.46	0.0111	1.80	1.64	0
4 min	75.92	10.35	9.79	0.0104	2.21	1.71	0

Gas sample: gf8							
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %	Ar %	CO %
	Microwave Heating (total time 20 min)						
2 min	72.82	5.15	19.40	0.0504	0.98	1.59	0.0276
4 min	76.61	4.22	16.68	0.0264	1.28	1.18	0.0149
6 min	76.04	5.71	15.46	0.0527	1.57	1.17	0.0050
8 min	75.89	5.70	15.34	0.0538	1.86	1.15	0
10 min	77.54	4.24	14.98	0.0271	2.07	1.13	0
12 min	74.55	6.33	15.97	0.0125	2.02	1.12	0
14 min	76.19	4.24	16.36	0.0126	2.06	1.14	0
16 min	73.67	7.68	15.51	0.0242	2.02	1.09	0
18 min	73.73	7.20	15.89	0.0238	2.05	1.11	0
20 min	75.91	5.86	15.01	0.0363	2.06	1.12	0
	Electric Arc Heating (total time 5 min)						
2 min	75.22	9.10	13.56	0.0317	2.09	1.28	0
4 min	74.22	9.71	13.39	0.0275	2.65	1.28	0

Appendix C continued

Gas sample: gf9							
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %	Ar %	CO %
	Microwave Heating (total time 20 min)						
2 min	76.59	3.85	18.49	0.0317	1.04	1.51	0.0194
4 min	76.67	3.42	18.96	0.0172	0.93	1.45	0
6 min	80.38	6.68	11.61	0.0179	1.32	1.31	0
8 min	78.38	7.22	12.92	0.0353	1.45	1.22	0
10 min	78.63	7.19	12.28	0.0336	1.87	1.20	0
12 min	79.39	7.57	11.21	0.0259	1.79	1.27	0
14 min	78.71	6.74	12.83	0.0257	1.69	1.17	0
16 min	77.00	8.10	13.25	0.0249	1.64	1.17	0
18 min	76.17	8.01	14.07	0.0166	1.72	1.13	0
20 min	76.35	8.02	13.81	0.0122	1.81	1.19	0
	Electric Arc Heating (total time 6 min)						
2 min	79.38	10.11	8.23	0.0204	2.26	1.19	0
4 min	78.36	11.00	7.92	0.0277	2.70	1.26	0

Gas sample: from coal					
	N_2 %	CO_2 %	O_2 %	SO_2 %	H_2O %
	Microwave Heating (total time 20 min)				
1.5 min	77.8	0.889	19.4	0.227	1.62
3 min	80.1	0.768	17.6	0.191	1.32
5 min	81.6	0.639	16.3	0.0730	1.39
8 min	80.7	0.655	16.7	0.103	1.82
11 min	80.5	1.31	16.1	0.109	2.04
14 min	79.7	2.24	15.9	0.155	2.02
16 min	79.7	3.93	14.1	0.155	2.11
19 min	77.6	5.77	14.4	0.149	2.03

Appendix D: Table.D.1 . Microwave DRI Heat Balance, Preliminary Operating Cost

Solids	Tonne/Hr Solids	SpH BTU/lb F	Tin F	Tout F	BTU/Hr	Watt Hr/Hr	Heating Eff (%)	Input Heat Watt Hr/Hr
Microwave Reduction								
Concentrate	88.70	0.16	60.00	1100.00	31,730,862	9,297,143	85.00	10,937,815
Coal to 220 (Dry)	16.23	0.30	60.00	220.00	1,717,372	503,190	85.00	591,988
Water to 220	4.06	1.00	60.00	220.00	1,431,143	419,325	85.00	493,324
Evap Moist	4.06	1000.00	220.00	221.00	8,944,646	2,620,781	85.00	3,083,272
220 to Final	16.23	0.30	220.00	1100.00	9,445,547	2,767,545	85.00	3,255,936
Total					53,269,571	15,607,984		18,362,334
SAF Smelting								
CaO	4.40	0.18	1100.00	2900.00	3,193,344	935,650	65.00	1,439,461
SiO2	4.75	0.24	1100.00	2900.00	4,596,480	1,346,769	65.00	2,071,952
CaSiO3	9.15	395.00	2900.00	2901.00	8,095,920	2,372,105	65.00	3,649,392
Steel	62.50	0.16	1100.00	2900.00	40,320,000	11,813,760	65.00	18,175,015
Melt	62.50	50.00	2900.00	2901.00	7,000,000	2,051,000	65.00	3,155,385
To 3100	62.50	0.16	2901.00	3100.00	4,457,600	1,306,077	65.00	2,009,349
Total					51,777,600	15,170,837		30,500,554
							Tot Elect.	48,862,888

62.50 tonne metal / hour (500,000 tonnes per year, 8000 hr /year)
1.35 tonne Concentrate / tonne metal
0.32 tonne Coal / tonne metal

Watts Hr/tonne		781,806	
MW Hr/tonne		0.78	
Costs /Tonne Hot Metal			
Based on $0.035/kW Hr	Power	$27.36	
Based on $20 / Tonne	Conc	$25.60	
Based on $20 / Tonne	Coal	$6.40	
Total Consumables			$59.36
Other SAF costs (Labor, R&M, etc)		$10.00	
Cash Operating Cost			$69.36
Capital, $150,000,000 at 10% over 10 years		$48.00	
Total Direct Operating Costs			$117.36

$Fe_3O_4+4C+2O_2=3Fe+4CO$ is an exothermic reaction

No electricity consumed for the reduction

Assume 5% CaO in concentrate & slag basicity=1

Slag is discharged after melt at 2900F

Appendix D: Table D.2. Operating Costs

Conversion to Steel	$/tonne Source	tonnes/ tonne Product	$/tonne Product	Total Cash Cost $/tonne
Hot Metal (Cash Cost)	$69.36	0.83	$57.57	
Scrap (Purchased and Reverts)	$100.00	0.21	$21.00	
Alloys			$15.00	
Oxygen			$3.00	
Flux			$3.00	
Energy			$2.50	
R&M Supplies			$8.50	
Labor			$3.00	
Cash Cost, Conversion to Steel				$113.57
Casting				
Liquid Steel	$113.57	1.03	$116.98	
Energy			$2.00	
R&M Supplies			$8.00	
Labor			$2.50	
Cash Cost Slabs, FOB Plant				$129.48
Debt Service, 270,000,000 @ 10% for 10 years				$73.85
Operating Cost / tonne steel slab				$203.32
Operating Cost / ton steel slab (2000 lbs)				$184.42
Tonnes Slab / Year				585,000

Capital Costs

Hot Metal	$150,000,000
Conversion	$70,000,000
Casting	$50,000,000
Total	$270,000,000

Debt Service / Year
10% over 10 Years.

Hot Metal	$24,000,000
Conversion	$11,200,000
Casting	$8,000,000
Total	$43,200,000

Debt Service / tonne Steel
10% over 10 Years

Hot Metal	$41.03
Conversion	$19.15
Casting	$13.68
Total	$73.85

Capital
Costs per Annual Tonne

Hot Metal*	$300.00
Conversion**	$119.66
Casting**	$85.47
Total**	$461.54

* 500,000 t/a hot metal basis

** 585,000 t/a steel basis

APPENDIX D: Figure 6.1. Material Flows in Microwave Steel Making

Hot Metal Operations:

		Million Tonnes per year	
Iron Ore			
1.35	Tonnes concentrate per tonne metal	0.675	Tonnes Iron Ore
Coal			
0.32	Tonnes coal per tonne metal	0.160	Tonnes Coal
Electricity			
667,233	Kwhr per tonne metal	333,617	Kwhr Electricity
	Yields	**0.500**	Tonnes Hot Metal Produced per year

Steel Making:

Hot Metal			
0.83	Tonnes hot metal per tonne steel	0.500	Tonnes Hot Metal
Scrap			
0.21	Tonnes scrap per tonne steel	0.127	Tonnes Scrap Metal
	Yelds	**0.602**	Tonnes Steel Produced per year

Casting:

Liquid Steel			
1.03	Tonnes liquid steel per tonne slabs	**0.585**	Tonnes Steel Slabs Produced per year

APPENDIX D: Table D.3A: Parameters and assumptions for producing hot metal:

Parameters & Assumptions:	Includes Inflation using $40/tonne iron ore
Hot metal production rate =	0.5
Steel product selling price =	$300.00
Royalty Rate =	1.0%
Steel price escallation rate =	1.0%
Cost inflation rate =	2.0%
Steel used per tonne steel slabs produced =	0
Hot metal used per tonne steel =	0
Iron ore used per tonne hot metal =	1.35
Coal used per tonne hot metal =	0.32
Iron ore cost per tonne =	$40.00
Electricity use per tonne hot metal =	667
Electricity cost per kwhr =	$0.035
Coal price per tonne =	$20.00
Labor wage rate =	$25.00
Employee overhead rate =	55%
HOT METAL OPERATIONS:	
Hot metal workers per year =	25
Salary cost per labor cost =	$0.38
R & M per tonne hot metal =	$2.00
General & office expense =	$1.50
Capital cost per tonne hot metal =	$300
Proportion of capital for structures =	25%
Property Tax Rate =	1.0%
State Income Tax Rate =	6.0%
Federal Income Tax Rate =	35.0%
Capital Gain Tax Rate =	20.0%
Equipment Salvage Value % =	10.0%
Building Salvage Value % =	25.0%
Working Capital % of Total Capital =	20.0%
Cost of Capital: MARR =	10.0%

APPENDIX D: Table D.3B: Parameters and assumptions for producing steel slabs:

Parameters & Assumptions	
Hot metal production rate =	0.5
Steel product selling price =	$400.00
Royalty Rate =	1.0%
Steel price escallation rate =	1.0%
Cost inflation rate =	2.0%
Steel used per tonne steel slabs produced =	1.03
Hot metal used per tonne steel =	0.83
Iron ore used per tonne hot metal =	1.35
Coal used per tonne hot metal =	0.32
Iron ore cost per tonne =	$40.00
Electricity use per tonne hot metal =	667
Electricity cost per kwhr =	$0.035
Coal price per tonne =	$20.00
Labor wage rate =	$25.00
Employee overhead rate =	55%
HOT METAL OPERATIONS:	
Hot metal workers per year =	25
Salary cost per labor cost =	$0.38
R & M per tonne hot metal =	$2.00
General & office expense =	$1.50
Capital cost per tonne hot metal =	$300
Proportion of capital for structures =	25%
STEEL MAKING OPERATIONS:	
Scrap used per tonne steel =	0.21
	$116.00
Alloy cost per tonne steel =	$15.00
Oxygen used per tonne steel =	$3.00
Flux used per tonne steel =	$3.00
Energy cost per tonne steel =	$2.50
Steel making workers per year =	22
Salary cost per labor cost =	$0.38
R & M per tonne steel =	$8.50
General & office expense =	$1.00
Capital cost per tonne steel =	$120
Proportion of capital for structures =	25%
STEEL CASTING OPERATIONS:	
Energy cost per tonne of slabs produced =	$2.00
Casting workers per year =	13
Salary cost per labor cost =	$0.38

R & M per tonne slabs =	$8.00
General & office expense =	$1.00
Capital cost per tonne slab =	$86
Proportion of capital for structures =	25%
Property Tax Rate =	1.0%
State Income Tax Rate =	6.0%
Federal Income Tax Rate =	35.0%
Capital Gain Tax Rate =	20.0%
Equipment Salvage Value % =	10.0%
Building Salvage Value % =	25.0%
Working Capital % of Total Capital =	20.0%
Cost of Capital: MARR =	10.0%

APPENDIX D: Table D.4A: Base case economic evaluation of producing hot metal:

Microwave Steel as Feed for Mini-Mill: From Iron Ore to Hot Metal

Includes Inflation using $40/tonne iron ore

Amounts in Millions (Display is rounded to nearest $0.1 million)

YEAR	0	1	2	3	4	5	6	7	8	9	10
REVENUES:											
PRODUCE STEEL SLABS											
Production, Mill. tonne/yr.		0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
Price, $/unit		$300.0	$300.0	$300.0	$300.0	$300.0	$300.0	$300.0	$300.0	$300.0	$300.0
Revenue & Inflation		$150.0	$153.0	$154.5	$156.1	$157.7	$159.2	$160.8	$162.4	$164.1	$165.7
Royalty Payments		-$1.5	-$1.5	-$1.5	-$1.6	-$1.6	-$1.6	-$1.6	-$1.6	-$1.6	-$1.7
Net Revenue		$148.5	$151.5	$153.0	$154.5	$156.1	$157.6	$159.2	$160.8	$162.4	$164.0
COSTS:											
IRON ORE TO HOT METAL:											
Iron Ore		-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0
Electricity		-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7
Coal		-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2
Labor		-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3
Salaries		-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5
Overhead		-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0
R & M Supplies		-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0
Lab, insurance, office		-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5
TOTAL CASH COST		-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2
INFLATED CASH COST		-$47.2	-$49.1	-$50.0	-$51.0	-$52.1	-$53.1	-$54.2	-$55.2	-$56.4	-$57.5
Equipment Depreciation		-$16.1	-$27.6	-$19.7	-$14.1	-$10.0	-$10.0	-$10.0	-$5.0	$0.0	$0.0
Building Depreciation		-$0.9	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0
TOTAL HOT METAL COST		-$64.1	-$77.6	-$70.7	-$66.1	-$63.1	-$64.1	-$65.2	-$61.2	-$57.3	-$58.4
Total Cost: Hot Metal Only		-$64	-$78	-$71	-$66	-$63	-$64	-$65	-$61	-$57	-$58
Income before Taxes	0	$84.4	$73.9	$82.3	$88.5	$93.0	$93.5	$94.0	$99.6	$105.1	$105.6
Property Taxes	0	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5

State Income Tax	0	-$5.0	-$4.3	-$4.8	-$5.2	-$5.5	-$5.5	-$5.6	-$5.9	-$6.2	-$6.2
Federal Income Tax	0	-$27.3	-$23.8	-$26.6	-$28.6	-$30.1	-$30.3	-$30.4	-$32.3	-$34.1	-$34.2
Income after Tax	0	$50.6	$44.2	$49.4	$53.1	$55.9	$56.2	$56.5	$59.9	$63.3	$63.6
CASH FLOW:											
After Tax Income	0	$50.6	$44.2	$49.4	$53.1	$55.9	$56.2	$56.5	$59.9	$63.3	$63.6
Non-cash Charges	0	$17.0	$28.5	$20.6	$15.0	$11.0	$11.0	$11.0	$6.0	$1.0	$1.0
Capital Investment											
Hot Metal Equipment	-$113										$9.0
Hot Metal Structures	-$38										$13.1
Steel Making Equipment	$0										$0.0
Steel Making Structures	$0										$0.0
Casting Equipment	$0										$0.0
Casting Structures	$0										$0.0
Working Capital		-$15.0	-$15.0								$30.0
Net Cash Flow	-$150	$53	$58	$70	$68	$67	$67	$68	$66	$64	$117

Net Present Value = $262 million (assumes a 10 year life)

Total Cash Costs including royalties, taxes & inflation		-$99	-$31	-$34	-$37	-$39	-$39	-$39	-$41	-$43	-$44

	Total per year	Per tonne per year	Per short ton per year
Present Worth of Cash Costs =	-$288		
Present Worth of Capital Costs =	-$150		
Annualized "operating" costs =	-$47	-$94	-$85
Annualized capital cost =	-$23	-$46	-$42
Total annual cost =	-$70	-$140	-$127

APPENDIX D: Table D.4B: Base case economic evaluation of producing steel slabs:

Stand Alone Plant: From Iron Ore to Cast Steel Slabs

Amounts in Millions (Display is rounded to nearest $0.1 million)

YEAR	0	1	2	3	4	5	6	7	8	9	10
REVENUES:											
PRODUCE STEEL SLABS											
Production, Mill. tonne/yr.		0.585	0.585	0.585	0.585	0.585	0.585	0.585	0.585	0.585	0.585
Price, $/unit		$400.0	$400.0	$400.0	$400.0	$400.0	$400.0	$400.0	$400.0	$400.0	$400.0
Revenue & Inflation		$233.9	$238.6	$241.0	$243.4	$245.9	$248.3	$250.8	$253.3	$255.9	$258.4
Royalty Payments		-$2.3	-$2.4	-$2.4	-$2.4	-$2.5	-$2.5	-$2.5	-$2.5	-$2.6	-$2.6
Net Revenue		$231.6	$236.3	$238.6	$241.0	$243.4	$245.9	$248.3	$250.8	$253.3	$255.8
COSTS:											
IRON ORE TO HOT METAL:											
Iron Ore		-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0	-$27.0
Electricity		-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7	-$11.7
Coal		-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2	-$3.2
Labor		-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3	-$1.3
Salaries		-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5
Overhead		-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0
R & M Supplies		-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0
Lab, insurance, office		-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5
TOTAL CASH COST		-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2	-$47.2
INFLATED CASH COST		-$47.2	-$49.1	-$50.0	-$51.0	-$52.1	-$53.1	-$54.2	-$55.2	-$56.4	-$57.5
Equipment Depreciation		-$16.1	-$27.6	-$19.7	-$14.1	-$10.0	-$10.0	-$10.0	-$5.0	$0.0	$0.0
Building Depreciation		-$0.9	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0
TOTAL HOT METAL COST		-$64.1	-$77.6	-$70.7	-$66.1	-$63.1	-$64.1	-$65.2	-$61.2	-$57.3	-$58.4
HOT METAL TO STEEL:											
Scrap iron		-$14.7	-$14.7	-$14.7	-$14.7	-$14.7	-$14.7	-$14.7	-$14.7	-$14.7	-$14.7
Alloys		-$9.0	-$9.0	-$9.0	-$9.0	-$9.0	-$9.0	-$9.0	-$9.0	-$9.0	-$9.0
Oxygen		-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8

Flux		-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8	-$1.8
Energy		-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5	-$1.5
Labor		-$1.1	-$1.1	-$1.1	-$1.1	-$1.1	-$1.1	-$1.1	-$1.1	-$1.1	-$1.1
Salaries		-$0.4	-$0.4	-$0.4	-$0.4	-$0.4	-$0.4	-$0.4	-$0.4	-$0.4	-$0.4
Overhead		-$0.9	-$0.9	-$0.9	-$0.9	-$0.9	-$0.9	-$0.9	-$0.9	-$0.9	-$0.9
R & M Supplies		-$5.1	-$5.1	-$5.1	-$5.1	-$5.1	-$5.1	-$5.1	-$5.1	-$5.1	-$5.1
Lab, insurance, office		-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0	-$1.0
TOTAL CASH COST		-$37.4	-$37.4	-$37.4	-$37.4	-$37.4	-$37.4	-$37.4	-$37.4	-$37.4	-$37.4
INFLATED CASH COST		-$37.4	-$38.9	-$39.7	-$40.5	-$41.3	-$42.1	-$43.0	-$43.8	-$44.7	-$45.6
Equipment Depreciation		-$7.7	-$13.3	-$9.5	-$6.8	-$4.8	-$4.8	-$4.8	-$2.4	$0.0	$0.0
Building Depreciation		-$0.4	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5
TOTAL STEEL COST		-$45.6	-$52.7	-$49.6	-$47.7	-$46.6	-$47.4	-$48.3	-$46.7	-$45.2	-$46.1
CASTING STEEL INTO SLABS:											
Energy		-$1.2	-$1.2	-$1.2	-$1.2	-$1.2	-$1.2	-$1.2	-$1.2	-$1.2	-$1.2
Labor		-$0.7	-$0.7	-$0.7	-$0.7	-$0.7	-$0.7	-$0.7	-$0.7	-$0.7	-$0.7
Salaries		-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3
Overhead		-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5	-$0.5
R & M Supplies		-$0.2	-$0.2	-$0.2	-$0.2	-$0.2	-$0.2	-$0.2	-$0.2	-$0.2	-$0.2
Lab, insurance, office		-$0.6	-$0.6	-$0.6	-$0.6	-$0.6	-$0.6	-$0.6	-$0.6	-$0.6	-$0.6
TOTAL CASH COST		-$3.4	-$3.4	-$3.4	-$3.4	-$3.4	-$3.4	-$3.4	-$3.4	-$3.4	-$3.4
INFLATED CASH COST		-$3.4	-$3.6	-$3.6	-$3.7	-$3.8	-$3.9	-$3.9	-$4.0	-$4.1	-$4.2
Equipment Depreciation		-$5.4	-$9.2	-$6.6	-$4.7	-$3.4	-$3.4	-$3.4	-$1.7	$0.0	$0.0
Building Depreciation		-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3	-$0.3
TOTAL SLAB COST		-$9.1	-$13.1	-$10.6	-$8.7	-$7.5	-$7.5	-$7.6	-$6.0	-$4.4	-$4.5
Total Cost: Metal+Steel+Casting		-$119	-$143	-$131	-$123	-$117	-$119	-$121	-$114	-$107	-$109
Income before Taxes	0	$112.8	$92.9	$107.8	$118.5	$126.3	$126.8	$127.3	$136.9	$146.4	$146.8
Property Taxes	0	-$2.7	-$2.7	-$2.7	-$2.7	-$2.7	-$2.7	-$2.7	-$2.7	-$2.7	-$2.7
State Income Tax	0	-$6.6	-$5.4	-$6.3	-$6.9	-$7.4	-$7.4	-$7.5	-$8.0	-$8.6	-$8.6
Federal Income Tax	0	-$36.2	-$29.7	-$34.6	-$38.1	-$40.7	-$40.8	-$41.0	-$44.1	-$47.3	-$47.4
Income after Tax	0	$67.2	$55.1	$64.2	$70.7	$75.5	$75.8	$76.1	$82.0	$87.8	$88.1

CASH FLOW:											
After Tax Income	0	$67.2	$55.1	$64.2	$70.7	$75.5	$75.8	$76.1	$82.0	$87.8	$88.1
Non-cash Charges	0	$30.9	$51.8	$37.5	$27.3	$20.0	$20.0	$20.0	$10.9	$1.7	$1.7
Capital Investment											
Hot Metal Equipment	-$113										$9.0
Hot Metal Structures	-$38										$13.1
Steel Making Equipment	-$54										$4.3
Steel Making Structures	-$18										$6.3
Casting Equipment	-$38										$3.0
Casting Structures	-$13										$4.4
Working Capital		-$27.3	-$27.3								$54.5
Net Cash Flow	-$273	$71	$80	$102	$98	$95	$96	$96	$93	$90	$184

Net Present Value = $316 million (assumes a 10 year life)

All non-capital costs including royalties, taxes & inflation		-$136	-$132	-$139	-$145	-$150	-$153	-$155	-$161	-$166	-$169
Only operating costs with inflation		-$88	-$92	-$93	-$95	-$97	-$99	-$101	-$103	-$105	-$107

	Total per year		
Present Worth of all non-capital Costs =	-$906		
Present Worth of only operating costs =	-$593		
Present Worth of Capital Costs =	-$273	$ per tonne	$ per ton
	(million $)	per year	per year
Annualized "operating" costs =	-$96	-$165	-$150
Annualized all non-capital costs =	-$147	-$252	-$229
Annualized capital cost =	<u>-$42</u>	<u>-$72</u>	<u>-$65</u>
Total annual cost =	-$189	-$324	-$294