FINAL TECHNICAL REPORT

Project Title: PAIRED STRAIGHT HEARTH FURNACE ï TRANSFORMATIONAL IRONMAKING PROCESS

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Principal Investigator(s): Dr. Wei-Kao Lu
Professor Emeritus
McMaster University
1280 Main Street West
Hamilton, Ontario, Canada L8S 4L7
(905) 525-9140 Ext. 24976
weikao.lu@gmail.com

Paul D. Debski
ANDRITZ Metals Inc.
500 Technology Drive
Canonsburg, Pennsylvania 15317
(724) 746-2300 Ext. 246
Paul.Debski@andritz.com

Recipient: American Iron and Steel Institute
25 Massachusetts Ave. NW, Suite 800
Washington, DC 20001

Project Partners: ArcelorMittal USA, LLC
United States Steel Corporation

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ACRONYMS:

PSH: Paired Straight Hearth
PSHF: Paired Straight Hearth Furnace
DRI: Direct Reduced Iron
LHF: Linear Hearth Furnace
PLC: Programmable Logic Controller
ESP: Electrostatic Precipitator
HMI: Human Machine Interface
MCC: Motor Control Center

NOTES ON UNITS:

All references to tons are metric tons (tonnes) consisting of 1000 kg or 2204 lb. For consistency, these units have been used even when referring to environmental emissions. When comparing to U.S. environmental regulations, emission rates should be converted to short tons or net tons (NT) consisting of 2000 lb.

Gas flows are given in metric units of normal cubic meters (Nm^3), referred to standard conditions of 0ºC and 1 bar (100 kPa), or in U. S. customary units of standard cubic feet (scf), referred to standard conditions of 60ºF and 1 atmosphere.

FIGURES:

TABLES:

1.0 EXECUTIVE SUMMARY

This report summarizes work that is a part of the continuing effort supported by the United States Department of Energy (DOE) and the American Iron and Steel Institute (AISI) to develop a new, coal-based, cokeless hot-metal production process. The present effort supports the reduction of iron-ore/coal composite agglomerates in tall beds in the Paired Straight Hearth Furnace (PSHF) process, followed by melting and separation of liquid iron and slag in a separate device. This new alternative ironmaking technology has the potential to replace blast furnaces and coke ovens while using only two-thirds of the energy required in the traditional processes. In addition, selected steel plant waste oxides can be processed in the PSHF to make a cost-effective direct reduced iron (DRI) feed, with a metallization level of up to 95 percent, for potential hot-charging to an electric arc furnace (EAF) or cold-charging to a basic-oxygen furnace (BOF) for the production of steel. This report details the results of Large Batch Furnace Tests, Supplementary Laboratory Tests, and Physical Simulation Tests and presents the Detailed Design and Cost Estimate for construction of a 50,000-tonne-per-year (t/a) Demonstration Plant to advance the PSHF process.

Preliminary Investigation and Concept Definition work completed in September 2002 by McMaster University [1] successfully demonstrated the technical feasibility of producing high-quality DRI from steelmaking waste oxides in a new type of furnace, the PSHF. Patents were granted to McMaster University on the PSHF technology [2, 3]. Advantages of the PSHF process over existing technologies include higher fuel efficiency, reduced CO_2 emissions, lower capital investment costs, and lower operating costs. Although further PSHF studies conducted with DOE support [4] corroborated the earlier small-scale tests that had been conducted in a static mode, additional information was required before continuing to the scale up of a Demonstration Plant.

The objective of this project was to develop and evaluate the scalability of the PSHF process through a comprehensive ñConcept Developmentò approach to address in a direct manner a number of critical furnace, engineering, and scale-up challenges that had to be resolved to decrease the technology integration and implementation risks associated with the design and construction of a robust Demonstration Plant.

The Concept Development approach was led by Bricmont Inc. (now ANDRITZ Bricmont Inc.) of Pittsburgh, Pennsylvania, with supplementary work by the project industrial partners, United States Steel Corporation and ArcelorMittal USA; the Coleraine Minerals Research Laboratory (CMRL), a division of the Natural Resources Research Institute (NRRI) of the University of Minnesota Duluth (UMD); and potential equipment vendors. The Concept Development work was divided into four parts: (1) Large Batch Furnace Tests by Bricmont, with supporting test work by potential equipment vendors and company partners; (2) Supplementary Laboratory Tests by CMRL to determine key parameters required for the production of strong dry (unfired) pellets from iron-oxide/coal mixtures and to obtain information on the kinetics of pellet reduction under PSHF conditions and the effect of several key variables on pellet reduction; (3) Physical Simulation Tests, in which the operation of one half of a PSHF reduction furnace was simulated using a pilot-scale Linear Hearth Furnace (LHF) at CMRL; and (4) the Detailed

Design and Cost Estimate for construction of a 50,000-t/a PSHF Demonstration Plant by Bricmont.

A number of issues had been identified in the earlier PSHF studies as being critical to the successful design of a commercially robust PSHF Demonstration Plant. These included the necessity for continuous pellet feeding and discharging, the location of flue gas stacks, burner configuration, furnace sealing, pallet train design, quantifying air emissions, and defining water treatment requirements. Each of these factors was considered in the Concept Development approach to provide a comprehensive battery-limit cost estimate for the proposed PSHF Demonstration Plant.

As part of this effort, Bricmont designed and constructed a Large Batch Furnace to approximate the conditions present in the PSHF process and conducted targeted tests to develop essential information for the design of the proposed PSHF Demonstration Plant. The Large Batch Furnace tests had three main objectives: (1) to determine the most appropriate method for discharge of the DRI product; (2) to measure emissions from the process; and (3) to develop data required for pre-engineering and costing of the proposed PSHF Demonstration Plant. Comparative testing of several DRI product discharge methods showed that scraping the reduced mass from the hearth was the best discharge method. Another discharge method that was tested, tilting the hearth to discharge the DRI product by gravity, was much less effective. Although accurate measurement of process emissions during the Large Batch Furnace tests proved to be difficult due to the batch nature of the tests, reasonable estimates were obtained. Measurements showed that process sulfur dioxide (SO_2) emissions reached 236 parts per million by volume (ppmv) in the early part of the Large Batch Furnace tests, as volatile matter was released from the coal contained in the iron-oxide/coal composite pellets, and dropped to zero in the later part of the tests. The average value for SO_2 emissions during the tests was less than 90 ppmv, based on the amount of sulfur contained in the coal. Emissions of NO_x varied widely from 3 ppmv to as much as 432 ppmv, although the maximum observed value was believed to be an outlier. An average value of 30 ppmv is expected for NO_x emissions from the Demonstration Plant.

The Coleraine Minerals Research Laboratory (CMRL) conducted a six-month study (Appendix A) to develop design criteria for a scalable process to prepare and pelletize the iron-oxide/coal mixture, dry the green pellets, and convey the dried pellets to the PSHF. Pelletizing tests were conducted to determine the effects of binder type and usage rate on green pellet strength, dry pellet strength, and handling characteristics of dried pellets. The tests included balling tests and a simulation of dropping dried pellets onto a moving hearth. Acceptable pellet strength and handling characteristics were obtained for both magnetite and waste-oxide bearing composite pellets produced with bentonite and with organic binders. Supporting test work by potential equipment vendors included raw material drying and additional pelletizing test work.

Tests were also conducted at CMRL in a two-zone, electrically-heated, laboratory furnace (Appendix B) to investigate the kinetics of pellet shrinkage, heat transfer, and gas evolution, as well as the effect of two hearth preheat temperatures on product metallization. These laboratory furnace tests resulted in a large amount of data that can be used for the development of a kinetic model of the PSHF process that incorporates vertical shrinkage, diametrical shrinkage, and variations in density, porosity, and chemical composition. Data on gas evolution during reaction

were also recorded. In addition, the laboratory tests have shown that a hearth preheat temperature of 1200°C (2190°F) or higher probably will result in adequate metallization of the bottom layer in a pellet bed with an initial depth of 120 mm (5 in.). Hearth preheat temperatures higher than 1200°C could improve the metallization level that can be achieved in the bottom layer to above 90 percent.

Physical simulation of the PSHF process was conducted at CMRL in its pilot-scale linear-hearth furnace (LHF), a 12.2-m-long by 0.6-m-wide (40-ft-long by 2-ft-wide) pusher furnace that has moving pallets capable of carrying beds of pellets up to 120 mm (5 in.) deep (Appendix C). The LHF is fired with oxygen-gas burners and can reach an operating temperature of 1500°C (2730°F). Physical simulation of the PSHF process was satisfactorily achieved in the LHF ï the reduction reactions proceeded as projected, with shrinkage of the three top-most layers and separation of the reduced mass into clusters that could be easily broken apart. The depth of reaction was limited to 75 mm (3 in.) due to two issues: (1) the hearth preheat temperature was limited to a maximum of 800°C (1470°F) with circulation of the pallets and (2) the high-rate of evolution of volatile matter from the coal contained in the pellets during attempted continuous operation of the LHF in PSHF mode, which caused the burnersô safety limits to stop the furnace. Slight reoxidation of the product DRI pellets was observed due to the methods used to discharge and cool the pellets.

Overall, the Large Batch Furnace Tests, Supplementary Laboratory Tests, and the Physical Simulation Tests confirmed the basic concepts of the PSHF process and demonstrated the capability of the PSHF process to make DRI from either magnetite concentrate or steel plant revert material. To improve the ability of the PSHF to handle feed materials with varying characteristics, further laboratory testing including testing at the CMRL LHF, should be conducted to provide additional detailed design information to assure that a PSHF Demonstration Plant, when built, will have a high probability of successful operation.

Full optimization of the PSHF process cannot be accomplished until a Demonstration Plant has been constructed and operated on a continuous basis. The comprehensive Detailed Design and Cost Estimate for such a Demonstration Plant is based on earlier preliminary design work by Bricmont [4, 6], the Large Batch Furnace Test results, and mathematical modeling, with support from the results of the Supplementary Laboratory Tests and the Physical Simulation Tests. The equipment list that was developed as part of the Detailed Design and Cost Estimate (Appendix D) will serve as the platform for construction of a 50,000-t/a PSHF Demonstration Plant. The PSHF Demonstration Plant will consist of pellet making, thermal processing, and emissions handling equipment, will fit within a footprint of approximately 110 m by 49 m (360 ft. by 160 ft.), and is estimated to cost $28,855,000 (2013 dollars basis).

The most likely point of initial entry into the mainstream market for the PSHF DRI pellets is an electric arc furnace (EAF) or integrated steel making facility that can consume DRI. Such plants could include producers of slab, coil, long products, or specialty steel products.

2.0 INTRODUCTION AND BACKGROUND

In January 2014, The American Iron and Steel Industry (AISI) reported the U.S. steel industry reduced its energy intensity per ton of steel shipped by approximately 33 percent since 1990. [13] This has been achieved by extensive use of technologies such as the EAF in addition to various energy efficiency processes. However, further significant gains in energy efficiency will require the development of new, transformational iron and steelmaking processes. McMaster University developed such a transformational process, the Paired Straight Hearth Furnace (PSHF) process. The technical feasibility study of the PSHF process and the preliminary design for a 42,000-t/a PSHF pilot-scale plant were successfully completed in September 2002 and February 2006, respectively, under AISI/DOE Cooperative Agreement DE-FC07-97ID13554. [1, 4]

The PSHF process is an emerging alternative high-productivity, direct-reduced-iron (DRI) production technology that has the potential to achieve very low fuel rates and has the potential to replace blast furnace ironmaking. The PSHF process can operate independently or may be coupled with other melting technologies to produce liquid hot metal that is similar to blast furnace iron and is suitable as a feedstock for basic oxygen furnace (BOF) or electric arc furnace (EAF) steelmaking furnaces when using virgin iron oxide feed.

The PSHF process uses medium and high-volatile non-metallurgical coal as a reductant to convert iron oxides such as iron ore or steelmaking revert material to a DRI product. In this process, a multi-layer bed of composite dried green balls (unfired pellets), made from fine iron oxide, fine coal, and a binder, is established on a moving refractory hearth in a tunnel or ñstraight hearthò furnace. Two of these tunnel furnaces, located side by side, are coupled, hence the name Paired Straight Hearth Furnace (PSHF). The pellet bed absorbs radiant heat energy during exposure to the high temperature of the interior refractory surfaces of the PSHF, and a strongly reducing gas atmosphere is generated in the bed from volatile matter released from the coal contained in the pellets. The reduction process that takes place yields a highly metalized DRI product.

A key feature of the PSHF system is that it consists of two parallel tunnel furnaces (Figure 1). This allows combustibles from one furnace to be used in the parallel furnace in order to maximize fuel efficiency and also prevent oxidation of the reduced pellets. [5]

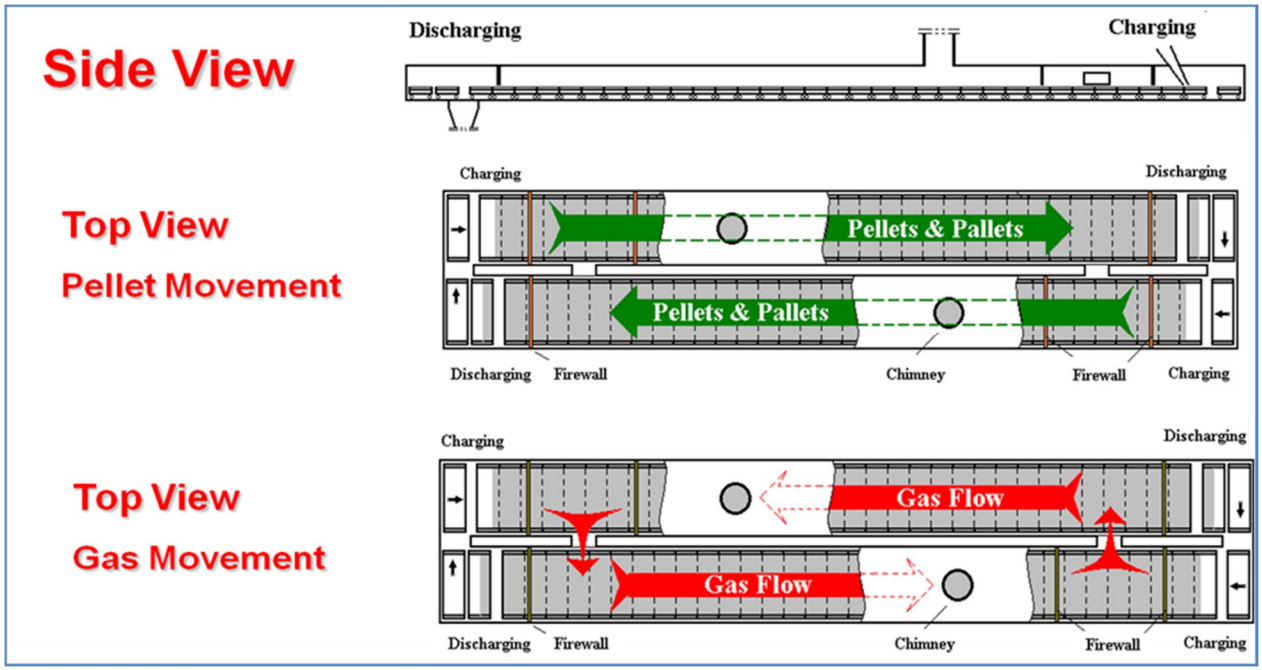


Figure 1. PSH Furnace—Conceptual views with material and gas flows shown. [4]

The PSHF, coupled with a melting furnace (smelter), will allow steelmakers to produce iron with approximately 30 percent less energy as compared to the traditional blast furnace route. [1, 4] An important benefit of the new technology is that it can use medium and high-volatile, non-metallurgical coals, which are plentiful in North America, to produce DRI pellets from either iron ore or iron-bearing steelmaking revert materials. This is a very important strategic advantage for domestic integrated steelmakers, as high-quality metallurgical coals, particularly the low-volatile-matter metallurgical coals required in most cokemaking coal blends in North America, are in short supply. Moreover, the PSHF process eliminates the need for both pellet induration and cokemaking, an energy intensive process required in traditional ironmaking.

Current viable coal-based and cokeless ironmaking processes that can be compared to the PSHF process include the rotary-hearth-furnace (RHF) DRI process and the ITmk3 process. Both processes use composite iron-oxide/carbon agglomerates and are heat-transfer limited. Both the RHF and ITmk3 processes use a single layer, or at most two layers, of pellets or briquettes on the hearth. Generally, the RHF is used to produce a metallized DRI product that requires an additional separate melting step to produce liquid iron. A typical RHF will operate at about 1250°C, and the DRI product will be discharged from it while still hot. The hot product can be melted in a subsequent processing stage or briquetted to form hot-briquetted iron (HBI).

The ITmk3 process operates at a slightly higher temperature to effect melting of the pellet or briquette feed so that metal and slag separate from each other while still on the hearth. Subsequent cooling of the melted composite, followed by a physical separation step, results in ñnuggetsò of iron and beads of slag. ITmk3 accomplishes full melting by adding extra coal and flux in the composite pellets to carburize iron, remove sulfur, and to supply more heat for melting to form slag and operates at a higher temperature than the conventional RHF. For the purpose of preventing the attack of hearth refractory by corrosive liquids, a layer of

carbonaceous materials is placed below the pellet bed. For the gain of melting and slag/metal separation, the hearth productivity, in terms of metallic iron produced, is decreased below that of the RHF DRI process.

The PSHF, by contrast, is a pair of linear-hearth furnaces working in parallel and at a temperature 200 to 250 °C higher than that in a typical RHF DRI process and with a deep (tall) bed of pellets or briquettes. There are four major differences between the PSHF and the RHF DRI processes: (1) the use of multiple-layers of pellets in the PSHF process allows excess gases generated by the devolatilization of the coal to prevent reoxidation of nascent DRI in the adjacent furnace; (2) the high flame temperature results in higher heat-transfer intensity to satisfy the needs of a tall pellet bed operation; (3) the furnace can be operated with a fully oxidized flame leading to higher energy efficiency, a thermodynamic advantage; and (4) the linear design of the hearth allows for discharge of DRI pellets without use of a screw conveyor, which is a major source of maintenance in most RHF designs, and individual pallets can be replaced off-line without interrupting the continuous operation.

The PSHF technology can be combined with an oxy-coal melter at additional capital cost to produce gaseous fuel and high quality hot metal for the benefit of a steelmaking operation, a particularly attractive possibility for EAF shops. With the use of the PSHF technology followed by a melting step, hot metal of very low sulfur and nitrogen contents may be made at low energy intensity. This is partly based on the use of medium to high-volatile non-metallurgical coals that are less expensive than those used in conventional cokemaking. Other PSHF benefits accrue in the area of environmental protection because less CO_2 and other emissions are generated and emitted.

The experimental successes obtained in the laboratory at McMaster University and in a static pilot plant at the Centro Sviluppo Materiali (CSM) Combustion Laboratory in Genoa, Italy (TRP-9810), demonstrated the validity of the thermal-chemical part of the PSHF process in a batch mode. [1] Excellent experimental results were obtained at McMaster University with 6-to-7-kg (13-to-15-lb) batches of dried balls configured in a tall bed in a specially-designed natural-gas-fired furnace. The dry balls had a relatively low coal addition in comparison with those used in RHF practice, and the product DRI had good chemical characteristics (95% degree of metallization) and good physical properties (density greater than that of molten slag for easy melting in a melting or steelmaking furnace). For confirmation of those results on a larger scale, five weeks of trials were conducted in the pilot plant at the CSM Combustion Laboratory with dry balls made from magnetite concentrate, as well as dry balls containing Brazilian hematite ore, BOF sludge, mill scale, and mixtures of BOF sludge and EAF dust. [1]

The CSM experimental results confirmed that the equipment at McMaster University produced meaningful results and also showed that steel plant revert materials can be converted to DRI using the PSHF technology. After the effectiveness of the McMaster facilities was confirmed by the static pilot-plant tests, McMaster designed a series of 15 experiments to characterize the performance of the PSHF process (e.g., productivity, DRI properties, etc.) as functions of three major process parameters: molar carbon-to-oxygen (C/O) ratio in the green balls, coal volatile-matter (VM) content , and processing rate. [1] These experiments were carried out at McMaster

University using the small natural-gas-fired furnace that was used in previous studies. The following key process variables were maintained constant in all of the experiments:

- Dry ball components (magnetite concentrate and bituminous coal);
- Dry ball size range (16 - 19 mm) and bed depth (120 mm);
- Flame temperature (1600 - 1650°C) and oxidation level of gases (fully oxidized);
- Temperature at the top of the crucible (1250°C for 5 minutes, then raised to 1500°C for the duration of the test).

The levels for the variables (factors) that were studied are given below:

- Dry ball molar C/O ratio ï centered at 1.0, with increments of 0.1;
- Coal VM content ï centered at 28.0 percent, with increments of 4.0 percent;
- Processing rate ï centered at 2.0 mm/min, with increments of 0.2 mm/min.

The mathematical model that was developed from the test results was very effective for technology transfer, particularly for selecting a set of process conditions for estimating optimal productivity, product degree of metallization, and fuel consumption. It is quite clear that thermal-chemical activities take place in the vertical direction and should be independent of the size, shape, and movement of the hearth, as established in the bench-scale tests. In this phase of the development of the PSHF process, two important process steps, pelletizing and materials handling, could not be adequately investigated; the laboratory furnace at McMaster University was too small to permit such studies, while the CSM Combustion Laboratory did not have the equipment required for pelletizing and materials handling testing.

Based on the early work at McMaster and CSM, Bricmont prepared a preliminary engineering estimate for the design of a Demonstration Plant for use in further assessment of the PSHF technology. The site that was chosen for the engineering estimate was the INMETCO facility in Ellwood City, Pennsylvania, and detailed estimates were prepared for the construction and operating costs for a 42,000-t/a Demonstration Plant at that site. [6]

The conclusions of the engineering study were as follows:

- It would be possible to build a PSHF Demonstration Plant and operate it on a continuous basis;
- The PSHF process would be expected to have a natural-gas consumption of 4.02 GJ/t (3.45 MMBtu/NT) of DRI. The estimate was based on production of DRI at a 95-percent metallization level.
- The preliminary cost of DRI production at the designated site, using domestic raw materials, was estimated to be about $213.63/t DRI ($193.86/NT) in February 2006, including a cost of $82.67/t ($75/NT) to ship the relatively small amount of magnetite concentrate required for the Demonstration Plant trials from the supplier in Northern Minnesota to the plant site.
- The preliminary cost to engineer, construct, and operate the Demonstration Plant for the planned trial period was estimated to be $16,729,000.
- The off-gas from the Demonstration Plant stack was estimated to contain SO_x at 117 mg/Nm^3 or 3.63 kg/h (8.00 lb/hr) and NO_x at 87 mg/Nm^3 or 2.69 kg/h (5.89 lb/hr). An afterburner would be expected to eliminate any trace amount of CO in the flue gas.

The design and cost estimate for the Demonstration Plant were very preliminary, given the limited resources and time provided under DOE Award DE-FC36-97ID13554, project number TRP-9941. AISI member opt-in companies, DOE, and McMaster University have been investigating this process since the early 2000ôs and have learned many important lessons that could not be fully incorporated into the knowledge base at the time of the preliminary design and cost estimate.

To improve the knowledge base for design of a PSHF Demonstration Plant, additional information on several facets of the process were considered to be necessary. These included better knowledge of process temperatures, emissions, gas evolution rates, reaction kinetics, and heat transfer. Also, although potential methods for discharging the DRI product from the PSHF had been discussed, they had not been tested under industrial conditions.

Therefore, a multi-part program was initiated to address those gaps in knowledge so that a more robust Demonstration Plant design could be developed. The program included the following parts:

1. Large Batch Furnace Tests ï Construction and operation of a stationary batch furnace with a movable/tilting hearth and an active hearth area similar to that anticipated for the pallets that will be used in the Demonstration Plant to gain information regarding emissions of SO_2 and NO_x and to determine the best method to discharge the DRI product.
2. Supplementary Laboratory Tests ï Conducted to obtain additional information required for the Demonstration Plant design through focused laboratory testing. Pelletizing tests were conducted to develop information on the amount and type of binder required to produce strong dry balls that can withstand handling and loading onto the PSHF hearth without generating excessive fines. Additionally, kinetic information on pellet shrinkage during reduction and the rate of gas evolution from coal devolatilization were obtained from tests conducted in a specially constructed laboratory furnace so that a comprehensive system model can be developed at a future date. The effects of variables such as hearth preheat temperature can be evaluated easily in the laboratory furnace.
3. Physical Simulation ï Physical simulation of the PSHF process on a pilot-scale linear hearth furnace (LHF) in a semi-continuous mode that approximates the operation of one half of the PSHF system fired with oxygen-gas burners.
4. Design ï Design of a 50,000-t/a PSHF Demonstration Plant utilizing the preliminary design information from the prior study, along with the results from the Large Batch Furnace Tests, the Supplementary Laboratory Tests, and the Physical Simulation Tests.

Key tasks are described in detail below and in the Appendices to this report.

3.0 LARGE BATCH FURNACE TEST PROGRAM

In order to evaluate discharge methods and emissions from the PSHF, a Large Batch Furnace was designed, fabricated, and tested by Bricmont. The furnace consisted of a stationary combustion hood and a movable/tilting hearth. The combustion hood could be moved slightly to allow movement of the hearth beneath. An oxygen-enriched combustion system was used to provide a chamber temperature in excess of 1480ºC (2700ºF). The furnace hearth could be discharged by three different methods: tilting, scraping, or raking. The furnace was used in a series of fourteen tests using dry balls made from a mixture of high-volatile coal and either magnetite concentrate or BOF sludge (revert material), with a small amount of binder.

3.1 Materials

For the Large Batch Furnace Tests, two iron-bearing materials were used to make pellets: (1) magnetite iron-ore concentrate produced in Northern Minnesota and (2) basic-oxygen-furnace (BOF) sludge obtained from a major steel producer, which was a mixture of 60 percent BOF clarifier sludge and 40 percent BOF classifier sands. The chemical analyses and size distributions of the iron-bearing materials are shown in Table 1. The magnetite concentrate was fine in size, with about 76 percent of the material passing a No. 270 (0.053-mm) sieve. The specific surface area (Blaine Index) of the magnetite concentrate was not determined, but according to the producer it is typically about 1700 cm^2/g (0.17 m^2/g). The BOF sludge was much finer in size than the magnetite concentrate. Although only about 62 percent of the material passed a No. 270 (0.053-mm) sieve, the specific surface area of the material by nitrogen adsorption was about 7 m^2/g, reflecting the extremely fine nature of the clarifier sludge component.

Magnetite concentrates produced from taconites are typically filtered on disc filters to 8 to 10 percent moisture, a level suitable for pelletizing. On the other hand, BOF sludge, as collected at the steel plant, contains too much water for proper pelletizing. As a result, drying tests were conducted to reduce the moisture content of the BOF sludge to a level suitable for pelletizing. In order to gain insight into the drying process, revert materials were dried in a large-batch-scale rotary dryer at Heyl & Patterson. [7] Key conclusions from the testing were as follows:

a. The as-sampled fine BOF sludge (clarifier sludge) will settle to release liquid water when allowed to stand.
b. As-sampled revert materials will ball and smear in a rotary dryer. To avoid this condition, back-feeding of dry material into the dryer in the ratio of 30:50 wet:dry will be required.
c. Roughly 10 percent of the revert material was entrained in the off-gas stream exiting from the rotary dryer.

While the Demonstration Plant will use a drying technology that is different from the rotary dryer used at Heyl & Patterson, the use of back-feeding of dried material to allow proper material handling will be incorporated. Filtering of exhaust from the Demonstration Plant dryer will be required, although the dust loading will be much lower than those observed in the rotary dryer tests.

Either the magnetite concentrate or the partially dried BOF sludge was used along with pulverized coal to make batches of pellets at Mars Mineral in Mars, Pennsylvania. [8] The coal that was used in the tests was pulverized high-volatile coal that was normally used for injection into a blast furnace. The ultimate analysis and size distribution of the coal are shown in Table 2. The pulverized coal was relatively fine in size, with about 63 percent passing a No. 140 (0.106-mm) sieve. Its specific surface area by nitrogen adsorption was 1.03 m^2/g.

Table 1. Chemical Analyses and Size Distributions of Iron-Bearing Materials used in Large Batch Furnace Tests

Chemical Composition, wt. %		
Constituent	**Magnetite Concentrate**	**BOF Sludge***
Fe (total)	68.38	53.35
Fe°	0.46	1.47
FeO	29.96	14.68
MnO	0.20	0.84
SiO_2	4.06	2.56
Al_2O_3	0.16	0.40
CaO	0.39	10.65
MgO	0.62	3.26
TiO_2	0.018	0.065
Na_2O	0.028	0.387
K_2O	0.005	0.250
Cr_2O_3	0.056	0.112
SrO	0.015	0.015
ZrO_2	0.005	0.004
Cu	0.003	0.016
Ni	0.003	0.006
Zn	0.005	3.950
Pb	0.005	0.153
Cl	0.021	0.3
P	0.02	0.040
S	0.01	0.122
C	0.210	1.80
LOI	-	n.d.
CaO/SiO_2	0.10	4.16
Moisture	7.56	27.9*

Particle Size Distribution, wt. % in Given Size Range			
U.S. Std. Sieve Size	**Screen Opening, mm**	**Magnetite Concentrate**	**BOF Sludge***
+10	+1.70	-	1.28
-10+20	-1.70+0.85	0.04	2.08
-20+40	-0.85+0.425	0.15	4.49
-40+70	-0.425+0.212	0.56	
-70+140	-0.212+0.106	1.60	8.65
-140+270	-0.106+0.053	22.08	
-270+500	-0.053+0.025	24.46	6.09
-500	-0.025	51.12	56.09

*60/40 mixture of BOF sludge and BOF classifier sands. (also called reverts)

Table 2. Ultimate Analysis and Size Distribution of Coal used in Large Batch Furnace Tests – Amount of Coal Used at Two Molar C/O Ratios.

Component	wt. %, dry basis
C	76.92
H	5.18
N	1.51
O	8.31
S	0.94
Ash	7.14
Total	100.00

U. S. Std. Sieve Size	Screen Opening, mm	Wt. %
-20+40	-0.85+0.425	0.17
-40+70	-0.425+0.212	8.93
-70+150	-0.212+0.106	28.35
-140+270	-0.106+0.053	22.31
-270+500	-0.053+0.025	10.99
-500	-0.025	29.26

Molar C/O Ratio	g dry coal/100 g dry concentrate
1.0	25.34
0.8	20.27

3.2 Binder Evaluation

Minimizing dust generation during the entire PSHF process is critical to avoid dust interference with reduction inside the PSHF. One key to minimizing dust formation is producing strong, abrasion-resistant pellets. To do so, it is important to use the proper type and amount of pellet binder. Note: earlier tests at CMRL suggested what binders might be used and in what amounts [Appendix A].

Testing of three binders, bentonite, pre-gelatinized cornstarch, and cooked cornstarch, was carried out at Mars Mineral in a small, 400-mm (16-in.) diameter pelletizing disc shown in Figure 2a. Key results of this testing were as follows:

a. When the cooked cornstarch binder was used, very strong pellets were produced, but pelletizing was difficult and the yield of on-size pellets was poor.
b. Pelletizing was improved when drier raw materials were used.
c. When either bentonite or pre-gelatinized cornstarch was used, pellets with adequate strength were produced. In addition, pelletizing was easier and the yield of on-size pellets was higher.

In the Demonstration Plant the pellets will undergo five drops: pelletizing drum to screen, screen to conveyor, conveyor to dryer, dryer to screen, and screen to PSHF. Any of the binders tested will yield pellets that meet the requirement to successfully survive these drops without significant breakage or dusting. Since bentonite is easier to handle, convey, and feed, as compared to the other binders, it was decided to use bentonite as the binder for the pellets that were used in the Large Batch Furnace Tests. Bentonite binder was included at a weight fraction of 2 percent (dry basis).

a. **b.**

Figure 2. Pelletizing Discs at Mars Mineral (not to scale).
a. Smaller test disc (Model P30), 400-mm (16-in.) diameter.
b. Larger production disc (Model D20), 914-mm (36-in.) diameter.

The pellets used in the initial Large Batch Furnace Tests were produced by Mars Mineral in a larger, 914-mm (36-in.) diameter pelletizing disc equipped with water sprays, shown in Figure 2b. A total of 277 kg (610 lb) of on-size green balls was produced, and the green balls were dried at the U. S. Steel Research and Technology Center in Munhall, Pennsylvania. The properties of the wet green balls and dried balls are shown in Table 3.

Table 3. Properties of Pellets Made at Mars Mineral.

	Mars Mineral Pellet Disc	
Property	**Small Disc (P30)**	**Large Disk (D20)**
Average Diameter, in.	0.68	0.69
Moisture, %	10.3	9.8
Avg. green ball weight, g	6.9	7.0
Wet Drop Strength*		
18-inch	19.8	20.0
36-inch	13.4	12.4
Dry compression, lb.	9.6	14.1

* Average number of drops from the given height required to break green balls.

3.3 Procedures for Green Ball Production and Green Ball Quality Testing

3.3.1 Pellet Production

Pellets for the Large Batch Furnace Tests were produced at either Mars Mineral (August 16 ï October 4, 2012) or at the U. S. Steel Research and Technology Center (October 24, 2012 ï

December 5, 2013). All pellets had a nominal size distribution of minus-19.0-plus-16.0 mm (-3/4+5/8 in.) and all were dried at the U. S. Steel Research and Technology Center. All were made with bentonite as the binder. Pellet chemical composition and pellet strength by size fraction are shown in Table 4.

The coal addition to the iron oxide source was varied slightly during the final tests, but was generally set for a molar carbon-to-oxygen ratio of 1.0, including the carbon contained in the coal volatile matter. A charge weight of 60 kg (133 lb) resulted in a bed depth of 120 to 140 mm (5 to 5.5 in.), about eight pellet layers, while a charge weight of 45 kg (100 lb) resulted in a bed depth of 90 to 100 mm (3.5 ï to 4 in.) or five to six pellet layers. From test to test the bed depth varied to a lesser or greater extent across the hearth, depending on how well the charge was leveled after it was placed on the hearth.

3.3.2 Pellet Quality

Table 4. Composition and Strength of Pellets Used in Initial Large Batch Furnace Tests

	Wt. %, dry basis		
Parameter	**+19.0 mm (+3/4 in.)**	**-19.0+12.5 mm (-3/4+1/2 in.)**	**Pellets Used in Large Batch Furnace Tests 2 and3**
Chemical Composition, % dry basis			
Fe	58.92	58.68	58.10
FeO	21.46	21.28	21.84
MnO	0.13	0.14	0.13
SiO_2	4.71	4.73	4.67
Al_2O_3	0.76	0.74	0.78
CaO	0.33	0.30	0.31
MgO	0.11	0.10	0.10
TiO_2	0.03	0.06	0.07
Cr_2O_3	0.16	0.19	0.16
Na_2O	<0.10	<0.10	<0.10
K_2O	0.02	0.02	0.025
P	<0.01	<0.01	<0.01
S	0.222	0.122	0.132
C	14.44	13.56	13.55
Pellet Strength			
Dry compression, lb.	5.51	6.58	9.75
Dry Drop Strength*			
12-inch	3.1	3.5	4.6
18-inch	2.1	2.4	2.5
30-inch	1.0	1.4	1.2

* Average number of drops from the given height required to break dry balls.

3.4 Large Batch Furnace Development and Testing

3.4.1 Early Tests – Large Batch Furnace (Version 1)

Starting in December 2011, several preliminary tests were run to develop an operating procedure for the Large Batch Furnace. The initial version of the Large Batch Furnace (Version 1) was designed and constructed with the stationary combustion hood of the system raised vertically with a system of chain-falls, as shown in Figure 3. The burner was operated with a gas-air mixture and air preheated by the chamber exhaust in a heat exchanger was also used. The hearth size was designed to simulate the anticipated Demonstration Plant hearth dimensions of 1-m-wide by 0.6-m-long (3-ft-wide by 2-ft-long). The single burner was installed to fire over the long dimension of the hearth opposite the exhaust port. The burner that was selected was expected to have a flame length that would be within the length of the chamber.

In the initial tests difficulties were encountered in five areas: (1) the burner response was too slow and an excessive amount of time was required to reach the desired furnace temperature; (2) the maximum air preheat temperature was 320°C (600°F), well below the desired preheat temperature of 425°C (800°F); (3) while designed to industry standards, the exhaust duct may have been too small in cross-sectional area to permit the free flow of hot gases from the chamber, resulting in internal recirculation; (4) oxidation and melting of part of the pellet bed occurred during testing, as shown in Figures 4, 5, and 6; and (5) the mechanism for raising and lowering the upper furnace box was problematic and ultimately failed. Therefore, modifications were made to the furnace to counter these difficulties.

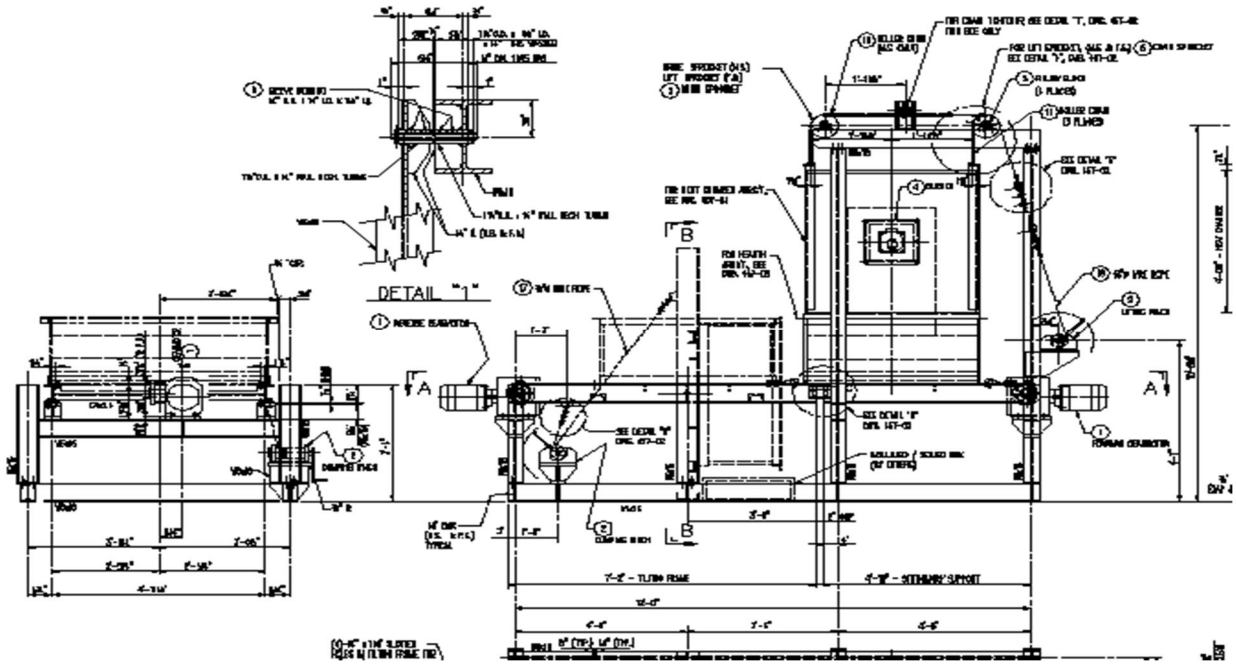
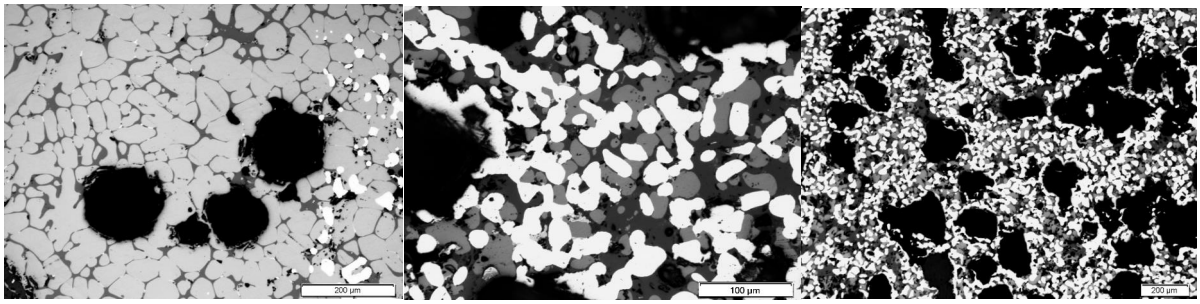


Figure 3. Illustration of Version 1 of Large Batch Furnace with lifting of entire furnace chamber by dual chain-fall system.

Figure 4. Appearance of reduced pellets after test in Large Batch Furnace, Version 1. (Note melted area on reduced pellet surface on lower left corner of pallet.)

Figure 5. Cluster of pellets from early Large Batch Furnace Test with overheating/reoxidation of pellet surface.



a. **b.** **c.**

Figure 6. Photomicrographs of partially metallized pellets from early Large Batch Furnace Test. (white = metallic Fe, light gray = wustite/iron oxides, dark gray = slag, black = pores)
a. Oxidation-melting near surface of partially metallized pellet.
b. Partial metallization within pellet.
c. Initial metallization occurring throughout pellet.
(Note large porosity in 6c. resulting from consumption of coal particles).

3.4.2 Modifications to the Large Batch Furnace

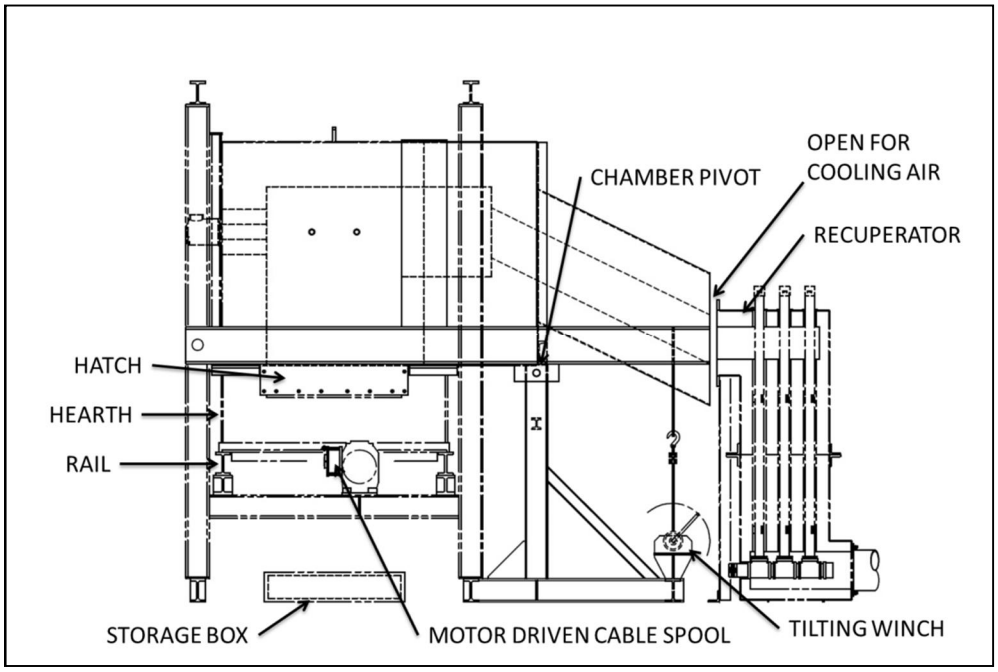
The Large Batch Furnace design went through several changes before reaching a workable state. These changes included:

a. Changing the combustion-chamber lift mechanism from a chain-fall to a tilting mechanism,
b. Adding the capability for oxygen enrichment of the combustion air to increase flame temperature and achieve desired operating temperatures more rapidly,
c. Reducing the active hearth dimensions to 0.6-m-by-0.6-m (2-ft-by-2-ft) to minimize the temperature decrease associated with adding the cold charge of green pellets,
d. Abandoning auxiliary air wickets,
e. Abandoning computer control of furnace and combustion-air temperatures in favor of manual control,
f. Increasing the diameter of the exhaust flue to minimize recirculation of gases onto the pellet bed,
g. Recessing the burner into the refractory to allow longer flame expansion, and
h. Installing dust and fume collection, initially a single sock, and subsequently a-bag house to capture the zinc oxide fume emitted during processing of green balls containing revert material.

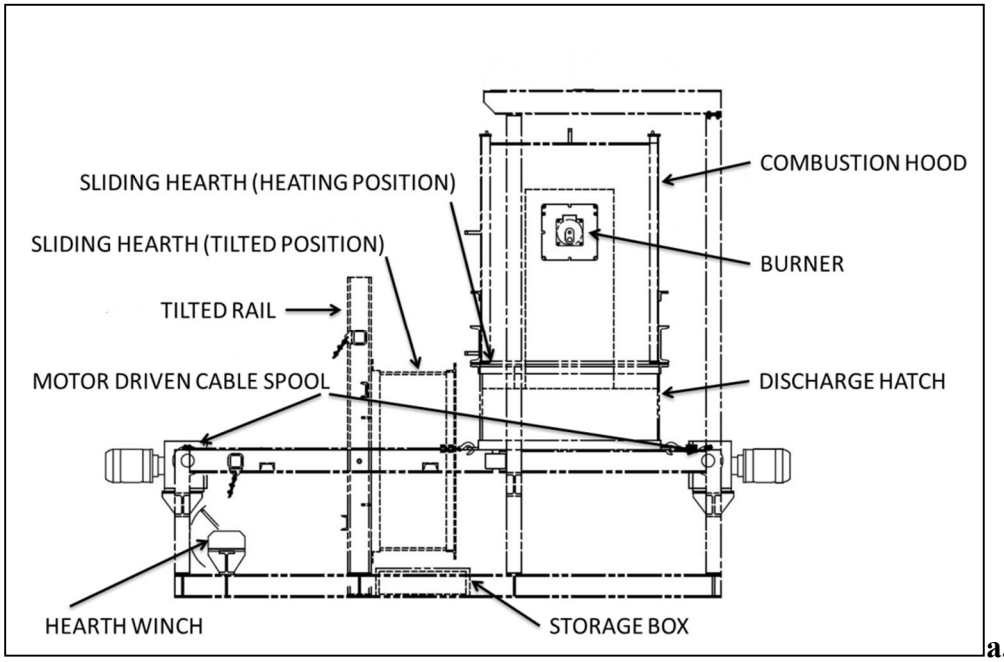
3.4.3 Large Batch Furnace Design (Version 2)

The Large Batch Furnace (Version 2) consisted of two primary components: a stationary combustion hood and a sliding hearth, as shown in Figures 7a and 7b. The combustion hood was made so that it could tilt slightly by means of a winch to relieve the load on the hearth so the hearth could slide out for loading and discharging. The hearth was made so that one side could be removed to allow the reduced pellets to be discharged by raking (pulling) or scraping (pushing) the pellets from the hearth or by gravity by tilting the hearth. The general Large Batch Furnace specifications are shown in Table 5.

An as-built view of the Version 2 furnace is shown in Figure 8. The burner (Figure 9a) was installed on the right end of the furnace. The blower that provided air to the burner is shown in Figure 9b. A recuperator was provided to preheat combustion air for the burner. It was located to the left of the furnace, after the down-angled furnace exhaust, as shown in Figure 8. Exhaust gas from the recuperator was mixed with ambient air to cool it. It was then exhausted through an induced draft fan (Figure 10a) when pellets made from magnetite concentrate were being processed. When pellets made from revert material were being processed, the cooled off gas was instead sent through a bag house, discussed later, to capture the zinc-oxide fume that resulted from the zinc contained in the revert pellets. The hearth was moved on rails using a motorized winch and cable (Figure 10b). The gas cylinders that were used to provide oxygen for the oxygen-gas burner are visible in Figure 10a.



a.



a.

b.

Figure 7. Illustration of Version 2 of Large Batch Furnace Schematic Drawing with tilting of furnace chamber with cable and manual winch.
a. Rear elevation – Burner is on left end of furnace, exhaust duct and recuperator are on right.
b. Right-side elevation – Hearth winch is used to slide hearth to left on rails.

Table 5. Large Batch Furnace Specifications (After Modifications)

Active hearth dimensions	610 mm x 610 mm (24 in. x 24 in.)
Active hearth area	0.37 m^2 (4.0 ft^2)
Operating temperature	1500°C (2730°F)
Burner capacity	234,500 W (800,000 Btu/hr.)
Oxygen content of oxygen-enriched air	31% by volume
Maximum charge weight	60.3 kg (133 lb)
Achieved charge weight	45.4 kg (100 lb)
Insulation in the furnace hood	Maftec Fiber Modules [1650°C (3000°F) service temperature]
Refractory in the hearth base hot face	Rescocast 17AC [95% alumina, 1870°C (3400°F) service temperature]
Refractory in the hearth sides	Rescocast 8 [46% alumina, 1540°C (2800°F) service temperature]

Figure 8: Large Batch Furnace – Front view (burner located on end of furnace at right).

a. **b.**

Figure 9. Burner equipment on Large Batch Furnace.
a. Burner assembly (air-gas and oxygen-gas firing).
b. Blower for burner.

a. **b.**

Figure 10. Auxiliary equipment on Large Batch Furnace.
a. Exhaust fan (furnace gas later exhausted through bag house).
b. Motor driven spool and cable for moving the hearth.

3.4.4 Combustion System

The combustion system utilized a Bloom Engineering S-1360-030 Uni-Heat burner with spark ignition. This burner had a rated input of 844 MJ/h (800,000 Btu/hr). The burner could be fired with air (20.9% oxygen) or with air enriched with oxygen up to a level of 34.0 percent. The observed flame length when operating with air enriched to 34 percent oxygen was roughly 450 mm (18 in.).

Oxygen was supplied for use in the burner from a bank of cylinders, through a metering orifice and control valve, and then it was mixed with preheated air and entered the burner. Combustion air was supplied by a Bush Martec blower with a rated capacity of 7.08 m^3/min at 12.5 kPa [250 cfm at 50.0 in. of water column (in. WC)]. The temperature of the preheated combustion air ranged from 230 to 260°C (450 to 500°F).

The products of combustion were tempered with ambient air to protect the recuperator. After heat was transferred from the tempered off gas to the combustion air in the recuperator, the temperature of the off gas was further tempered with ambient air provided via a dilution air valve to protect the exhaust fan. The Bush Martec exhaust fan had a rated capacity of 66.2 m^3/min (2338 cfm) at 149°C (300°F) and 3.2 kPa (13 in. WC). A variable frequency drive on the exhaust fan allowed the furnace chamber pressure to be controlled; higher speeds drew more exhaust gas, thereby lowering the furnace pressure, while lower speeds had the opposite effect.

3.4.5 Control System

The furnace was controlled with an Allen Bradley SLC500 PLC-based system with a PC-based human machine interface (HMI). The HMI also served as a data logger. A view of the monitoring screen is shown in Figure 11. Air, fuel, and oxygen-flow data were collected, as were furnace-chamber and combustion-air temperature data.

Air, fuel, and oxygen flow rates to the furnace were automatically controlled to a set point provided by the operator. Combustion-air flow rates were compensated for temperature. Temperature control was achieved by manually adjusting the flow rates; increasing the natural-gas flow rate increased the furnace temperature, while decreasing the natural-gas flow rate had the opposite effect. Air and oxygen flow rates were varied in proportion to the natural-gas flow rate. No attempt was made to increase the air flow rate to the furnace to burn the combustible off gas that was generated from the pellets. Instead, the off gas burned once it was mixed with tempering air in the exhaust system.

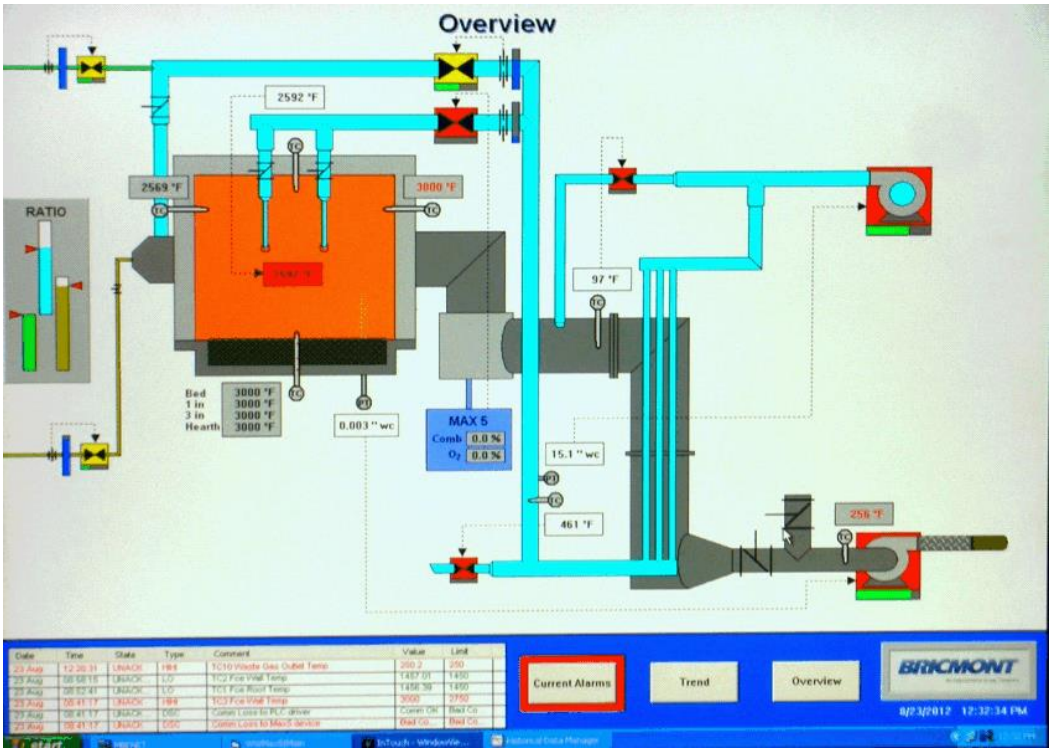


Figure 11. View of the monitoring screen for the Large Batch Furnace installation.

3.4.6 Operating Procedure

In order to gage the temperature of the pellets in the bed, a thermocouple was inserted through a hole in the hearth and then up into the pellet layers. Typically the thermocouple was first inserted 38 mm (1.5 in.) up into the pellets. Then, once 1150ºC (2100ºF) was achieved at that level, the thermocouple was retracted to be even with the hearth (bottom of the pellet bed). Originally, a multiple-junction thermocouple assembly was planned to be used to measure temperatures throughout the height of the pellet bed. Unfortunately, due to its high mass, this assembly proved to be too slow to respond adequately to changes in pellet temperature. The assembly was also difficult to maintain.

The general operating sequence for the furnace was as follows:

a. The combustion hood sealed over the sliding hearth, and the furnace was preheated to 1482ºC (2700ºF).
b. The combustion hood was tilted away from the sliding hearth using the tilting winch.
c. The sliding hearth was pulled to the charge/discharge position using a motor-driven cable spool.
d. The pellet charge was poured onto the hearth from buckets and the pellet bed was leveled (Figures 12a and 12b).
e. The hearth was moved back to the charge position using a second motor-driven cable spool.

f. The combustion hood was released from the tilted position so that it rested on the sliding hearth.
g. The pellets were heated to 1480 to 1500°C (2700 to 2730°F) for roughly 80 minutes or until a thermocouple inserted through the hearth registered 1150ºC (2100ºF).
h. The combustion hood was tilted away from the hearth.
i. The hatch was removed from the back of the hearth.
j. The sliding hearth was pulled to the discharge position using the motor-driven cable spool.
k. The reduced pellets were discharged into the waiting storage box by one of two methods:
k-1 ï Manual discharge by pushing the reduced pellets from the hearth with a hoe (Figures 13a and 13 b) or
k-2 ï Gravity discharge by bolting the hearth to the rail and releasing the hearth winch so that the rail and hearth pivot toward the storage box, thereby releasing the reduced pellets (Figures 14a, 14b, and 14c).
l. The storage-box lid was closed and the box was purged with nitrogen provided from a cylinder.

a. **b.**

Figure 12. Charging the hearth of the Large Batch Furnace.
a. Dumping dried pellets into the hearth from a basket.
b. Leveling the pellet charge with a hoe.

a. b.

Figure 13. Discharging DRI pellets from the hearth of the Large Batch Furnace.
a. Pushing DRI pellets off the hearth with a hoe.
b. Pellets in quench box located below the furnace prior to being covered.

a. b. c.

Figure 14. Discharging DRI pellets by tilting the hearth of the Large Batch Furnace.
a. Hearth with hot DRI pellets (note: bed has shrunk from its original level).
b. Example of unsuccessful discharge test performed with hearth at 60° from vertical; no pellets were discharged from the hearth.
c. Example of successful discharge test; note that hearth is empty.

3.5 Large Batch Furnace Testing

3.5.1 Test Program

A total of fourteen Large Batch Furnace Tests were performed. One of the revert-pellet discharge tests was aborted due to the presence of visible emissions in the furnace area. One test, performed using pellets made from magnetite concentrate, was dedicated to emissions measurements. The remaining tests were performed to evaluate DRI product discharge methods, eight with pellets made from magnetite concentrate and four with pellets made from revert material. Key parameters for the tests are summarized in Table 6.

Table 6. Large-Batch Furnace Tests Conditions and Observations

Test	Date	Pellet Iron-Oxide Source	Weight, lb.	Time, min	Process Temp., °F	Discharge	
						Type	Observations
1	8/16/2012	Magnetite concentrate	133	80	2540	Push	Easy discharge
2	8/23/2012	Magnetite concentrate	133	85+	2750	Push	Easy discharge
3	8/24/2012	Magnetite concentrate	100	80	2750	Push	Easy discharge
4	9/5/2012	Magnetite concentrate	100		2750	N/A	Dedicated emissions test
5	9/12/2012	Magnetite concentrate	100	70	2750	Push	Easy discharge
6	9/13/2012	Magnetite concentrate	100	50	2750	Tilt	Easy at 45°
7	9/20/2012	Magnetite concentrate	100	130	2550	Tilt	Stuck at 90°
8	9/25/2012	Revert	100	75	2750	Push	Stuck to hearth
9	9/26/2012	Magnetite concentrate	100	65	2750	Tilt	Easy at 90°
10	10/4/2012	Magnetite concentrate	100	70	2750	Tilt	Discharged at 90° after tapping with hoe
	10/24/2012	Revert	100		2750	Push	Test aborted due to visible fume
11	12/19/2012	Revert	100	90	2750	Push	Fused to hearth (Air Compliance Test)
12	2/19/2013	Revert	100	63	2750	Push	Easy discharge
13	12/5/2013	Revert	100	79	2750	Tilt	Discharged at 90° with much assist with hoe

3.5.2 DRI Product Discharge Methods

Three potential methods were considered for discharging the product DRI from the hearth: mechanically raking (pulling) or scraping (pushing) the reduced mass from the hearth or tilting the hearth to discharge the product by gravity. During the Large Batch Furnace Test program, due to space constraints raking and scraping were simulated in a single manner, by pushing the reduced mass with a hoe towards the back or open end of the hearth. Tilting was accomplished by rotating the hearth from a horizontal position to a vertical position. The discharge method investigated in each test is indicated in Table 6.

There was significant variability from test to test in the ease with which the DRI pellets could be discharged. Product discharge was accomplished easily in seven of the twelve discharge tests, while in five of the tests product discharge was difficult. In the tests in which discharge was difficult, the DRI pellets were either fused to the hearth or they were extremely difficult to discharge due to sticking and clustering. Generally, if the pellets in the bottom layer were unreduced or at least unsintered, it was easier to discharge the pellets. There was no clear cause of this variation in the state of the bottom layer in the tests that were conducted.

Of the five tilting discharge tests, the reduced product in three of the tests did not discharge even after the hearth was tilted to the fully vertical position. It should be noted that if a tilting discharge system were to be used in a Demonstration Plant, it would cause the pallet refractory material to experience 18 daily cycles of tension stress. Refractory material generally does not accommodate tension stresses, so a tilting discharge will have a negative impact on refractory life. For this reason, it was suggested that the tilting discharge method not be used in the Demonstration Plant design.

The forces required to discharge the DRI product using raking or scraping are the same; they are just applied in opposite directions. Scraping will put the refractory material in compression against the edge stop of the pallet, but the refractory material can accommodate compression loading quite well. Scraping discharge will also have the advantage of mechanical simplicity, a critical point considering the high temperature environment during discharge. Scraping will assure that the pellets are actually removed, preventing the charging of fresh pellets on top of any reduced pellets that might remain fused to the pallet (double-charging). Unfortunately, if reduced pellets are fused to the hearth and removed by scraping, some of the hearth refractory may be removed as well. However, this is considered to be preferable to the issues associated with double-charging. In the Demonstration Plant, the scraping process will be driven by hydraulics, and so it will be able to apply a discharge force that is significantly greater than the force of gravity, the maximum force available for the tilting discharge method. This means that use of the scraping method will assure that the reduced pellets will be reliably discharged from the hearth.

3.5.3 Furnace Emissions

Emissions from the Large Batch Furnace were measured using a Testo Model 340 gas analyzer. This is a chemical-cell-type analyzer that uses separate cells for the measurement of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and oxygen (O_2). The NO_x measurements are expressed in terms of total nitrogen oxides. The emission results were highly variable from test to test as shown in Table 7.

Table 7. Large-Batch Furnace Emission Data

Date	Time	Concentration, ppm by volume			
		SO_2	NO_x	O_2	CO
9/5/2012	14:25	0	57	13.3	OL*
9/12/2012	13:26	128	29	2.0	1221
9/12/2012	13:55	0	217	1.4	38
9/13/2012	13:18	236	22	4.6	2614
9/13/2012	13:53	0	432	1.3	2927
9/20/2012	14:27	168	3	0.3	1908
9/26/2012	13:24	60	70	9.9	249
9/26/2012	14:02	75	29	27.0	5905

* Over limit of testing device.

During the emission test that was performed on September 5, 2012, the furnace burner was operated with air only; the natural gas was turned off and no oxygen enrichment was used. Its purpose was to show the NO_x level that would be expected from burning only the combustible off-gas from the pellets. The results of that test showed that the NO_x emissions from that source were low. This was as expected; the combustibles were too dilute to result in a high flame temperature and therefore their combustion produced little NO_x.

During the test with pellets containing revert materials that occurred on September 25, 2012, the gas analyzer became plugged with fine fume from the furnace off gas, thereby making the emissions results suspect, especially the oxygen values. As a result, the emission data from that test were not reported here.

3.5.3.1 SO_x Emissions

The primary source of the SO_x emissions was from the oxidation of sulfur contained in the coal that was present in the pellets. The sulfur content of the coal was about 0.85 percent (dry basis), so the total amount of sulfur contained in a 45-kg (100-lb) batch of pellets used in a Large Batch Furnace Test was about 0.072 kg (0.16 lb) (100 lb pellets/batch x 0.19 lb coal/lb pellets x 0.0085 lb S/lb coal). If the sulfur contained in the coal were completely converted to SO_2, the average concentration in the Large Batch Furnace exhaust gas would be roughly 90 ppm by volume. The test data reached as high as 236 ppm early in the process and then fell to as low as 0 ppm late in the process. This suggested that the sulfur exited the pellets early in the process, when volatile matter was being driven off from the coal. The PSHF process is a continuous one, and the sulfur will be emitted continuously on an averaged basis rather than as a function of time, as was the case in the Large Batch Furnace testing, which was a batch process.

3.5.3.2 NO_x and CO Emissions

Generally NO_x emissions result from the reaction of very small amounts of nitrogen with oxygen during combustion. The nitrogen usually comes from the air used for combustion. Higher

combustion temperatures result in higher rates of NO_x formation. As a result, NO_x generation rates depend on a number of factors, including the ratio of fuel to air, the mixing of fuel and air, the type of fuel, the extent of air preheating, and the extent of oxygen enrichment. Generally, operating under fuel-rich conditions results in low combustion temperatures and low NO_x emissions. Fuel-rich combustion is also characterized by high levels of CO emissions. Thus, the general correlation between high CO and low NO_x concentrations found in the data obtained in the Large Batch Furnace emission tests is not surprising, notwithstanding the unexpected results obtained in the second emission test performed on September 13, 2012 (high NO_x and high CO). Although these results are believed to be outliers, they are included here for the sake of completeness.

For the continuous Demonstration Plant operation, it will generally be the case that the furnace is operated very slightly fuel-rich. In this case, fuel-rich refers to the combination of both burner fuel and combustible CO from the reduction reaction. A fuel-rich operation will have the advantage of limiting reoxidation of the product DRI. It will also have the benefit of keeping NO_x emissions low. Based on the above data, NO_x concentrations of roughly 30 ppm by volume are expected from the Demonstration Plant.

Although CO emissions are considered to be hazardous, they can be easily measured and dealt with. Post-combustion of the PSHF off gas will decrease CO emissions to levels of 30 ppm by volume or less. In addition, since post-combustion results in relatively low combustion temperatures, it will not cause a significant increase in NO_x generation.

3.5.3.3 Particulate Emissions

There was no practical way to measure particulate emissions from the Large Batch Furnace. As a result, judgments regarding expected particulate emissions from the proposed PSHF Demonstration Plant were expected to be developed from knowledge of emissions from similar processes and the known efficiencies of particulate emission control devices. When pellets containing magnetite concentrate were processed in the Large Batch Furnace there were no visible emissions from the stack. However, when pellets containing revert material were tested, it was possible to see emissions that were white in color exiting the stack. These emissions were suspected to be fine zinc oxide fume. The revert material contained zinc oxide, about 3.7 percent by weight on a dry basis. During the reduction process, the zinc oxide was reduced to metallic zinc, heated past its boiling point of 907ºC (1665ºF), and entered the exhaust gas stream. The zinc vapor was subsequently oxidized to form the fine zinc oxide fume that was observed. Due to industrial hygiene concerns, the decision was made to delay further testing of pellets containing revert material until a bag house was procured and installed to capture the zinc oxide fume.

The bag house that was installed was a Torit brand (Model 1158501) with cotton-sateen, flame-resistant rectangular bags. The filter area was 900 ft^2 (83.6 m^2), which gave a nominal air-to-cloth ratio of 2 acfm/ft^2 (0.61 $m^3/min \cdot m^2$). The bag house is shown in Figure 15.

Figure 15. Bag house installed at Large Batch Furnace facility.

After the bag house was installed, additional tests were performed with pellets containing revert material. Although the visible emissions were significantly decreased, some white fume was still visible. While the nominal air-to-cloth ratio was considered to be adequate, the effective air-to-cloth ratio proved to be much smaller. This was due to an insert that fit inside the bag to keep it from collapsing. The insert was made from a material that was similar to steel wool, and as a result the insert created a significant increase in pressure drop. The increase in pressure drop caused the area near the bottom of the filter bags to be effectively unavailable for filtering. The result was that some of the fume was not captured by the filter bags, as shown in Figure 16.

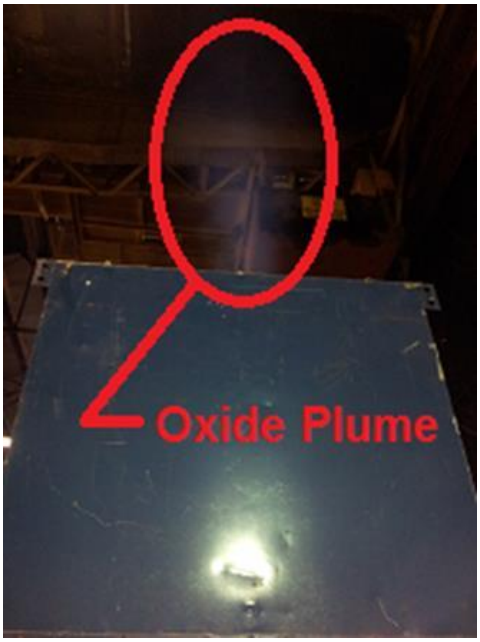


Figure 16. Zinc oxide fume exiting the bag house.

The presence of the fume continued to be an industrial hygiene concern, and arrangements were made to test the ambient air quality in the Large Batch Furnace area when pellets containing revert material were being processed to determine if the fume did indeed pose an industrial hygiene risk. The results of that testing showed that the concentration of zinc oxide in the building ambient air was below regulatory limits.[9] The testing also detected low concentrations of lead in the ambient air, presumably from the reduction of the small amount of lead contained in the pellets made from revert material. The measured lead concentration levels were below regulatory threshold limits at ground level, but not always at higher elevations in the building. [9] Although the pellets were not heated past the boiling point of lead, it was found that lead can indeed volatilize below its boiling point. As a result, the recommendation was made that proper respirators should be worn by anyone present during the few remaining Large Batch Furnace Tests employing pellets made with revert material.

A metals reclamation facility that is located near Pittsburgh, Pennsylvania, faces the same emissions challenge, effective capture of fine zinc oxide and lead oxide fume. The bag house at this facility utilizes regular Nomex bags with a true air-to-cloth ratio below 2.0 acfm/ft^2, and the exhaust gas exiting the bag house successfully meets all regulatory limits. Two practices are employed to assure high fine-particulate capture efficiency: coating of the bags with polytetrafluoroethylene (PTFE), followed by preloading of the coated bags. The PTFE-coated bags improve capture efficiency and ease of cleaning due to the low coefficient of friction of the coating. However, preloading of a new set of filter bags is considered to be critical to assuring high-efficiency filtering of the fine fume. In preloading, a benign substance, usually fine limestone, is used to generate a filter-cake layer on the bags that acts to capture fine particulates that might otherwise pass through new, clean filter bags. Since this approach has been used successfully at the above plant, it is expected it will work at the Demonstration Plant as well.

3.5.4 Productivity

Quantifying the effect of furnace heating rate on reaction rates and hearth productivity was not part of the original scope of this phase of the project. However, significant insight into the process productivity was gained when it was noted that the pellets reacted more slowly in the Large Batch Furnace than they had in the furnaces at either McMaster University or the CSM Combustion Laboratory. [1] With an 8-layer bed of pellets, about 120 to 140 mm (4.7 to 5.5 in.) in height, it was found that after 80 minutes residence time in the Large Batch Furnace, the bottom pellet layers were unreacted, even though a reaction time of 80 minutes provided fully reduced pellets in the tests at the above-mentioned facilities.

Many potential causes of this difference can be proposed. It was considered that the bottom layers were blocked from receiving furnace heat because the upper layers of pellets were not shrinking as they had previously. This was unlikely to be the sole reason, because the bottom pellets are heated almost exclusively by radiation from the top pellets with only a small portion of the heat penetrating the mass through conduction. This is true regardless of the amount of shrinkage of the upper pellets. The upper layers of pellets block almost all furnace radiation from reaching the bottom pellets directly. Excessive fines were also proposed as a reason for blocking the heat transfer; however, very few fines were seen in the discharged pellets. It now seems likely that the slower reaction rates observed in the Large Batch Furnace Tests were a

result of the hearth refractory having a lower than required heat storage capacity relative to the mass of pellets that was charged to the hearth. Even when the Large Batch Furnace hearth was preheated to temperatures that were above those that are likely to be achieved in a full-scale PSHF, the heat stored in the hearth was not adequate to sufficiently preheat the bottom of the charged pellet mass.

When the charged pellet mass was decreased from 60.3 to 45.4 kg (133 to 100 lb), it was found that the bottom pellets reduced in about 80 minutes, as was found in the tests performed at both McMaster University and the CSM Combustion Laboratory. Decreasing the height of the pellet bed from 8 pellet layers high [120 to 140 mm (4.7 to 5.5 in.)] to 5-to-6 pellet layers high [90 to 100 mm (3.5 to 4 in.)] was sufficient to allow the heat from the top of the pellet bed to penetrate down to the bottom pellets so that the reduction reaction could be completed. The Demonstration Plant will be designed based on this decreased bed height. Since the lower bed height decreases the specific hearth productivity from 121 to 91 kg/m^2·h (25 to 19 lb/ft^2·hr), the hearth area of the PSHF in the Demonstration Plant will be increased to compensate for the decreased specific productivity.

4.0 SUPPLEMENTARY LABORATORY TEST WORK

4.1 Investigation of Material Handling

The equipment and conditions required for the continuous production of composite iron-oxide/coal pellets that are of sufficient quality for use in the PSHF Demonstration Plant are quite different from those used to produce the pellets used in the laboratory furnace tests that were performed in this and previous studies. The Coleraine Minerals Research Laboratory (CMRL) of the Natural Resources Research Institute (NRRI), University of Minnesota Duluth (UMD), an organization that has extensive experience with the design of commercial pelletizing and materials handling circuits, was engaged to develop the conditions required for the commercial production of dry pellets having sufficient quality for charging to a PSHF from the required mixtures of iron oxide (iron ore or revert material) and coal.

CMRL conducted a six-month pelletizing and pellet handling study to determine the operating conditions required (i.e., required moisture content, type and amount of binder required, etc.) to produce pellets from the planned iron-oxide/coal mixtures and to characterize the strength and handling characteristics of the pellets in both the wet (green) and dry state (Appendix A). The test program was guided by input from McMaster University and the industrial participants.

The CMRL tests were also designed to establish a method to charge a tall bed, nominally 120 mm (4.7 in.) in height, of dried or partially dried iron-oxide/coal pellets to a moving hearth with minimum pellet breakage in an effective, stable, and economical manner.

The CMRL tests produced pellets with characteristics more closely similar to commercially produced pellets and evaluated pellet handling under conditions closer to those expected in a commercial facility. These tests helped to define a maximum allowable height from which the pellets could be dropped through an automated charging device onto a moving belt or onto a

moving hearth outfitted with retaining walls. The pelletizing disc used at CMRL to produce batches of green balls for subsequent drying is shown in Figure 17a, while the CMRL pellet-loading simulator is shown in Figures 17b.

a. **b.**

Figure 17. PSHF pellet making and charging simulator undergoing calibration at CMRL.
a. Pellet disc, 914-mm (36-in.) diameter, during making of pellets for simulation of charging.
b. Charging simulator with moving hearth and expected drop height.

4.2 Kinetic Study

A two-part program was conducted at the Coleraine Minerals Research Laboratory (CMRL) to further study the kinetics of the reactions that occur in the PSHF process. For the studies CMRL constructed a two-zone, electrically-heated box furnace that could accept a crucible of up to 120 mm (4.7 in.) in height (Appendix B). In the PSHF process, the iron-oxide/coal pellets are heated first to 1200°C (1290°F) for a short time and then to about 1500°C (2730°F) for a period of forty minutes or more, depending upon the depth of the pellet bed. The CMRL furnace was designed to accommodate the PSHF heating pattern; it had two heated zones in which the retention times could be varied (Figure 18).

The pellets used in the studies were sized to minus-19.0-plus-16.0 mm (-3/4+5/8 in.). They were made from fine magnetite concentrate, obtained from a taconite mining and processing operation in Northern Minnesota, with an addition of about 20 percent by weight of a finely ground high-volatile coal. Conventional batch-balling methods were used to produce the green pellets, with either cooked starch or bentonite clay being used as binder. Dried pellets were placed in insulated crucibles (Figure 18) prior to being placed in the furnace. The insulated crucibles were made by inserting a fused-magnesium-oxide cylindrical tube, 100 mm (4 in.) in inside diameter and about 120 mm (4.7 in.) long, into a block of insulating firebrick through which a hole had been made to accept the ceramic tube. The firebrick block was of the same height as the ceramic tube, was 200-mm wide by 230-mm long (8 in. by 9 in.), and had a piece of wire-mesh screen attached to its bottom face to act as a retainer for the dried pellets. Insulated crucibles were used

in an attempt to limit heat transfer into the pellet bed to the top-down direction, so that the reduction reactions in the pellet bed proceeded in that direction only, as would be the case in the PSHF process (Figure 18).

Figure 18. Two-zone, electrically heated laboratory furnace and insulated crucible used in tests for measuring kinetic factors.

Tests were conducted in two phases. In Phase I, the effect of furnace temperature on reaction kinetics was investigated. Bottom temperature was high, up to 1500°C, because the crucible was moved over the preheated furnace bottom in the high-temperature zone. In Phase II, the effect of more controlled bottom heating was investigated by placing the insulated crucible on a preheated sliding refractory plate rather than on the furnace bottom. Pellets were tested at temperatures ranging from 1200 to 1500°C (2190 to 2730°F), and the bed of reduced pellets was analyzed after separating it into five layers. Samples were photographed from the top both before and after reaction, and the vertical shrinkage of the sample bed was recorded. The total iron (Fe_T), metallic iron (Fe°), ferrous iron (Fe^{++}), carbon (C), and sulfur (S) contents of the pellets in each of the five layers were determined. The apparent density of the pellets and the extent of pellet shrinkage were determined by ArcelorMittal Global R&D, East Chicago, Indiana.

The experiments demonstrated that high metallization levels of 90 percent and production rates of over one kilogram per square meter per minute are possible, depending upon the proper combination of furnace temperature, residence time, and the extent to which heat can be transferred into the bottom of the pellet bed from the refractory hearth. The experiments provided quantitative information that can be used to develop a kinetic model that can be used to describe the pellet reduction and shrinkage, heat transfer, and gas evolution to aid in PSHF process scale-up and in the development of a computational fluid dynamics (CFD model of the process. Although this testing was limited to evaluation of dried pellets containing magnetite concentrate, consideration should be given to additional work with pellets produced from revert material.

5.0 PHYSICAL SIMULATION – LINEAR HEARTH FURNACE AT CMRL

To confirm the successful results reported for tests intended to simulate the deep-bed PSHF process in a batch mode, first on a smaller scale at McMaster University, later on a larger scale by the CSM Combustion Laboratory, and confirmed in more detailed smaller scale studies completed by CMRL in the current phase of the PSHF project, validation studies and testing were performed at CMRL on a small, pilot-scale linear-hearth furnace (LHF). The CMRL LHF is a 12.2-m-long by 0.6-m-wide (40-ft-long by 2-ft-wide) pusher furnace that has moving pallets capable of carrying beds of pellets up to about 130 mm (5.1 in.) deep that was designed for the development of an iron-oxide reduction, melting, and solidification process. [10] The LHF contains three individual heating zones and a final cooling section (Figure 19). The LHF can accommodate pellet bed depths and hearth pallets of the size that were used in early PSHF batch tests that took place in a static batch furnace located at the CSM Combustion Laboratory. The CSM furnace was fired with oxygen-gas burners and was capable of reaching 1500°C (2730°F). The CMRL LHF also uses oxygen-gas burners and after modifications made for this test program could operate at 1500°C (2730°F). The CMRL LHF can be operated in either batch mode or semi-continuously. It is similar in many respects to one of the two straight-hearth furnaces that will be coupled to provide the furnace system that has been proposed for scale up of the PSHF process.

Figure 19. Pilot-Scale Linear Hearth Furnace at CMRL.

The CMRL LHF has been used routinely to test a number of the variables that were shown to be important to hearth-based DRI processes by the results obtained from laboratory-scale box-furnace and tube-furnace tests. The laboratory furnaces allowed very precise manipulation of

key variables under very controlled experimental conditions. The LHF facility allows these types of basic studies to be expanded to a significantly larger scale to further evaluate the opportunity for successful commercialization of hearth-based iron-oxide reduction processes such as the PSHF process. The test program that was conducted with the CMRL LHF is described in detail in Appendix C.

To be able to better simulate the PSHF process, CMRL modified the LHF refractories to accommodate higher operating temperatures up to 1500°C (2730°F). In addition, the furnace exhaust duct was relocated so that the furnace off-gas could be exhausted in a co-current flow mode. The ceramic fiber refractory used on the existing furnace cars (sample cars), known as ñpyro-logò cars, was modified to accommodate the required 120-mm (4.7-in.) deep bed of dry pellets, and the base of each sample car was lined with a single layer of dense, high-alumina brick to better simulate a castable or solid-brick refractory hearth. Fiber blankets were used to insulate the hearths of the sample cars after they exited the LHF and were moved via the return strand to the entrance of the LHF to maximize the retention of heat in the car hearth refractories.

The LHF testing program was conducted over approximately nine weeks. Dried pellets were prepared from magnetite concentrate and finely-ground high-volatile coal and were sized to 100 percent minus-19.0-plus-16.0 mm (-3/4+5/8 in.). The initial testing was conducted in a batch mode where up to three sample cars of material were moved through the furnace zones. The Preheat Zone (Zone 1) was operated at 1200°C (2190°F) and the reduction zones or ñHot Zonesò (Zones 2 and 3) were operated at 1500°C (2730°F), with the burners operating with a typical stoichiometric oxygen-fuel ratio. Empty sample cars were cycled through the furnace until the car hearth refractory reached a desired or equilibrium temperature. Hot sample cars then were charged with various depths of dried balls up to 120 mm (4.7 in.). After being held for predetermined times in the Preheat Zone and the Hot Zones, the sample cars entered the Cooling Zone where the product DRI was cooled. After exiting the LHF, the sample cars were further cooled, and samples were taken from the top, middle, and bottom of the bed of reduced pellets for determination of total iron (Fe_T), metallic iron (Fe°), ferrous iron (Fe^{+2}), carbon (C), and sulfur (S) content.

The test program, described in more detail in Appendix C, included tests with both dried balls made from magnetite concentrate as well as dried balls made from BOF electrostatic precipitator (ESP) dust (revert material) obtained from a major steel producer. In batch-mode tests performed with one to three sample cars, the effects of bed depth, temperature, and molar carbon-to-oxygen ratio were determined. During the program, it was necessary to alter the method of cooling the reduced pellets after they exited the LHF. Due to a high amount of heat retention by the sample cars, reoxidation of the reduced pellets occurred in an unpredictable way. Subsequently, a method was developed to remove the reduced pellets from the sample cars and quench them in nitrogen in an external hood.

In batch-mode tests with dried balls made from reverts, some difficulty was encountered due to deterioration of the balls during reaction. However, the deterioration did not cause the reaction to cease, and in addition, high levels of zinc (Zn) removal were observed. Since weights before and after reaction were not obtained, zinc removal was estimated from the initial zinc content of

the dry pellets and the final zinc content of the reduced pellets and found to be 90 percent or more.

With dried balls made from magnetite concentrate, it was found difficult to achieve full reduction from the top of the bed to the bottom of the bed with pellet depths of 100 to 120 mm (3.9 to 4.7 in.). It is believed that this limitation in depth resulted from the low preheat hearth temperature of 800°C. Therefore, with a preheat temperature of 800°C, the pellet bed depth should be initially limited to about 75 mm (3 in.) to achieve reasonably uniform metallization levels of 80 to 90 percent down through the bed with a retention time of 80 minutes in the hot zone.

From the various photographs taken during the test program and included in Appendix C, it is apparent that the pellets clustered together in small areas after reduction. This allowed further radiant heat penetration into the bed. The clusters of reduced pellets broke up into clumps upon discharge. Also, it was observed that the ease of discharge related to the extent of reaction of the bottom layer. In some photographs localized degradation of the ñpyro-logò material due to attack by a liquid phase presumed to be wustite (FeO) was observed. Generally, the sample cars lined with refractory brick were not as readily attacked as were the ceramic fiber ñpyro-logò materials. However, with the short test program, a complete analysis was not possible.

Following the batch-mode phase of testing, a semi-continuous run was conducted by sequentially pushing a series of sample cars that had been filled with dry balls to various depths through the LHF. The continuous run included a string of seven cars, but only three to four sample cars were considered to have been fully reacted, however. The large volume of gas that evolved from the devolatilization of the coal contained in the pellets on the sample cars combusted and increased the temperature in the Preheat Zone above established safe limits and caused termination of the test. The string of sample cars used in the semi-continuous simulation is shown in Figure 20a. Typical clustering of the DRI and a vertical profile of the reduced pellet bed are shown in Figure 20b.

a. **b.**

Figure 20. Pallet cars and product from a test of PSHF process on the LHF
a. String of sample cars from attempt at continuous operation of LHF.
b. Typical DRI product (top view and side view) from test run in batch mode pellets made from magnetite concentrate.

While the tests corroborated the general concepts of the PSHF process, experimental difficulties did not allow a perfect simulation to be achieved. The results from the initial tests run in batch mode in the LHF showed that heat transfer from top-down heating was sufficient to metallize only the top 75 mm (3 in.) of the taller pellet beds that were tested. This was likely due to the relatively low temperature of the sample-car hearths, 800°C (1470°F) at the time that the dried pellets were charged to them. As noted above, the sample cars were preheated before being used in the tests by circulating them through the LHF. This suggests that a higher hearth preheat temperature is critical to achieving good metallization in pellet beds of 120-mm (4.7-in.) depth. A picture of typical DRI pellets produced in batch-mode LHF tests from pellets made from magnetite concentrate is shown in Figure 20b. Note that all pellets were significantly metallized, but the bed was not completely metallized from top to bottom. Because the sample cars retained a large amount of heat after exiting the LHF, some product reoxidation occurred even with nitrogen cooling, unless the product was removed from the hearth pallet cars. The comprehensive report in Appendix C includes the detailed test results from the CMRL LHF study.

6.0 DEMONSTRATION PLANT

Information obtained from the Large Batch Furnace Tests was used to design the furnace that would be used in the proposed PSHF Demonstration Plant. The results from the Supplementary Laboratory Tests supported the basic conclusions from previous laboratory studies and helped to identify problem areas. For the purpose of capital and operating cost estimation, the PSHF Demonstration Plant was assumed to be located in the U. S. Steel Mon Valley Works Edgar Thomson Plant in Braddock, Pennsylvania. The capacity of the proposed Demonstration Plant was upgraded from 42,000 t/a, which had been used in earlier estimates, to 50,000 t/a. It was assumed that the facility would be operated with pellets made from magnetite concentrate for a period of several weeks to demonstrate process capability. After that, it was assumed that the Demonstration Plant would begin processing pellets made from zinc-bearing steel plant revert materials (BOF clarifier sludge and classifier solids) that are difficult to recycle in traditional iron and steelmaking processes. It was further assumed that the DRI produced in the facility would be used in blast furnaces located in the steel plant. It is possible that the zinc-oxide-rich dust that would be expected to be captured in the PSHF bag house when revert-containing pellets were being processed would be a saleable by-product.

6.1 Location

As noted above, the U. S. Steel Mon Valley Works Edgar Thomson Plant, located in Braddock, Pennsylvania, was assumed to be the location of the proposed PSHF Demonstration Plant. The location of the steel plant and the proposed Demonstration Plant site are shown in Figures 21, 22, and 23.

Figure 21. Map showing location of Braddock, Pennsylvania.

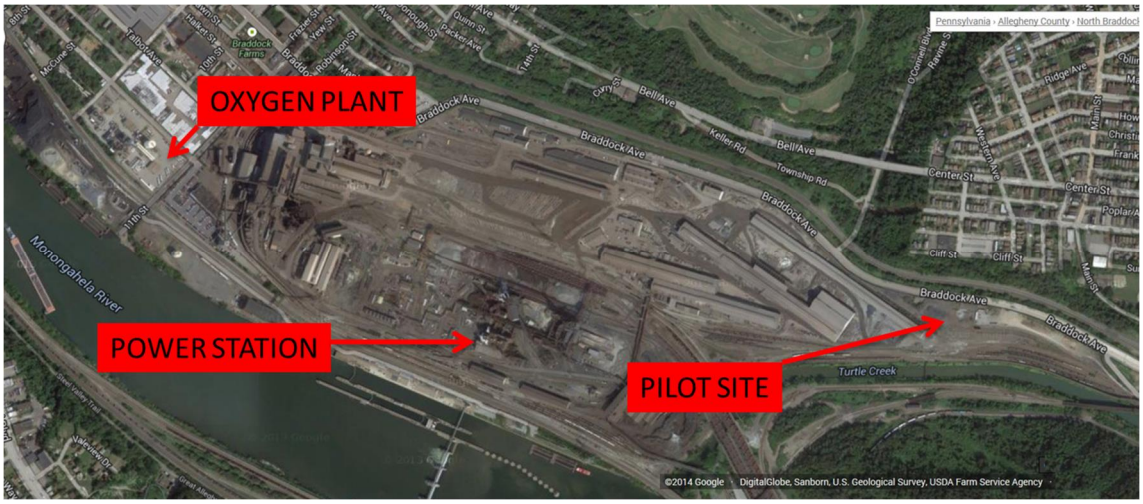


Figure 22. Aerial view of the southern end of the U. S. Steel Edgar Thomson Plant. Locations of key areas are highlighted: Oxygen Plant (industrial gas production facility), from which oxygen and nitrogen will be supplied; Power Station, from which steam will be supplied; and Pilot Site, site proposed for the PSHF Demonstration Plant.

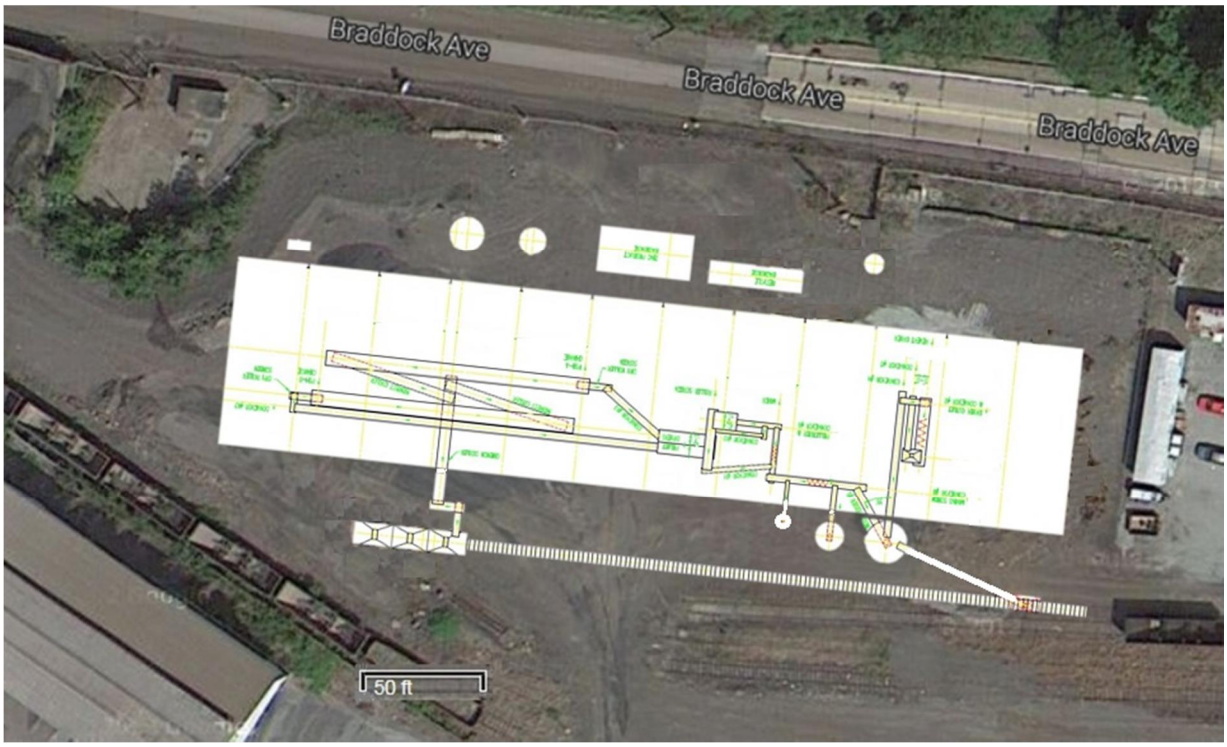


Figure 23. Closer view showing that the footprint of the proposed Demonstration Plant, roughly 110 by 49 m (360 by 160 ft.), fits into the space available at the site.

6.2 General Plant Specifications

The proposed PSHF Demonstration Plant will produce 50,000 t/a of direct reduced iron (DRI) from green pellets produced from a mixture of either magnetite iron-ore concentrate or steel plant revert material and finely-ground high-volatile coal. The plant is expected to process pellets containing magnetite concentrate for the first few weeks of operation. After that it is assumed that it will process pellets produced from revert material collected by the BOF steelmaking shop gas-cleaning system. A process flow sheet for the proposed PSHF Demonstration Plant is shown in Figure 24. Specifications for key operating parameters and utility requirements are shown in Table 8. A preliminary engineering drawing of the furnace system that will be used in the PSHF Demonstration Plant is shown in Figure 25. A list of the equipment required for the Demonstration Plant is given in Appendix D along with descriptions of key pieces of equipment.

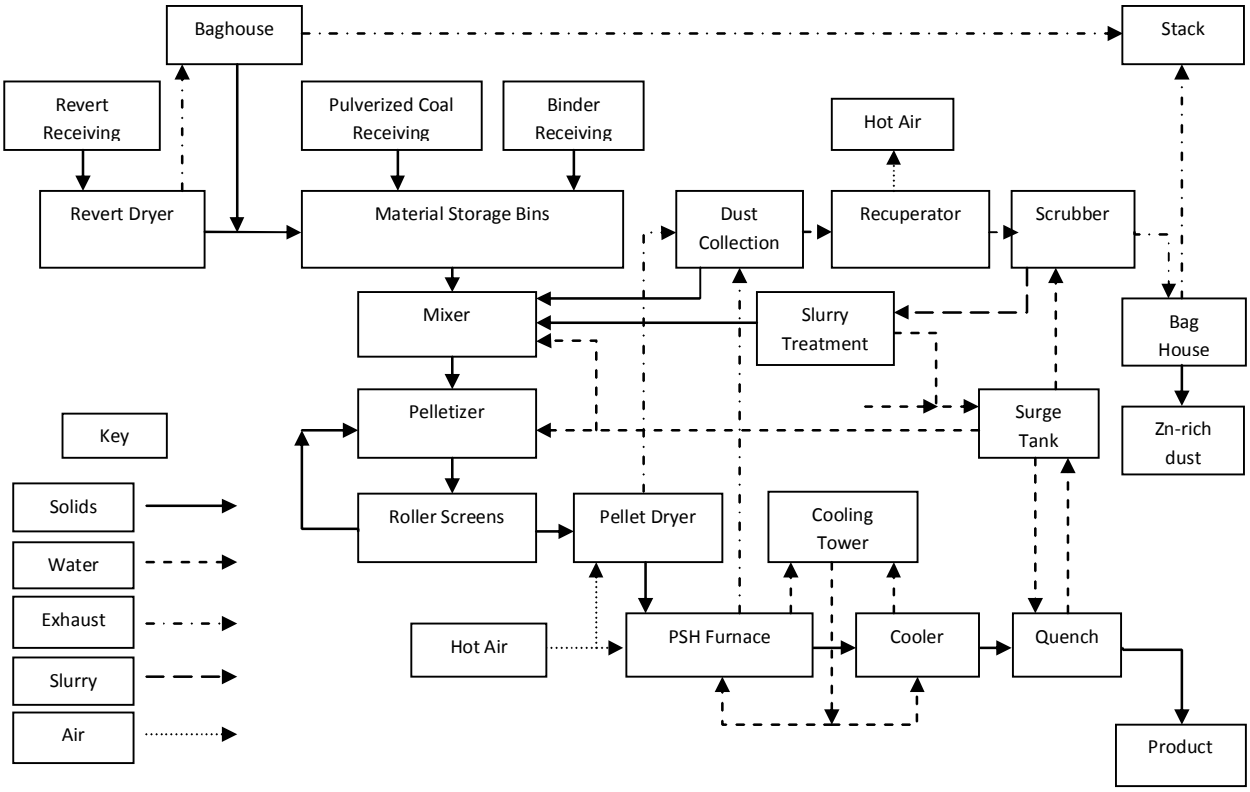


Figure 24. Block diagram of preliminary flowsheet for PSHF Demonstration Plant.

Fine magnetite iron-ore concentrate, ground coal, and bentonite binder will arrive at the Demonstration Plant by rail. The magnetite concentrate will be dumped into a hopper and then fed to the ore day bin by bucket conveyor. Alternately, ore concentrate can be delivered wet in gondola cars and emptied with a clamshell for storage in a bunker. Ground coal and binder will be transferred to material storage bins using pneumatic conveying. Raw materials will be metered from storage bins into the mixer by weigh feeders. The mixed raw materials will be

agglomerated into wet green pellets in a drum pelletizer. A roller screen will assure that the green pellets are consistently sized.

The pellets will drop from the roller screen onto a mesh-belt dryer, after which the dry green pellets will be screened again to remove fines. The pellets next will enter one of the two PSHF process furnaces, where the iron oxide contained in them will be reduced to metallic iron and the reduced pellets will be sintered into pellet cakes. The reduced product will then drop into an indirect cooler, and cooling will then be completed by water-quenching. From the quench cooler the product will be conveyed over a screen for fines removal and then transported for charging into the blast furnace.

Revert materials will be delivered by dump truck into bunkers that will be under roof in the Demonstration Plant. The revert materials will then be transported by front-end loader into the hopper of the revert dryer. After drying, the revert materials will enter the ore day bin by bucket elevator, after which they will follow the same path as described above for the magnetite concentrate.

Table 8. PSHF Demonstration Plant Specifications

DRI production, t/a	50,000
Annual operating hours, h/a	8400
Production rate, t/h	5.96
Ore feed rate, t/h (dry basis)	8.31
Coal feed rate, t/h (dry basis)	1.87
Binder feed rate, t/h (dry basis)	0.125
Green pellet feed rate, t/h (wet basis)	12.1
Utility Requirements:	
Electricity, kVA	1000
Natural Gas, Nm^3/h	3100
Oxygen, Nm^3/h	2350
Nitrogen, Nm^3/h	8850
Steam, kg/h	3000
Contact cooling water, l/min	600
City (potable) water, l/min	250

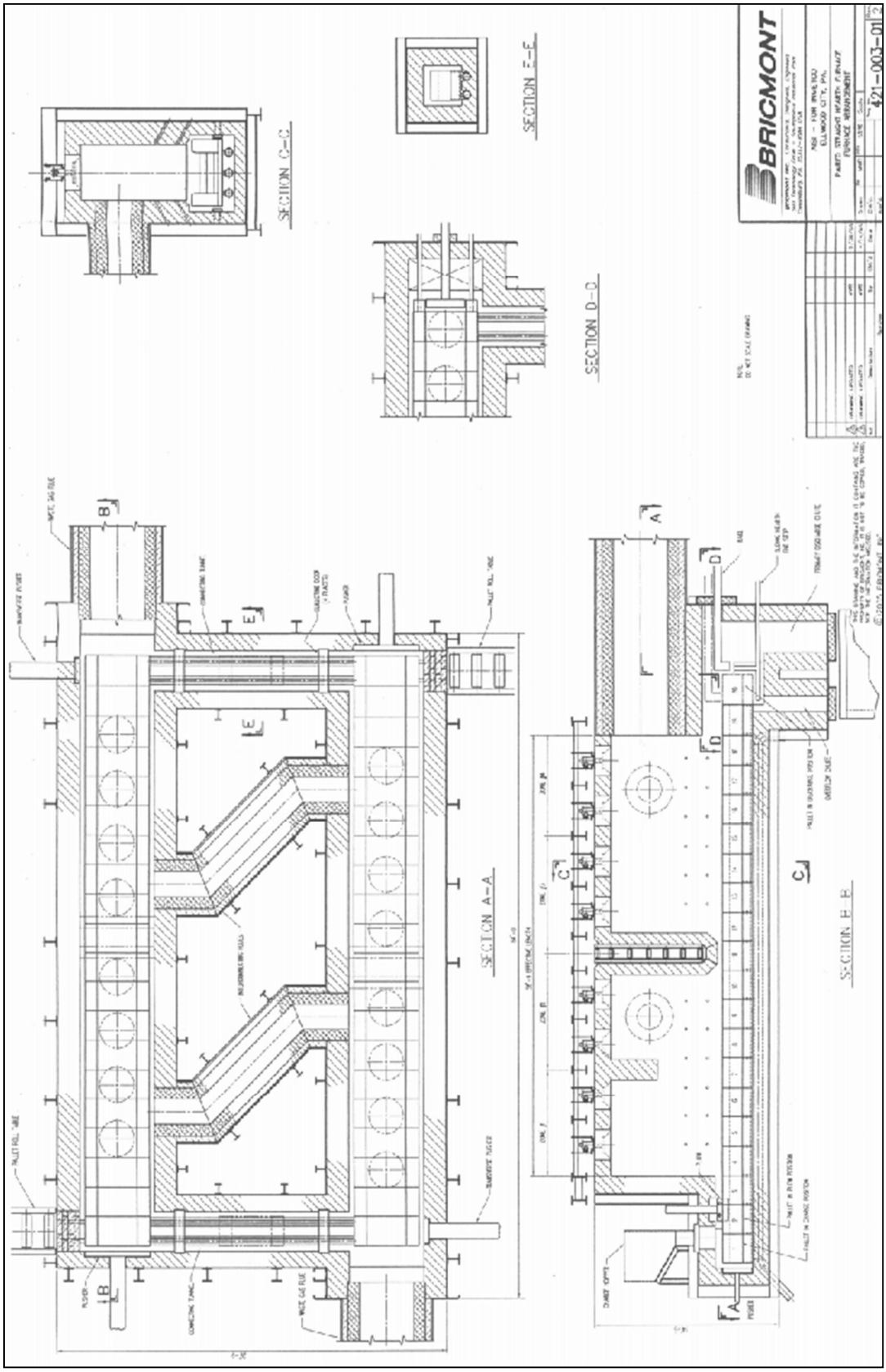


Figure 25. Preliminary engineering drawing of furnace system for PSHF Demonstration Plant.

6.3 Environmental Emissions

The proposed PSHF Demonstration Plant will not generate waste water or water emissions. Water that decants from the BOF classifier solids will be collected in a sump and pumped to the pelletizing drum for use in the pelletizing process.

Air emission control requirements will be more significant. The Edgar Thomson Plant is located in an area that is considered to be non-attainment for particulate emissions. Particulate dust generated at raw-material transfer points in the Demonstration Plant will be collected in a bag house and recycled back to the ore day bin. The off gas from the PSHF system will include mechanically-generated particulates and also will include fine process fume, consisting primarily of zinc vapor, when pellets made from revert materials are being processed. A separate bag house will collect this fine fume after the zinc vapor has been oxidized to fine zinc-oxide particles. It is possible that the zinc-laden dust that will be captured in this bag house might be sold as crude zinc oxide for use in a zinc-recovery facility. Before the off gas reaches the bag house, residual carbon monoxide in it will be post-combusted and the gas will then be cooled by water sprays. Heavier dust will fall out in a separation chamber and then finer particulates, including the fine zinc-oxide fume if it is present, will be filtered out in the bag house. The cleaned off gas from both bag houses will be exhausted to the same stack. The stack will be fed by separate ducts that include sufficient straight run for emission testing.

The emission specifications for the PSHF Demonstration Plant are expected to be as shown in Table 9.

Table 9. PSHF Demonstration Plant Emission Rates

Stack Emissions, t/a	
Total Particulates	51.5
NO_x	22.7
SO_x	111.8
CO	13.8
Total stack off-gas flow rate, Nm^3/h (scfm)	177,000 (109,856)
Stack temperature, °C (°F)	89 (193)

The SO_x emissions were calculated based on the assumption that 40 percent of the sulfur contained in the green pellets will be released and oxidized during processing in the furnace system. The estimated SO_x emissions are above the major source threshold. While this could force control of the SO_x emissions, it may be more appropriate to utilize coal with a lower sulfur content or simply to reduce annual DRI production by about 10 percent to remain below the threshold. Otherwise, limestone injection easily can be performed at the spray cooler to capture SO_x. Unfortunately, limestone injection would dilute the zinc oxide content of the by-product dust, thereby decreasing or eliminating its value. No provision for limestone injection was included in the capital cost estimate.

The required stack height will have to be based on the results of emissions dispersion modeling. For cost-estimation purposes, the stack height was assumed to be 36.6 m (120 ft.). The stack will be of the forced-draft type, so there will be no minimum stack height required for drafting of the equipment.

6.4 Electrical System

The Demonstration Plant electrical system will be fed by a single 480-V transformer. The connected load will be 1000 kVA. The motor control center (MCC) will be housed in an electrical room located below the operatorôs pulpit. The MCC will serve the following motors, listed in Table 10 below.

Table 10. Motor List for PSH Demonstration Plant

Description	HP	Description	HP
Ore Bin Rotary Valve	5	Quench Return Pump	2
Coal Bin Rotary Valve	5	Air Heater Fan	50
Binder Bin Rotary Valve	1	Recycle BH* Exhaust Fan	125
Revert Dryer	75	Recycle BH Rotary Valve 1	1
Ore Weigh Feeder	5	Recycle BH Rotary Valve 2	1
Coal Weigh Feeder	5	Recycle BH Rotary Valve 3	1
Binder Weigh Feeder	1	Recycle BH Rotary Valve 4	1
Mixer	20	Recycle Bag House Screw	5
Pelletizer Feeder	10	Afterburner Fan	30
Pelletizer Drum	30	Settling Rotary Valve	1
Roller Screen (Wet)	5	Spray Cooler Dust Rotary Valve	1
Oversize Return	5	PSH BH Exhaust Fan	200
Oversize Return (2)	5	PSH BH Rotary Valve 1	1
Undersize Return	5	PSH BH Rotary Valve 2	1
Wet Pellet Conveyor A	5	PSH BH Rotary Valve 3	1
Wet Pellet Conveyor B	5	PSH BH Rotary Valve 4	1
Dryer A Conveyor	5	PSH Bag House Screw	5
Dryer B Conveyor	5	NC** Water Cold Well 1	25
Dryer Fan	50	NC Water Cold Well 2	25
PSHF Air Fan	150	NC Water Cold Well 3 (standby)	25
PSHF Hydraulic Pump 1	25	NC Water Hot Well 1	10
PSHF Hydraulic Pump 2	25	NC Water Hot Well 2	10
PSHF Hydraulic Pump 3	25	NC Water Hot Well 3 (standby)	10
PSHF Hydraulic Pump 4 (standby)	25	Cooling Tower Fan	10
Indirect Cooler A	10	Contact Water Pump 1	5
Indirect Cooler B	10	Contact Water Pump 2 (standby)	5
Quench Cooler Conveyor	50	Compressor	200

* BH: Bag house.

** NC: Non-contact.

The electrical room also will house the control panels. The process control will be handled by a series of PLCs including for the following areas: (1) Drying and Pelletizing; (2) Combustion Safety; (3) Combustion Control; (4) Thermal Material Handling; and (5) Emissions Control. The bag houses will be controlled by their own separate PLCs. All PLCs will communicate via Ethernet with the HMI and remote input/output (I/O). The HMI will be PC-based, with access from the control pulpit or a programming station in the electrical room.

7.0 COST ESTIMATE

The estimated cost for engineering, supply, fabrication, and installation of the proposed PSHF Demonstration Plant, as described above, is $28,855,000. The estimate is broken down by process area in Table 11, and more detailed estimates for each process area given in the sections that follow.

Table 11. Overall Cost Estimate

Pellet Making	$	4,299,000
Thermal Processing	$	18,822,000
Exhaust System	$	2,777,000
Utilities/Balance of Plant	$	2,957,000
TOTAL	**$**	**28,855,000**

The estimate is based on 2013 dollars and does not include escalation.

7.1 Pellet Making

The estimate for the Pellet Making area is $4,299,000, as broken down in Table 12.

Table 12. Pellet Making Cost Estimate

Revert Dryer	$1,400,000
Day Bins	$172,000
Mixer	$171,000
Pelletizer	$290,000
Wet Roller Screen	$46,000
Conveyors	$779,000
Controls/PLC	$125,000
Subtotal	**$2,983,000**
Engineering	$358,000
Installation	$958,000
TOTAL	**$4,299,000**

Revert Dryer: Dryer for the BOF clarifier sludge and classifier solids; uses a steam-heated agitator and enclosure.
Day Bins: Ore, reductant, and binder day bins, with integral bag filters and rotary valves for flow metering.
Mixer: Spatulate mixer.
Pelletizer: Drum-type pelletizer.
Wet Roller Screen: Green pellet sizing screen
Conveyors: Conveyors between the pellet making equipment, including the weigh-belt feeders.
Controls/PLC: PLC, HMI and instrumentation for the pellet making system.

7.2 Thermal Processing

The estimate for the Thermal Processing area is $18,822,000, as broken down in Table 13.

Table 13. Thermal Processing Cost Estimate

Pellet Dryer	$1,027,000
Dry Roller Screens	$78,000
PSH Furnaces	$9,846,000
Indirect Coolers	$1,905,000
Quench Cooler`	$797,000
DRI Screen	$24,000
Conveyors	$338,000
Subtotal	**$14,015,000**
Installation	$4,807,000
TOTAL	**$18,822,000**

Pellet Dryer: Mesh-belt dryer for green pellets, including engineering and controls.
Dry Roller Screens: Screens to remove fines from dried green pellets before they are charged to the PSHF hearths.
PSHF's: Two parallel furnaces, including support structures, engineering, and controls.
Indirect Coolers: Two indirect coolers with conveyor, including engineering and controls.
Quench Cooler: One water-spray cooler with jets and conveyor, including engineering and controls.
DRI Screen: Simple stationary screen to remove fines from the DRI product before it is shipped.
Conveyors: Equipment to transport dried pellets from the dryer to the PSHFôs, including the interrupting conveyors.

7.3 Exhaust System

The estimate for the Demonstration Plant Exhaust System is $2,777,000, as broken down in Table 14.

Table 14. Exhaust System Cost Estimate

Settling Chamber	$	177,000
Spray Cooler	$	93,000
PSH bag house	$	999,000
Stack	$	124,000
Recycle bag house	$	441,000
Exhaust Ductwork	$	154,000
Subtotal	**$**	**1,988,000**
Engineering	$	218,000
Installation	$	571,000
TOTAL	**$**	**2,777,000**

Settling Chamber: Settling chamber with post-combustion equipment.
Spray Cooler: Equipment to cool the PSHF exhaust gas, using water sprays, to a safe temperature for the bag house.
PSH Bag House: Bag filter unit for removing particulates from the PSHF exhaust gas, including control PLC.
Stack: Free-standing stack with sampling platform.
Recycle Bag House: Bag filter unit for the pellet dryer and various pellet making transfers, including control PLC.
Exhaust Ductwork: Interconnecting ductwork between emission sources and emission control equipment, including the pellet making fume hoods.

7.4 Utilities and Balance of Plant

The estimate for Demonstration Plant Building and Utility Systems is $2,957,000 (installed), as broken down in Table 15.

Table 15. Utilities and Balance of Plant Estimate

Cooling Water System	$	139,000
Electrical System	$	320,000
Air Compressor	$	8,000
Utility Piping	$	191,000
CO Alarm System	$	14,000
Building	$	2,104,000
Roads/Railways	$	105,000
Mobile Equipment	$	76,000
Subtotal	**$**	**2,957,000**

Cooling Water System: Cooling tower, hot and cold wells, pumps, and piping for the cooling water system.
Electrical System: Transformer, MCCôs, and back-up generator
Air Compressor: Air compressor to provide high-pressure air for the bag houses and general plant use.
Utility Piping: Piping to run oxygen and nitrogen from the industrial gas production facility to the site and steam from the power station to the site, as well as 366 m (1200 ft) of natural gas piping.
CO Alarm System: Five CO alarms located around the PSHF installation.
Building: Foundations, building proper, operatorôs pulpit, and electrical room.
Roads/Railways: Allowance for extending the existing transportation systems to the PSHF plant.
Mobile Equipment: One front-end loader for transporting revert material and one fork truck for general maintenance use.

8.0 BENEFITS ASSESSMENT

In the late 1980ôs and early 1990ôs, AISI, acting on behalf of its member companies, with funding support from DOE, developed an improved alternative ironmaking process that incorporated a bottle-shaped smelter vessel and used coal as a reductant, rather than coke. The goal was to find an economical replacement for the traditional coke-oven/blast-furnace ironmaking route. The project was a technical success, but unfortunately, the production rate was smelting-intensity-limited and insufficient for the process to be considered a viable replacement for the coke-oven/blast-furnace hot-metal production route. Over $90 million was invested in this effort, including more than $60 million provided by DOE. [11]

Blast furnace fuel rates can vary significantly from furnace to furnace, depending on site-specific conditions. For the period 1997 to 1998, Stubbles [12] estimated that the energy intensity for ñgood-practiceò blast-furnace hot metal production in the U.S. was 15.48 MMBtu/NT (18 GJ/t).

Stubbles also estimated that blast-furnace hot-metal production accounted for 72 percent of the overall energy intensity in ñgood practiceò integrated steel plants, 14.88 out of a total of 20.66 MMBtu/NT of shipped steel in the same time period. [12] For EAF operations, the availability of hot metal on-site will bring advantages in power consumption, tap-to-tap time, stability in operation and cost, as well as, energy intensity.

The PSHF process, when coupled with an oxy-coal or electric melter, has the potential to allow steelmakers to produce hot metal with approximately 30 percent less energy than is possible in the traditional coke-oven/blast-furnace route.[1,4] An important advantage of the new technology is that it can use non-metallurgical, medium to high-volatile coal as both the reductant and primary heat source in the production of DRI pellets from either virgin iron ore or steelmaking revert materials. This addresses a very important strategic raw materials issue for domestic integrated steelmakers, the scarcity of high-quality, low-volatile metallurgical coal that is required for use in coal blends that are utilized in cokemaking.

The significantly greater energy efficiency of the PSHF process may be accounted for by two major factors: (1) the elimination of the high temperature preparatory steps (and associated energy consumption) of making coke and firing iron oxide pellets and (2) the fact that carbon leaves the blast furnace mainly in the top gas in the form of CO and CO_2 in approximately equal amounts (this is a thermodynamic limitation which cannot be changed); on the other hand, carbon leaves the PSHF mainly in the process off gas, in which it occurs as nearly 100 percent CO_2. When carbon is oxidized to CO, less than one third of its available chemical energy is released as heat (i.e., the heat released is less than 1/3 of that released when carbon is oxidized to CO_2). Carbon gives nearly all of its available heat content to support the reactions in the PSHF process, in which it is nearly fully oxidized to CO_2, but this is not the case in the blast furnace. This leads to the conclusion that the total carbon input for hot metal made from PSHF DRI in a follow-on melter is one third lower than for the same amount of hot metal produced through the coke-oven/pellet-plant/blast-furnace route. It should be pointed out that from the same raw materials (coal and iron-ore concentrate) to the same products (hot metal and liquid slag) the theoretical net energy requirement must be the same; however, the actual minimum energy and carbon consumptions are different in different processes due to differences in process design. Quantitative documentation of this comparison is available in the TRP-9810 Final Report submitted by McMaster University. [1]

Further, there are no fundamental technology barriers associated with development and commercialization of the PSHF process; it consists of a combination of proven conventional reactors that are operated under new conditions.

9.0 ACCOMPLISHMENTS

The Large Batch Furnace Tests conducted by ANDRITZ Bricmont, in conjunction with the industrial partners, yielded the following findings.

- The most reliable method for discharging the PSHF product DRI was determined to be by scraping the reduced pellets off the PSHF hearth.

- The emissions of NO_x and SO_x from the proposed PSHF Demonstration Plant were estimated to be 22.7 and 95.0 t/a, respectively. Stack particulate emissions were estimated to be limited to 51.5 t/a as a result of filtering the PSHF process off gas in a bag house.

- The proposed Demonstration Plant for producing 50,000 t/a of DRI from either magnetite concentrate or steelmaking revert materials will fit within a footprint of approximately 110 m by 49 m (360 ft by 160 ft). The capital cost to construct the facility was estimated to be $28,855,000 (2013 dollars).

The Supplementary Laboratory Tests and Physical Simulation Tests conducted at the Coleraine Minerals Research Laboratory (CMRL) provided the following information.

- High-quality green pellets could be produced from a mixture of ground high-volatile coal, either magnetite concentrate or steelmaking revert material, and either a cooked-starch or bentonite binder. The green pellets, after drying, had sufficient strength to resist degradation during a simulation of transferring and charging the pellets to the hearth of the PSHF system.

- High average DRI product metallization levels of about 90 percent or more and specific metallic-iron productivities of more than one kilogram per square meter per minute were possible under simulated PSHF process conditions. High metallization levels could be achieved throughout the pellet bed from top to bottom, depending upon the furnace temperature, reaction time, and the degree of preheating of the refractory hearth plate.

- Quantitative information was provided for developing a kinetic model to describe pellet shrinkage, heat transfer, pellet composition, and gas evolution to aid in scale-up of the PSHF process and for development of a computational fluid dynamics (CFD) model of the PSHF process.

- Semi-continuous tests on the pilot-scale linear hearth furnace (LHF) that were performed to simulate one train of the PSHF system demonstrated that the general concepts of the PSHF process are correct, but the PSHF hearth preheat temperature must be sufficiently high to assure high metallization levels in pellets located in the bottom of the pellet bed. In addition, there is the potential for further optimization of the volatile-matter content of coal used in the PSHF process.

10.0 CONCLUSIONS

Testing of the PSHF concept under DOE Award No. DE-FG36-08GO18133, administered through AISI, has been completed. The results from several series of laboratory and pilot-scale tests have confirmed the general viability of the PSHF concept, and the detailed design information that was developed using these as well as previous test results can be used to guide the construction of a Demonstration Plant. The program successfully completed four tasks: (1) Large Batch Furnace Tests to better define the method of DRI product discharge, ascertain the process emissions control requirements, and identify productivity limitations; (2) Supplementary Laboratory Tests to develop a method to produce strong green pellets for use in the PSHF process and identify kinetic factors and important parameters to consider in design of the Demonstration Plant; (3) Physical Simulation Tests in a LHF that was similar in many ways to one train of the furnace system that will be used in the scale-up of the PSHF process; and (4) Design and Costing of a Demonstration Plant. The information that was obtained from the testing programs was used along with information from previous studies to develop a process flow sheet and to select equipment suitable for use in a Demonstration Plant with a DRI production capacity of 50,000 t/a. Equipment needs were defined and the capital cost of the facility was estimated in 2013 dollars.

Key results include.

10.1 Large Batch Furnace Tests

a. **Discharge Method:** Use of a fixed blade to scrape the DRI product from the hearth will provide adequate force to discharge the reduced product from the furnace reliably. In the proposed Demonstration Plant, the pallets containing the reduced pellets will be pulled under the fixed scraper blade to discharge the DRI product from the hearth. Testing of the tilting discharge method showed that under certain circumstances, tilting the pallets to even 90 degrees was insufficient to discharge the product.

b. **NO_x Emissions**: The NO_x emissions from the PSHF Demonstration Plant are expected to be 30 ppm by volume or 22.7 t/a. If the Demonstration Plant is located at the proposed site in Allegheny County, Pennsylvania, it would be considered to be a research installation and no special NO_x-abatement equipment would be required for the facility.

c. **SO_x Emissions**: The SO_x emissions from the PSHF Demonstration Plant are expected to be 90 ppm by volume or 95.0 t/a. Since this is slightly over the major source threshold, it may be necessary to use a coal with a sulfur content lower than that used in the present study. Alternatively, a limestone injection system can be installed to abate SO_x, or the Demonstration Plant annual production rate could be reduced by 5 percent.

d. **Particulate Emissions**: Particulate emissions from the Demonstration Plant will originate both from mechanically generated dust and from particulates released during the reduction process. Dust from pellet making and handling will be collected in a bag house that is separate from the one that will be used for the PSHF off gas. In this way, the zinc-rich dust that will be collected from the PSHF off gas when pellets made from

steelmaking revert material are being processed will not be diluted by the pellet-making dust. The zinc-rich dust can be adequately abated using a bag house with an air-to-cloth ratio of no more than 2.0 acfm/ft^2.

e. **Zinc and Lead Emissions**: When pellets containing steelmaking revert material are reduced in the PSHF process, zinc is released as metal fume and subsequently oxidized to zinc oxide. The off-gas system will be designed to capture the zinc oxide in a bag house. The small amount of lead oxide in the revert pellets will be reduced to metallic lead, which will volatilize to some extent, even though the pellets are not processed to temperatures as high as the boiling point of lead (1749°C). The lead vapor will enter the emissions stream and later be oxidized to lead oxide. The lead oxide can be then be collected in the bag house as well.

f. **Productivity**: While not one of the original goals of the study, the reaction rates observed in the Large Batch Furnace Tests have suggested that the productivity that will be seen in a large furnace will not be as high as that observed in the previous small-scale furnace tests. As a result, a larger PSHF system will be required for the Demonstration Plant than was previously anticipated. The Demonstration Plant PSHF system has been designed assuming a specific production rate of 91.0 kg/m^2·h (18.8 lb/ft^2·hr). This will be achieved with a 90-to-100-mm (3.5-to-4-in.) high, five-layer bed of pellets and a residence time of 80 minutes.

10.2 Supplementary Laboratory Tests

a. Pelletizing: The Coleraine Minerals Research Laboratory (CMRL) successfully produced strong dry pellets from mixtures of ground high-volatile coal and either magnetite concentrate or dried steelmaking revert material (BOF sludge), using either organic binders or bentonite. Excellent dry ball strength was obtained, with the pellets being able to survive being dropped 3 to 18 times from a height of 46 cm (18 in.), depending upon the amount and type of binder added. A mechanical device was fabricated to simulate charging dried pellets onto a moving PSHF hearth. The pellets were loaded satisfactorily into moving cars to a depth required by the PSHF process. (Appendix A)

b. Kinetic Study: A two-zone, electrically-heated box furnace was designed and built to allow measurement of various kinetic parameters associated with the PSHF process. Gas composition was measured in each test, as was vertical shrinkage of the pellet bed. The bed of reduced pellets was separated into 5 layers, and each layer was analyzed for chemical composition and pellet diametrical shrinkage. These parameters were successfully measured over a range of reaction temperatures and with two different hearth preheat methods. The results showed the importance of obtaining a hearth preheat temperature in excess of 1200°C (2730°F) to maximize metallization in pellets located at the bottom of the bed. This information will be useful for constructing system models. (Appendix B)

10.3 Physical Simulation Tests:

a. Simulation of One-Half of PSHF: A physical simulation of one train of the proposed PSHF system was conducted on a pilot-scale linear hearth furnace (LHF) at CMRL. The 0.6-m-wide by 12.2-m-long (2-ft-wide by 40-ft-long) LHF is a pusher-type furnace that is fired with oxygen/natural-gas burners and is capable of operation at a hot-zone temperature of 1500°C (2730°F). Both batch-mode tests and a semi-continuous test were made. (Appendix C)

b. Burners: The LHF oxygen/natural-gas, flat-flame burners were capable of providing the required process heat and desired temperature of 1500°C (2730°F) in the furnace without any of the pellet damage that is often observed with turbulent gas atmospheres.

c. Discharge of Pellets: Overall, the tests were successful and demonstrated that in the horizontal plane, the reduced pellets will sinter together into clusters that can be broken up easily. In some instances, pellets in the bottom layers of the bed were unreduced or barely reduced; however, this made it easy to discharge the pellets from the hearth.

d. Refractory: It was visually observed that carts lined with the ceramic fiber ñpyro-logò on the sides held up well except when attacked by molten wustite (FeO). Care needs to be taken to avoid formation of liquid wustite. High density refractory bricks on the hearth held up better.

e. Semi-Continuous Run: An attempt at a semi-continuous run was only partially successful. Due to the release of copious amounts of volatiles from the coal contained in the pellets and its subsequent combustion in the overhead space, the furnace automatic control shut down the system.

f. Productivity: The semi-continuous test on the LHF did not achieve as high a specific productivity as desired because the hearth preheat temperature was limited to 800°C. The pellet bed depth was limited to about 75 mm (3 in.) to achieve reasonably uniform metallization levels of 80 to 90 percent down through the bed with a retention time of 80 minutes in the hot zone.

g. Cooling: The large mass of the pallet cars relative to the mass of pellets contained on them prevented adequate cooling of the reduced pellets. This resulted in partial reoxidation of the reduced pellets. Removal of the DRI pellets from the carts, followed by cooling with nitrogen under an external hood minimized the amount of oxidation that occurred.

h. Zinc Removal: Although tests with pellets made from BOF electrostatic precipitator (ESP) dust were not as successful as those performed with pellets made from magnetite concentrate due to deterioration of the pellets, the amount of zinc removed from the pellets during reduction appeared to be over 90 percent based on a rough estimate made from the starting zinc value and the zinc in the products.

10.4 Design of Demonstration Plant

a. General Demonstration Plant: A Demonstration Plant with the capacity to produce 50,000 t/a of DRI from either magnetite concentrate or steelmaking revert material will consist of pellet making, including revert material drying, pelletizing, thermal processing, an exhaust system, including emissions control equipment; and utilities. The facility will fit within a footprint of approximately 110 m by 49 m (360 ft. by 160 ft.). The equipment is listed in Appendix D.

b. Revert Material Drying: The pellet making operation will include a facility for drying steelmaking revert material. The revert material will arrive in dump trucks for storage in bunkers. A front-end loader will place the revert material into the dryer hopper. Back-feeding partially dried material as 50 percent of the dryer feed will assure that the sticky, wet revert material can be handled properly. From the dryer the revert material will go into the ore day bin.

c. Pellet Making: The pellet making facility will have the capability to transport 8.31 t/h of fine magnetite concentrate, 1.87 t/h of ground coal, and 0.125 t/h of bentonite binder into day bins. Downstream processes include weighing, mixing, and pelletizing in a drum pelletizer with added water to produce 12.1 t/h of wet green pellets.

d. Thermal Processing: The thermal processing includes pellet drying on a mesh-belt dryer, reduction in the PSHF system, indirect cooling to 815°C (1500°F), and final cooling to 90°C (200°F) by quenching with water. The PSHF system will be fired with oxygen-enriched air without preheating. This avoids problems with dust clogging of the heat recuperators that might occur if preheated air were required to achieve adequate flame temperature in the PSHF system.

e. Emissions Control System: The exhaust system will consist of two separate off-gas streams feeding a single stack. Dust-laden air collected from the pellet making and handling areas will enter a bag house with a cloth area of 870 m^2 (9300 ft^2) before being routed to the stack. Products of combustion from the PSHF system will enter a settling chamber, which also acts as a post-combustor, and will be water-spray quenched. The gases will then be passed through a bag house with a filter area of 3420 m^2 (36,600 ft^2) before passing to the stack.

f. Facility Utilities: The Demonstration Plant PSHF facility will require 1000 kVA of electricity, 3100 Nm^3/h (1900 scfm) of natural gas, 2350 Nm^3/h (1460 scfm) of oxygen, 8850 Nm^3/h (5500 scfm) of nitrogen, and 3000 kg/h (6700 lb /hr) of steam. These are as-installed values and not average usage rates. The Demonstration Plant will be otherwise self-contained, with its own cooling tower, air compressor, and emergency power generator.

g. Demonstration Plant Capital Cost: The capital cost of the Demonstration Plant has been estimated to be $28,855,000 (2013 dollars), as broken down in Table 16:

Table 16. Breakdown of Estimated Costs by Function

Pellet Making	$	4,299,000
Thermal Processing	$	18,822,000
Exhaust System	$	2,777,000
Utilities/Balance of Plant	$	2,957,000
TOTAL	**$**	**28,855,000**

11.0 RECOMMENDATIONS

Full optimization of the PSHF process cannot be accomplished until a Demonstration Plant is constructed and operated on a continuous basis. The comprehensive Engineering Design for the Demonstration Plant is based on earlier preliminary design work performed by Bricmont, [4, 6] results from the Large Batch Furnace Tests, and mathematical modeling performed with support from the results from the Supplementary Laboratory Tests and the Physical Simulation Tests. The finalized PSHF Engineering Design and estimate detailed equipment list in Appendix D will serve as the platform for construction of a 50,000-t/a PSHF Demonstration Plant. The PSHF Demonstration Plant will consist of material handling, pellet making, thermal processing, and emissions control equipment, will fit within a footprint of approximately 110 m by 49 m (360 ft by 160 ft), and is estimated to cost $28,855,000 (2013 basis).

To improve the ability of the PSHF to handle feed materials with varying characteristics, further laboratory testing, including testing at the CMRL LHF, should be conducted to provide additional detailed design information to assure that a PSHF Demonstration Plant, when built, will have a high probability of successful operation. These tests should include ones to verify the requirements and methodology for making green pellets from a variety of iron-bearing oxide and steel plant revert materials that will be acceptable for use in the PSHF process.

11.1 Perform Additional Tests to Support PSHF Process

a. **Effect of Refractory**: Determine the effect of the nature and condition of the hearth refractory material and the hearth preheat temperature on overall DRI metallization levels, especially in the bottom layer of the bed. The heat-retaining capacity of the refractory is also of importance. This relates to the ability of the pallet hearth refractory to retain heat and maintain sufficient temperature as the pallets, after discharge, are cycled from the exit end of the PSHF system to the entrance for loading with a new batch of dried pellets.

b. **Effect of Volatile Matter:** Determine the effect of volatile-matter content of the reductant on the rate of release of the reducing gas (volatile matter) from the pellets and on metallization levels that can be achieved in the bottom layers of the pellet bed as a function of hearth preheat temperature and furnace preheat temperature. This

relates to the ability to fully reduce a deep bed of pellets as well as to the gas-handling requirements of the process.

c. **Pelletizing Parameters**: Determine from testing a suite of samples of BOF ESP dust and BOF sludge what the critical variables are that affect green ball formation and dry green-ball strength. This relates to the need to minimize fines production in the pellet bed, where the fines retard heat and mass transfer through the bed and promote sticking and clustering of the DRI. Initial pellet swelling during reduction may also be a phenomenon that leads to degradation.

d. **LHF Modifications**: Implement modifications to the CMRL LHF to allow it to more closely simulate the PSHF process. This would require including a preheat zone with a short retention time as part of the first zone or in addition to the first zone, developing a means to preheat hearth cars to temperatures higher than those achieved in the recent tests, increasing the capacity of the off-gas system to remove volatiles, improving the capacity of the cooling zone and adding the image of the cooling zone to the control screen. Also, a means to rapidly discharge reduced pellets from the hearths needs to be developed. Tests with the best conditions previously identified for the LHF should be repeated and the program expanded to include tests with bed depths up to 120 mm (4.7 in.) when the LHF has been suitably modified. Subsequently, a semi-continuous run with multiple sample cars should be attempted when optimum parameters for the LHF have been defined.

To accomplish these recommendations, a follow-on program at CMRL is proposed to begin early in 2015 to; (1) conduct laboratory tests in the small batch PSH furnace (Appendix B) to define the required hearth pre-heat temperature for conversion of a deeper bed of pellets, carbon-to-oxygen ratio for raw materials, and volatile matter of the coal to be used in subsequent LHF tests; (2) evaluate modifications needed to the LHF to increase hearth pre-heat temperatures beyond 800 °C, feeding of dried pellets to sample cars, and mechanical removing/dumping of reduced pellets from hot hearths to facilitate rapid cooling; (3) implement design changes developed to the LHF. Subsequently, a comprehensive testing program for recommended process changes on the modified LHF would be conducted.

11.2 Construct a PSHF Process Demonstration Plant

After the successful completion of the testing program outlined above, and once the PSHF Demonstration Plant has been constructed and successfully operated, the true benefits of the PSHF process can be quantified. These benefits include: (1) elimination of standard iron-ore agglomeration and thermal induration and elimination of the coking process, thereby decreasing raw material costs as well as environmental concerns associated with those processes; (2) decreased emissions of carbon monoxide; and (3) the lower energy intensity of the PSHF process and the potential for a significant decrease in energy intensity for the further production of liquid iron from the PSHF DRI product.

Such a Demonstration Plant would include the following.

a. **Revert Drying:** A facility for drying revert material by means of indirect steam heating. Back-feeding of 50 percent partially-dried material should be employed to assure that the sticky, wet revert material can be handled properly.
b. **Pelletizing:** A pellet making facility consisting of raw material transport, storage in day bins, weighing, mixing, and drum pelletizing to produce 12.1 t/h of green pellets.
c. **Furnaces:** A pellet thermal processing system that includes the capability to dry the green pellets on a mesh belt dryer, transport them to the PSHF system, preheating them there in a preheat zone to 1200°C (1290°F), reducing them at 1500°C (2730°F), indirectly cooling them to 815ºC (1500ºF), with final cooling to 90ºC (200ºF) by quenching with water. The PSHF system should be fired with non-preheated, oxygen-enriched air, thereby avoiding the problems of dust clogging of the recuperators that would otherwise be required to achieve adequate flame temperature in the PSHF system. The furnace system will consist of two parallel furnaces to allow gas transport between the two to minimize pellet reoxidation after reduction.
d. **Emission Control:** An off-gas exhaust system consisting of two separate treated off-gas streams feeding a single stack. Dust-laden air from pellet making and handling will enter a bag house with a cloth area of 870 m^2 (9300 ft^2). Products of combustion from the PSHF will enter a settling chamber which also will act as a post-combustor and the post-combusted off gas will then be cooled by a water-spray quench. The gases will then be passed through a bag house with a filter area of 3420 m^2 (36,600 ft^2) before passing to the stack.
e. **Instrumentation:** An instrumented system to sufficiently capture all relevant information regarding material feed rates, industrial gas and natural-gas flow rates, furnace gas compositions and temperatures, and emissions. The purpose will be to acquire all information necessary to quantify the energy efficiency of the process and to define the system productivity.

The most likely point of initial entry into the mainstream market for the PSHF DRI product is an electric arc furnace (EAF) or BOF steel making facility that can consume DRI containing a limited amount of gangue. Such plants could include producers of slab, coil, long products, or specialty steel products.

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13.0 APPENDICES

Appendix A: ñAgglomeration and Green Ball Handling Study for the AISI PSH Furnace Project,ò Natural Resources Research Institute Coleraine Minerals Research Laboratory, August 25, 2009.

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Appendix D: ñEquipment Descriptions for PSHF Demonstration Plant,ò ANDRITZ Bricmont Inc., August 15, 2014.

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Appendix A: AGGLOMERATION AND GREEN BALL HANDLING STUDY FOR THE AISI PSH FURNACE PROJECT (Coleraine Minerals Research Laboratory) August 25, 2009

Agglomeration and Green Ball Handling Study for AISI PSH Furnace Project

COLERAINE MINERALS RESEARCH LABORATORY

August 25, 2009

By_____
Richard Kiesel – Deputy Director
High Temperature Processing

Approved by_____
David Hendrickson – Director
Coleraine Minerals Research Laboratory

NRRI/TR-2009/21

Natural Resources Research Institute
University of Minnesota – Duluth
5013 Miller Trunk Highway
Duluth, Minnesota 55811

Coleraine Minerals Research Laboratory
P O Box 188
One Gayley Avenue
Coleraine, Minnesota 55722

Summary

The Coleraine Minerals Research Laboratory (CMRL) of the Natural Resources Research Institute (NRRI), University of Minnesota Duluth (UMD) conducted an agglomeration and green ball handling study for the AISI Paired Straight Hearth (PSH) Furnace Project. The objective was to determine the green ball quality and material handling characteristics of both wet and dry coal-containing agglomerates that will be fed to a PSH furnace to produce direct reduced iron (DRI). Green balls were developed in both batch and pilot scale for physical quality determination, and were optimized for surviving a prescribed material handling circuit. Several industry standard binder systems were evaluated for production of quality green balls in batch scale experimentation and subsequently verified in pilot scale tests. A device was fabricated to simulate the moving hearth of the PSH furnace and green ball performance was evaluated for stacking a tall bed in an effective, stable, and economical manner.

Based on bench and pilot scale test results, the superior properties of green balls can be achieved to successfully withstand the material handling described for the Paired Straight Hearth Furnace. A conventional binder system using cooked starches or commercially available CMC binders added in slight excess to typical iron oxide production facilities can be added to achieve the desired strength. Green balls containing approximately 1.8% binder and 12.3% moisture were successfully green dropped 18" over 20 times without fracture and dry dropped 18" onto a brick surface 18 times. Reducing the binder content to 0.9% still retained significant green ball properties with relatively the same moisture, with a green ball drop of 20+ and dry drop of 3.0. Intensive mixing is recommended for improving green ball quality through dispersion of the binder in the iron oxide-coal mix. Further optimization of the binder addition can likely be achieved with minimal effort; however, for the purpose of demonstrating the technology, the proposed green ball quality is recommended. Iron ore concentrate balling and handling was very straightforward and performed very well. In the case of the waste oxides, additional material preparation steps should be considered prior to balling. The blending of coal into the fine waste oxides was best achieved in a dry state without micro-balling. Drying to the desired moisture content or lower is recommended and/or blending with another coarse fraction of iron oxide. Material handling characteristics for green balls prepared with iron ore concentrate and BOF sludge resulted in 99% or better retained integrity or generation of less than 1% fines.

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Test Program Overview

The goal of this program was to establish and recommend methods for preparation of wet and dry iron oxide/coal green pellets, capable of attaining material handling properties necessary for stacking a tall bed in an effective, stable, and economical manner. The methods tested were used to provide minimum degradation and breakage from dropping through an automated device, onto a moving refractory hearth while achieving adequate bed height and level.

Green balls were developed in both batch and pilot scale for physical quality determination, and were optimized for surviving a prescribed material handling circuit. Several industry standard binder systems were evaluated for production of quality green balls in batch scale experimentation and subsequently verified in pilot scale tests. A device was fabricated to simulate the moving hearth of the PSH furnace, and green ball handling performance was measured.

The purpose of this study was to confirm prior laboratory tests conducted elsewhere during process development bench testing and produce green pellets with characteristics more closely related to commercial pellets. In addition, the pellets produced were evaluated for material handling characteristics under the conditions closer to real world conditions. The results of this program will serve as a decision tool for further design and construction of a pilot plant for potential commercialization of AISI technology for metallization in a tall bed in a PSH (Paired Straight Hearth) furnace from ore/coal composite agglomerates.

Feed Materials Characterization

Four basic materials were required to make green pellets for testing. These are iron oxide bearing material, carbon bearing material, binder material, and water. Two basic iron oxide sources were provided to CMRL for evaluation: 1) finely ground magnetite from Minnesota Ore Operations and 2) BOF sludge generated at the U. S. Steel Mon Valley Works. The specifications for iron ore concentrates was unfluxed acid concentrate containing approximately 4 percent silica (SiO_2). Minnesota magnetite concentrate does not typically contain other significant impurities; although these parameters were measured, they were not considered in concentrate selection. It should be noted that the initial phase of this study was conducted with available raw material, then confirmed with "site-specific" raw materials provided by AISI or concerned companies.

Magnetite

Finely ground magnetite concentrate was initially obtained from the ArcelorMittal, Minorca Mine in northern Minnesota. The concentrate is described as standard concentrate containing less than 4 percent silica (SiO_2), and no significant flux stone. The concentrate chemistry was reported on a dry weight basis and is described in Table 1:

Tot Fe	Fe^{++}	SiO_2	Al_2O_3	MnO	CaO	MgO	P	S	TiO_2	Na_2O	K_2O
67.6	22.1	3.83	0.03	0.10	1.12	0.47	0.002	0.006	<0.020	0.008	0.012

Table 1. ArcelorMittal Magnetite Concentrate Chemistry

Unusually high levels of CaO and MgO, highlighted in red, indicate that some flux-stone was added to the concentrate prior to obtaining the sample. The relatively small amount was determined to be insignificant in developing green ball properties for material handling purposes.

Additional analyses resulted in concentrate grind of 81.7% passing 325 mesh[1] (45µm), Blaine specific surface area of 1909 cm^2/g, specific gravity of 4.93 g/cm^3 and free moisture content of 8.4%. Based on the results indicated above, the concentrate was determined to be acceptable for preliminary evaluation of green ball properties in reference to the project objectives.

Subsequent testing was done to verify the previous work using magnetite concentrate obtained from U. S. Steel Minntac in Mountain Iron, Minnesota. During the testing period, this plant was operating on fluxed pellet production. To satisfy the acid concentrate requirement of the raw material specifications described above, the concentrate was collected as slurry following flotation and prior to flux addition, (flot concentrate). The slurry was then mixed well and filtered in the lab to achieve the desired concentrate moisture of approximately 9.0%. The U. S. Steel Minntac concentrate chemistry is based on a dry weight and is shown in Table 2 below.

Tot Fe	Fe^{++}	SiO_2	Al_2O_3	MnO	CaO	MgO	P	S	TiO_2	Na_2O	K_2O
69.3	23.2	3.55	0.05	0.09	0.14	0.10	0.008	0.010	< 0.020	0.007	0.004

Table 2. U. S. Steel Minntac Magnetite Concentrate Chemistry

Further analysis resulted in concentrate grind of 81.9% passing 325 mesh, (45µm), Blaine specific surface area of 1834 cm^2/g, and specific gravity of 5.01 g/cm^3. A comparison of the two magnetite concentrates shows the similarities in size distribution in Figure 1 below:

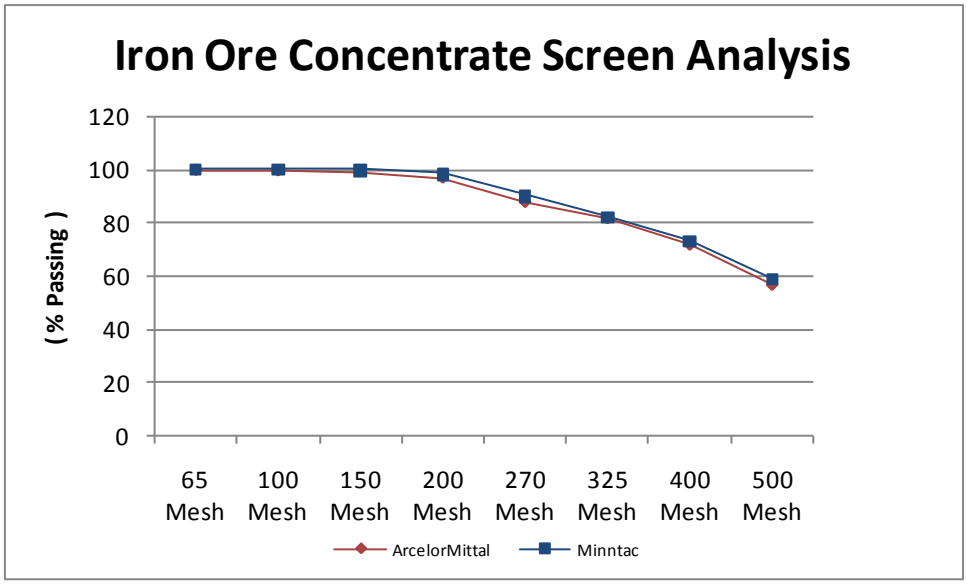

Figure 1. ArcelorMittal and U. S. Steel Minntac Concentrate Screen Comparison

[1] The mesh designation used throughout this report is based on the Tyler Sieve Series, used commonly in the taconite mining industry of northern Minnesota.

Marfork Coal

An eastern U.S. coal was provided through U. S. Steel Research (Marfork Coal from West Virginia) as an additive, and can be defined as a high-volatile bituminous type. Coal was added from 16 to 18 percent by weight, (17% baseline) and the effect of coal addition was determined with respect to the handling properties of the resultant green pellets. The coal contains relatively low ash and low sulfur. A total carbon analysis of the "as received" coal was 82.4%. Proximate and Ash Mineral analyses are provided in Tables 3 and 4.

Table 3. Marfork Coal Proximate Analysis

Proximate Analysis			
	ASTM Method	**As Received, %**	**Dry Basis, %**
Moisture	D2961 D3302 D3173	0.84	
Volatile	D3175M	31.51	31.78
Fixed Carbon	D3172	60.98	61.49
Ash	D3174	6.67	6.73
Sulfur	D 4239 Method B	1.03	1.04
BTU/lb.	D5865	14357	14479
lbs. SO2/MM BTU		1.44	1.44
lbs. Sulfur/MM BTU		0.717	0.717

Table 4. Marfork Coal Ash Mineral Analysis

ASTM Method	**D2795**	**D3682**
SiO2	51.50%	
Al2O3	24.40%	
Fe2O3	15.37%	
TiO2	1.17%	
P2O5	0.20%	
CaO	1.45%	
MgO	1.08%	
Na2O	0.52%	
K2O	2.00%	
SO3	1.25%	

The coal was dried and pulverized using various grinds to obtain approximately 80 percent passing 100 mesh (150 μm). A series of grinding tests was completed resulting in a 12 minute grind to achieve 77.2% passing 100 mesh (150 μm), shown in Figure 2. Optimum strength of dry pellets may require a different grind that will be determined by experimentation.

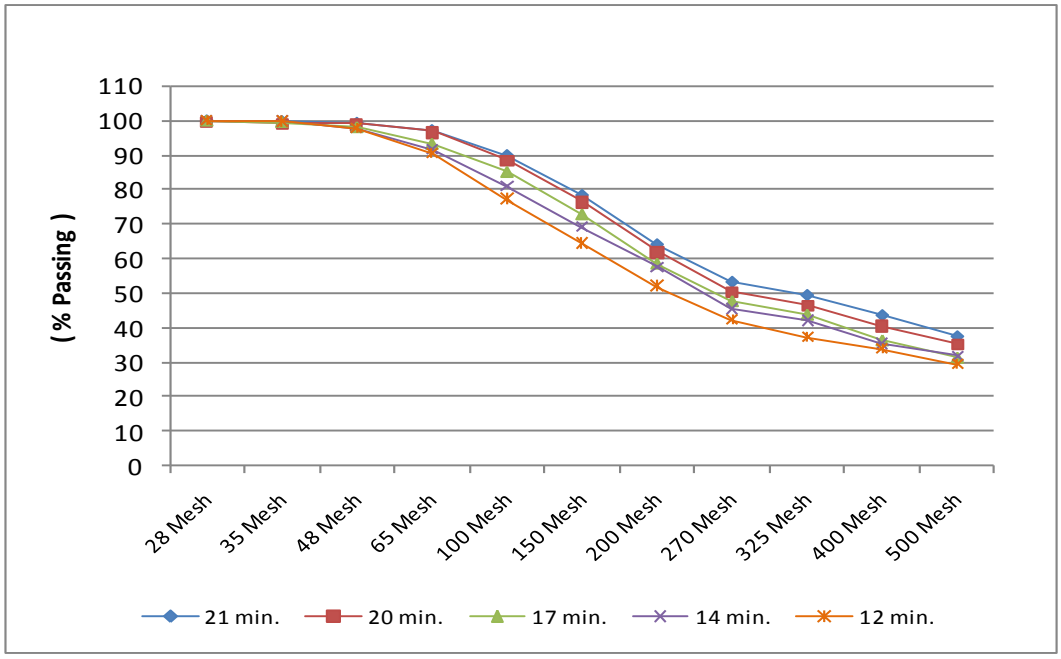

Figure 2. Marfork Coal Grinding Screen Comparison

Binders

Bentonite clay is the most common binder used for agglomerating taconite concentrate for standard blast furnace iron oxide pellets and was therefore chosen as a baseline. Although bentonite was considered, for this process organic binders were the primary focus so as not to add additional mineral gangue components for production of direct reduced iron (DRI) pellets. Several binders were evaluated, including carboxymethyl cellulose (CMC), corn and wheat based starches, polymeric, lime-molasses, and Portland cement. Further characterization or analysis of binders was not performed due to the proprietary nature of individual binders and agreements with suppliers.

Waste Oxides

The waste oxide (BOF sludge) was received in Coleraine from U.S. Steel Research. The material arrived with approximately 50-75mm (2-3") of water on top. The water was decanted off and base moisture for the BOF sludge was found to be 28%. Material chemistry, based on dry weight, is provided in Table 5 below:

Chemistry, %												
Tot Fe	Fe^{++}	SiO_2	Al_2O_3	MnO	CaO	MgO	P	S	TiO_2	Na_2O	K_2O	ZnO
48.74	9.16	1.22	0.09	0.69	9.57	2.07	0.029	0.15	0.029	0.283	0.111	7.7
46.36	7.91											

Table 5. BOF Sludge Chemistry

It should be noted that the total iron concentration appears to be relatively low for BOF sludge. The analysis was re-run on a separate sample, and was determined to be in range of acceptable analysis error. Particle size distribution of the BOF sludge was found to be significantly finer

than the iron ore concentrate (~17,000 cm^2/g vs. 1909 cm^2/g). The material is 86% passing 500 mesh (25 μm), but it is believed a significant portion of the fine fraction is –5 micron due the extremely high Blaine specific surface area. A comparison of the BOF sludge vs. the iron ore concentrate is provided below.

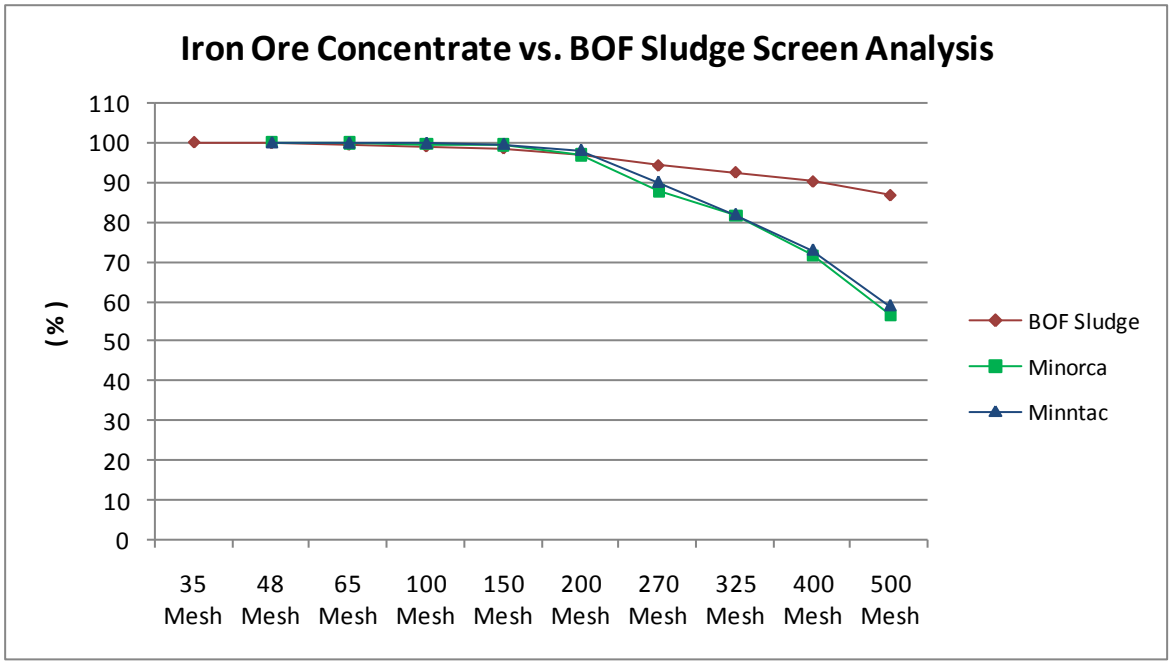

Figure 3. BOF Sludge Screen Comparison to Iron Ore Concentrate

Since the fine BOF sludge is very much like clay and not manageable for agglomeration as received, we attempted several techniques for sample preparation. For a full description of the preparation techniques established for pilot testing of waste oxides, see Appendix A.

Water Chemistry

Water chemistry can play an important role in surface-area-based agglomeration due to the relatively low additive rates of binders and high surface areas. In the initial phase of this study, using the ArcelorMittal concentrate, CMRL tap water was used for agglomeration. Although no formal analysis was done, in subsequent tests with U. S. Steel concentrates, water removed from decanting the received samples was used. Since the focus of this project was to produce sufficient quality green agglomerates for material handling, excess binder was likely used that may have masked any influence of water chemistry.

Batch Pelletizing Tests

Batch-wise green ball development tests are routinely used to establish the binder addition rate necessary to achieve adequate wet and dry strengths. Batch balling studies are designed for comparing the influence of binders, additives, or balling techniques on individual green ball physical quality parameters. Green ball physical quality is evaluated by comparing green ball moisture content, 18" wet drop number, wet compressive strength, dry compressive strength, and

sizing to a baseline binder. Figure 4 shows the batch balling test equipment and arrangement, consisting of a Mueller mixer, shredder, and balling tire.

Figure 4. Batch Balling Test Equipment and Arrangement

The balling apparatus consists of a 380 mm (15") diameter airplane tire that operates at approximately 50 rpm. Raw materials were weighed in proper proportions using magnetite concentrate, coal and binder. Bentonite was added in excess (1.5%) to establish a baseline for comparison purposes.

The typical procedure consists of accurately weighing out the desired mix, 83% concentrate and 17% coal. For this series of tests the starting weight of raw material was 2000g dry basis (vs. our typical lab standard of 3000g dry) due the relatively low bulk density of coal and large volume required to achieve the weight percentage. Moisture was then added to obtain approximately 9.5% to get uniform starting moisture. Binder is added in addition to the 2000g at the requested dosage rate and thoroughly blended. With some binders, high intensity mixing is required, and a "V" mixer is used.

The green ball target size was between 16.0 and 19.0 mm (– 3/4"+5/8"). To achieve this, a starting weight of "seed" balls was used. Seed balls are initially prepared from the sample as a first step to the balling procedure. Our lab standard procedures are then used to grow the seed balls to the desired size. It should be noted that size distributions from batch balling studies are used primarily as an indicator of growth rate and are not necessarily a scalable factor to achieve a specified size range[2]. For this project, the seed ball starting weight was reduced to produce larger than typical green balls (+12.5mm) while keeping our standard balling practices. Moisture is used as required to coalesce the green agglomerates and provide the necessary plasticity for growth rate and wet strength. Green ball moisture was consistently on the high side (+12%) compared to typical iron ore agglomerates, due to the additional moisture required to agglomerate the blend of coal and concentrate. Initial green ball evaluations were based upon moisture content, wet compression strength, 18" wet drop number onto a standard steel plate, 18" and 36" wet drop number onto a brick, dry compression strength and sizing.

[2] A 16.0mm (5/8") screen was not included in the sieve set for batch balling studies for this reason.

Magnetite Concentrate (ArcelorMittal)

As stated earlier, bentonite clay is the most common binder used for magnetite concentrate agglomeration and was therefore chosen as a baseline for comparison purposes. The nominal addition rate is 0.6-1.2 percent by weight; however, for purposes of enhancing green ball properties above the normal range, a 1.5% bentonite baseline addition was used. With these feed materials, we found using slightly larger seed balls than our standard test procedure (6.3mm vs. 4.75 mm) and decreasing the starting weight (noted in Appendix B) produced green balls in the desired size range. Preliminary targets of 15-20 lbs dry compressive strength on -19.0mm +16.0mm dried green balls were established as evaluation criteria in the initial proposal. However, since definitive green strength quality targets are not known for this process, it was decided that they must be established in pilot scale and material handling tests. Further discussions with Dr. Wei-Kao Lu altered this evaluation to use both wet and dry drop numbers. As a result, test procedures were developed for dry drops from 6", 12" and 18" onto a refractory brick surface. Results from these tests along with the standard 18-inch wet drop test from 18 inches were used as primary decision criteria. Subsequently, the 36" wet drop number was eliminated[3]. As a secondary criterion, sizing was also considered on the basis of green ball growth rate, considering the targeted size range was significantly larger than typical iron ore green balls.

The results of the batch balling study are provided in Appendix B. Several commonly used iron oxide binders were evaluated in Test ID AISI-1 through AISI-29. Some of these tests did show possibility, and may likely have potential for further optimization. However, Test ID AISI-31 and AISI-32 using a cooked starch binder at 0.9% and 1.8% were established as a baseline for further testing with the magnetite concentrate. The cooked starch product is readily available, easy to use, and provides sufficient strength and size characteristics to establish as a baseline binder for subsequent pilot scale testwork. Test ID AISI-30, using the CMC binder was also comparable however resulted in slightly lower quality than the starch binder technique. Increasing the size of seed balls from 4.75mm to 6.3mm also appears to show an improvement in green ball quality, specifically in the case of the CMC binder, however this was not confirmed with the cooked corn starch binder testwork. The result of all cooked starch binder tests shows +95% in target size range indicating a good growth rate. AISI-31 with 0.9% binder addition resulted in a standard 18-inch wet drop number of 6, a 6-inch dry drop number of 18 and an 18-inch dry drop number of 3. AISI-32 with 1.8% binder addition resulted in a standard 18-inch wet drop number of 20+, a 6-inch dry drop number of 20+ and an 18-inch dry drop number of 18. The cooked starch binders also produced superior dry compression strength to the binders tested. For this binder evaluation, wet drop numbers and the dry strength values were measured on the standard -12.5mm +11.1mm (-1/2" + 7/16") dried green balls, due to limited material in the case of some binders in the -19.0mm +16.0mm size fraction. The wet and dry drop values reported are an average of 20 green balls dropped individually from a stationary point at the height specified until they fracture (crack, break or chip). Green ball quality results for test ID AISI 30-32 are shown in Table 6 below:

[3] The drop numbers are reported in inches vs. mm based on the standard practice routinely used in US industry

Test	Coal	Binder	Binder	Moist.	Wet Drop #	Dry Comp	Dry Drop # (Brick)		
	%		%	%	18" std	lbs.	6"	12"	18"
AISI-30	17.0	CMC	0.25	12.3	20+	18.1	16.5	3.4	2.9
AISI-31	17.0	Cooked Corn Starch	0.90	12.3	6.2	21.9	18.8	5.2	3.0
AISI-32	17.0	Cooked Corn Starch	1.80	12.5	20+	46.0	20+	20+	18

Table 6. Magnetite Concentrate Batch Balling Green Ball Quality

Waste Oxides (BOF Sludge)

The result of high surface area and the blending of coal and binder resulted in the BOF sludge micro-balling when used as a standalone source of iron oxide, and it was essentially unsuccessful in our batch balling arrangement. Although green agglomerates could be made with 100% BOF sludge and coal, the standard techniques produced significant amounts of micro-agglomerates that did not satisfactorily grow into a sufficient quantity of properly sized green balls. To prep the BOF sludge for testing it was determined that it must be dried, then pulverized to break up the micro-agglomerates formed when drying to get it back into a workable form for balling. In batch balling testwork, due to the fineness of this material, it was also found that the dried pulverized material had to be blended with a coarse fraction to get the material to a size distribution that would generate properly sized green balls (See APPENDIX A for full detail). Initial study was done using ArcelorMittal Minorca iron ore concentrate however, due to the lack of available concentrate at the source of the BOF sludge, fired pellet fines (unknown source) were substituted. The pellet fines were screened at 48 mesh (300 μm) to eliminate any of the larger chips. Batch balling test AISI-41 results are shown below using a 50:50 blend (BOF sludge to pellet fines) with 0.25% CMC binder. The cooked starch binder was substituted with the CMC to minimize the addition of excess moisture creating the micro balling. Bench scale green ball data for the BOF sludge testwork are shown in Table 7.

						Green Ball Quality					
Test	Iron Oxide	Coal	Binder	Binder	Seeds	Moisture	Drop #	Dry Comp	Dry Drop #		
		%		%	g	%	18" std	lbs.	6" Brick	12" Brick	18" Brick
AISI-34**	Dried BOF Sludge	17.0	Cooked Corn Starch	1.8	150 (+20M)	20.9	20+	19.7	20+	20+	17.2
AISI-36**	Dried BOF Sludge	17.0	CMC	0.25	150 (+1/4")	16.9	20+	7.8	16.0	4.4	2.3
AISI-37**	Dried BOF Sludge	17.0	CMC	0.25	150 (+1/4")	16.9	20+	14.1	9.8	2.8	1.6
AISI-38	Dried BOF Sludge(20%) Mag Con (80%)	17.0	CMC	0.25	150 (+1/4")	13.0	20+	15.9	11.2	4.2	2.0
AISI-39	Dried BOF Sludge(40%) Mag Con (60%)	17.0	CMC	0.25	150 (+1/4")	14.6	20+	14.1	12.5	5.3	2.8
AISI-40**	Dried BOF Sludge	17.0	CMC	0.25	150 (+1/4")	15.8	20+	11.6	9.6	2.8	1.8
AISI-41	Dried BOF Sludge(50%) Pellet Fines (50%)	17.0	CMC	0.25	150 (+1/4")	16.2	20+	13.7	15.8	8.8	2.6

** See Appendix A for sample preparation methodology / techniques relating to variation between individual tests

Table 7. Dried BOF Sludge Batch Balling Green Ball Quality

The results show that quality green balls can be attained using the BOF sludge with the pellet fines additive.

Pilot Disc Pelletizing Tests

Test work was carried out using the pilot scale pelletizing disc (Figure 5) available at CMRL. The pellets produced on a 3-ft diameter disc were assumed to be a good first approximation to those that will be produced in the PSH pilot-plant. Once binder and addition rates were established from batch tests, green balls were prepared in 45 kg (100 lb) batches. Proper

proportions of magnetite concentrate, coal, and binder were blended using high intensity mixing with a pilot-scale Littleford mixer (Figure 6) to ensure uniform blends.

Figure 5. Balling Disc

Figure 6. High-Intensity Mixer

The pellet size target was 16.0mm to 19.0mm on a continuous basis with the undersize fractions returned to the mix. Green ball evaluation was the same as used in batch balling tests. Digital video, displaying the agglomeration and screening techniques, has also been provided for both iron oxide portions of this agglomeration testwork.

Waste Oxides (BOF Sludge)

Dried BOF sludge was successfully agglomerated without blending in any coarse fractions, and the similar issues observed on the bench scale were minimized. Cooked starch binder at 0.9% resulted in satisfactory quality, however, in the case of the dried BOF sludge, CMC binder (0.35%) produced higher quality green balls. Results from BOF sludge balling trials are shown in Table 8.

					Green Ball Quality					
Test	Iron Oxide	Coal	Binder	Binder	Moisture	Drop #	Dry Comp		Dry Drop #	
		%		%	%	*18" std*	lbs.	*6" Brick*	*12" Brick*	*18" Brick*
B09503	Dried BOF Sludge	17.0	Cooked Corn Starch	0.9	15.2	20+	18.4	20+	8.3	3.3
B09504	Dried BOF Sludge	17.0	Cooked Corn Starch	1.3	14.9	20+	28.8	20+	16.3	10.9
B09506	Dried BOF Sludge	17.0	Cooked Corn Starch	0.9	12.6	20+	16.4	11.1	3.2	2.1
B09507	Dried BOF Sludge	17.0	Cooked Corn Starch	0.9	13.3	20+	17.9	20+	9.1	3.5
B09510	Dried BOF Sludge	17.0	CMC	0.35	13.9	20+	23.3	20+	14.2	4.5

Table 8. Pilot Scale Balling Test Results with Dried BOF Sludge

In all cases significant amount of fines were generated in the production of sized green balls and it is expected that commercialization of this process will result in higher recycle loads than conventional iron oxide balling circuits. In these tests, undersize fractions were returned to the balling disc to grow, however limited amount of feed materials prevented full utilization of all of the prepped feed. To ensure sufficient quantities, the size distribution of these tests was initially reduced to -16.0mm +12.5 mm green balls due to the slower growth rate. However, subsequent testing found that achieving the -19.0mm +16.0mm green balls was attainable. Figures 7 to 9 below, show the result of pilot scale balling test B095003 using dried BOF sludge with 17% coal and 0.9% CMC binder.

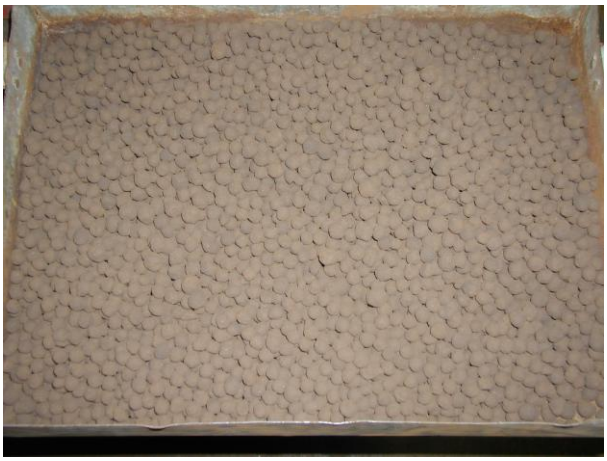

Figure 7. Dried BOF sludge +12.5mm Product

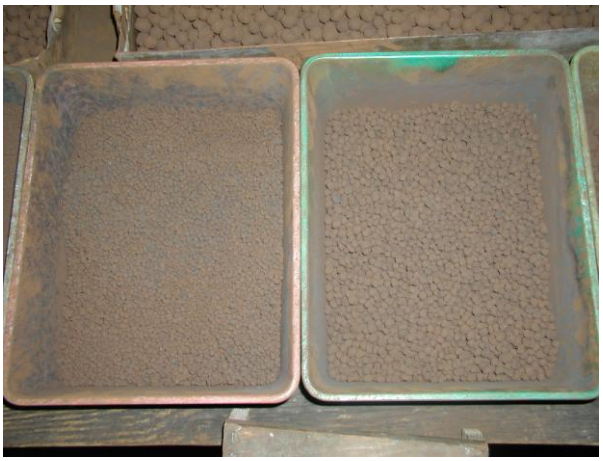

Figure 8. Dried BOF Sludge Seed Balls

Figure 9. Dried BOF Sludge Fines

Magnetite Concentrate

Preparation of green balls with the ArcelorMittal concentrate, coal and binder resulted in improved green ball quality over the batch balling tests. This testwork was confirmed with a single test using U. S. Steel Minntac concentrate[4]. Superior strength green balls were made with both concentrates, coal and 1.3% cooked starch binder. Further reduction of binder is likely; however, for the purposes of this study, binder optimization is not necessary at this stage of process development. No significant issues were observed and the material seemed to ball quite readily. It should also be noted that the coal addition was varied ±1% in test ID# B09508 and B09509 with no significant change in green ball quality results. Pilot-scale green ball quality results using iron ore concentrates are provided in Table 9.

[4] U. S. Steel Minntac was operating with fluxed concentrate during the trial period. Acid concentrate was unavailable in large quantities for multiple pilot scale testwork.

Test	Iron Oxide	Coal	Binder	Binder	Green Ball Quality					
					Moist.	Drop #	Dry Comp	Dry Drop #		
		%		%	%	18" std	lbs.	6" Brick	12" Brick	18" Brick
NA	Minorca Mag Con	17.0	Cooked Corn Starch	1.8	12.7	20+	56.7	20+	20+	20+
B09505	U.S. Steel Minntac Mag Con	17.0	Cooked Corn Starch	1.3	13.8	20+	52	20+	20+	18.8
B09508	Minorca Mag Con	16.0	Cooked Corn Starch	1.3	11.9	20+	94.4	20+	20+	20+
B09509	Minorca Mag Con	18.0	Cooked Corn Starch	1.3	12.4	20+	83.3	20+	20+	20+
B09511	Minorca Mag Con	17.0	Cooked Corn Starch	1.3	12.5	20+	67.3	20+	20+	19.6

Table 9. Pilot Scale Balling Test Results with Magnetite Concentrate

Material Handling

A simple device was fabricated with a moving belt and hopper chute that discharges onto a moving refractory hearth with sidewalls. The dried balls drop from a variable but minimal height to a moving hearth fabricated with a brick hearth and side walls to accommodate adequate depth (up to 200 mm) and level measurement. The hearth is pulled by a motorized cable/winch at constant speed to simulate grate movement. The speed of the belt feeder and rolling refractory hearth is regulated by a variable frequency drive for setting desired control parameters.

Dry balls were fed from the belt feeder/hopper to regulate dry ball flow and distribution. The drop distance can be adjusted by manually setting the rail height of the moving hearth simulator. The feed rate was controlled to correspond to 1-1.5 tonnes per square meter per hour (t/m^2-hr) feed rate, and separately to provide a 120mm and 200 mm bed depth. The hearth width is 12" with segmented dividers to allow for accurate measurement of green balls per unit area. Loading of 16.0mm x 19.0mm pellets into the hopper was accomplished by hand. The target for fines was to have less than 5 percent smaller than 12.5 mm on the charge to the pilot-plant furnace. A schematic description of the device is shown in Figure 10, with actual photos shown in Figures 10 and 11.

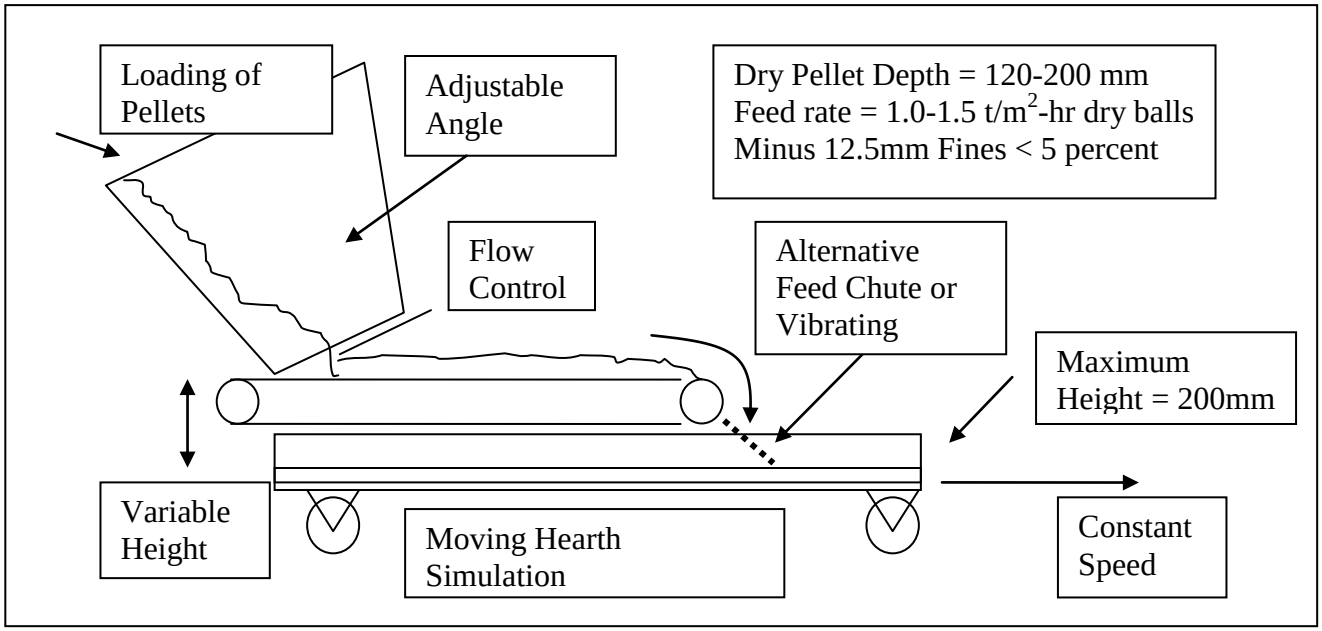

Figure 10. Schematic Representation of the Moving Hearth Simulator

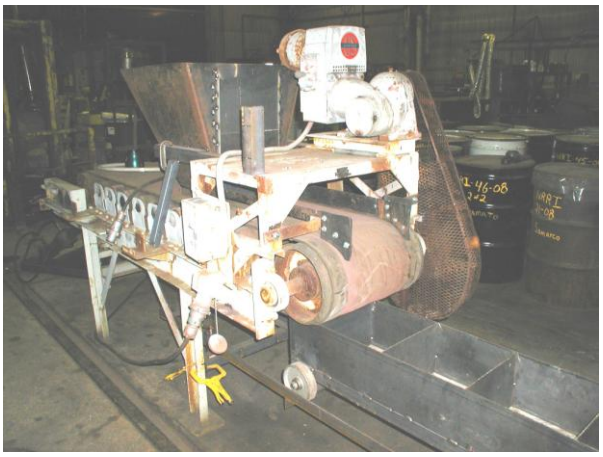

Figure 11. Moving Hearth Simulator

Figure 12. Moving Hearth Simulator Feed

The initial trial started with 100% +12.5mm dried green balls, dropped 420mm (16.5") onto the brick hearth (120mm depth), resulting in generating 0.1% -12.5mm (99.9% +1/2") fines. Figures 13-16 below show photos of the initial test (Test #1) with ArcelorMittal concentrate, 17% coal addition and 1.8% cooked starch binder.

Figure 13. Green Ball Feeding Hearth Simulator (Initial Test)

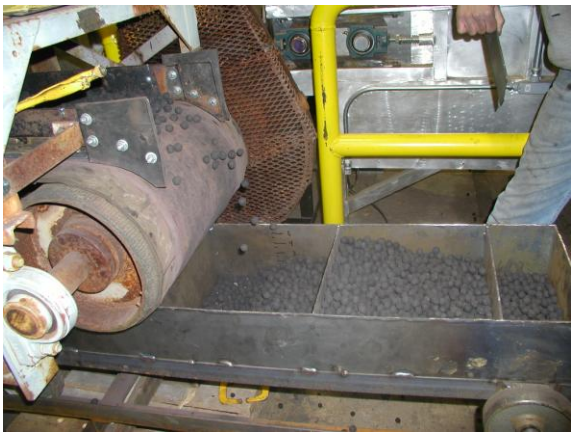

Figure 14. Hearth Simulator - (2) (Initial Test)

Figure 15. Results of Hearth Feeding, (Initial Test) - Test 1

Figure 16. Hearth Feeding, (2) (Initial Test) - Test 1

Initial trials were conducted without regard to feed rate or car movement, focusing primarily on green ball integrity. Subsequent test results are shown in Table 10, where superior green ball quality resulted in a minimum of 97.6% +12.5mm with a bed depth of 120mm, and a drop height of 420mm. The resulting deep bed was very level; however the dividers shown in the above photo resulted in a slight buildup at the edge that would not be present in a continuous process.

				Moving Hearth Simulation Test Results				
Test	Iron Oxide	Coal	Drop Height	Bed Depth	Feed Rate	+12.5mm	+6.3mm	-6.3mm
		%	(mm)	(mm)	t/m^2-hr	%	%	%
NA	Minorca Mag Con	17.0	400	100		99.9	0.0	0.1
B09503	Dried BOF Sludge	17.0	420	125		98.0	1.5	0.4
B09504	Dried BOF Sludge	17.0	400	100		97.8	2.0	0.2
B09505	U. S. Steel Minntac	17.0	420	120		97.6	2.3	0.1
B09506	Dried BOF Sludge	17.0	400	110		99.1	0.0	0.1
B09507	Dried BOF Sludge	17.0	400	125		98.0	1.8	0.2
B09508	Minorca Mag Con	16.0	400	120		99.9	0.0	0.1
B09509	Minorca Mag Con	18.0	400	120		99.9	0.0	0.1
B09510	Dried BOF Sludge	17.0	400	120		99.5	0.2	0.3
B09511	Minorca Mag Con	17.0	400	100	9.2	99.9	0.0	0.1
B09511	Minorca Mag Con	17.0	450	200	16.1	99.9	0.0	0.1
B09511	Minorca Mag Con	17.0	400	65	1.0	99.8	0.0	0.2
B09511	Minorca Mag Con	17.0	400	80	1.5	99.7	0.1	0.2

Table 10. Moving Hearth Simulator Test Results

Test ID # B09508 and B09509 show no significant variance in material handling characteristics between the additions of 16-18% coal. Test B09511 was prepared in large volume (+200 lbs.) to compare 100mm to 200mm bed depth and 1.0 – 1.5 t/m^2-hr feed rates using the same sample. The results of both 100mm and 200mm bed depth tests are shown in Figures 17 and 18 respectively, resulting in generation of less than 0.3% -12.5mm fines in all cases. To accommodate the deeper bed, an extension was added to the moving hearth to increase the depth.

Figure 17. 120mm Bed Depth

Figure 18. 200mm Bed Depth

No significant dissimilarities were found with respect to material handling properties of these feed variations.

Conclusions

Based on bench and pilot scale test results, the superior properties of green balls can be achieved to successfully withstand the material handling described for the Paired Straight Hearth Furnace. A conventional binder system using cooked starches or commercially available CMC binders added in slight excess to typical iron oxide production facilities can be added to achieve the desired strength. Green balls containing approximately 1.8% binder and 12.3% moisture were successfully green dropped 18" over 20 times without fracture and dry dropped 18" onto a brick surface 18 times. Reducing the binder content to 0.9% still retained significant green ball properties with relatively the same moisture, with a green ball drop of 20+ and dry drop of 3.0. Intensive mixing is recommended for improving green ball quality through dispersion of the binder in the iron oxide-coal mix. Further optimization of the binder addition can likely be achieved with minimal effort; however, for the purpose of demonstrating the technology, the proposed green ball quality is recommended. Iron ore concentrate balling and handling was very straightforward and performed very well. In the case of the waste oxides, additional material preparation steps should be considered prior to balling. The blending of coal into the fine waste oxides was best achieved in a dry state without micro-balling. Drying to the desired moisture content or lower is recommended and/or blending with another coarse fraction of iron oxide. Material handling characteristics for green balls prepared with iron ore concentrate and dried BOF sludge resulted in 99% or better retained integrity or generation of less than 1% fines.

APPENDIX A

Waste Oxide Sample Preparation

Since the fine BOF sludge is very much like clay and not manageable for agglomeration as received, we attempted several techniques for sample preparation. The initial sample was dried down to 13% moisture in a standard drying oven at 220^{o}F using weight loss. With this technique, the BOF sludge did not uniformly dry and created wet pockets, which resulted in significant micro-balling and plugging of the mixer/shredder while trying to blend in the coal and get it into a "workable" form. Filtering to attain target moisture was also unsuccessful. Using various solids percentages as well as surfactants, the BOF sludge generated cracks in the filter cake, directing the airflow through the cracks, and filter cake moisture remained essentially 22.6% regardless of retention time.

Our most successful trials were done by drying the material completely, which resulted in a solid "brick" of material (Figure 2). This material could then be brushed through a 20 mesh screen to get it back into a workable material (Figures 3-4). Attempts to produce green balls with these materials resulted in significant difficulty generating sized green balls due to micro-balling (Figures 5-7). It was decided that to make this stuff work we had to get it back into a "powder" state. We found that putting the material into a ball mill (for only a few seconds) resulted in the dust gumming up on the sides of the mill. Pulverizing the micro-agglomerates with a hand buckboard mill was successful in generating enough material to run a test (Figures 8-9). This material was easily mixed with the coal and it was possible to blend in water and binder for balling. A dry organic (CMC) binder was chosen so as not to add any more water than necessary. The fine pulverized material was capable of generating many more sized green balls than the previous try using the material at – 20 mesh, however, it still generated significant micro-balls. The resulting green balls look like "bunches of grapes" (Figures 10-13). This test was also repeated a second time using a smaller amount of initial seeds which resulted in the same size distribution and very similar looking agglomerates. Green strength of these agglomerates was much weaker than "round" sized green balls.

To speed up the process for raw material preparation, we adopted the technique of drying the BOF sludge completely, brushing it through a 20 mesh screen, and pass this product through Braun Pulverizer (single pass), to break up the micro-balls. The product was then brushed through a 48 mesh screen to get it into the "powder" state. This is the preparation state of the BOF sludge for the pilot scale balling tests. In batch balling testwork, due to the fine nature of the dried BOF sludge we needed to add in some coarser material to generate properly sized balls. Therefore, we blended in 20% and 40% of the BOF sludge (by weight) into iron ore concentrate. The results of this blended material (shown in Figures 14-17) were successful in generating properly sized green balls. Since iron ore concentrate is not readily available at the source of the BOF sludge, fired pellet fines were subsequently substituted (Figures 18-19).

Figure A-1. "As- received", 2-3" Water Decanted

Figure A-2. "As-received" and Dried

Figure A-3. Dried and Pushed through 20 Mesh

Figure A-4. Dried and Pushed through 20 Mesh - (2)

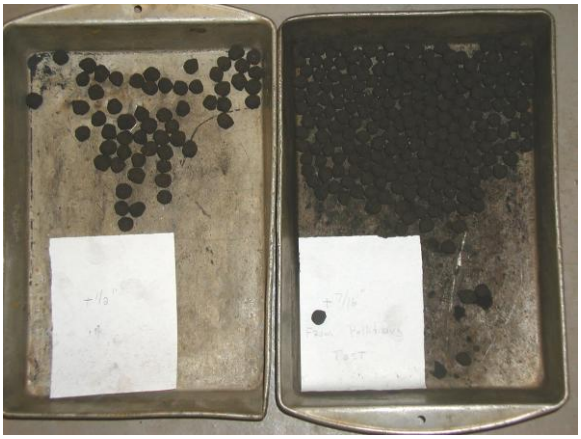

Figure A-5. 100% BOF +1/2" / +3/8 (from +20M micro-balls)

Figure A-6. 100% BOF +3/8 / -1/4 (from +20M micro-balls)

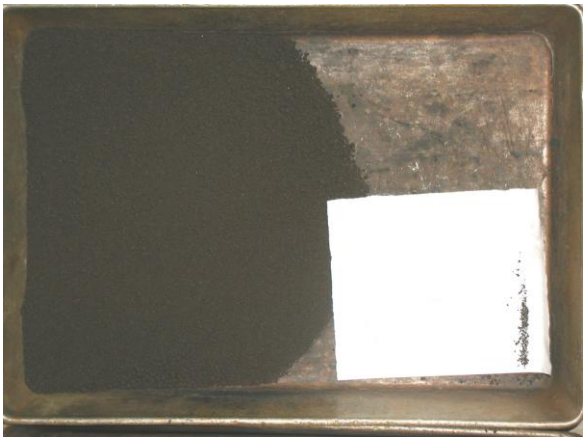

Figure A-7. 100% BOF Under-sized Green Balls (from +20M micro-balls)

Figure A-8. Dried and Pulverized BOF Sludge

FigureA-9. Dried and Pulverized BOF Sludge

Figure A-10. +1/2" Green Balls (100% BOF Sludge)

Figure A-11. +3/8" -1/2" Green Balls (100% BOF)

Figure A-12. Under-sized Green Balls (100% BOF)

Figure A-13. Seed Balls - 100% BOF Sludge

Figure A-14. 20% BOF Sludge – 80% Ore Conc. (+1/2") Test ID# AISI-38

Figure A-15. 20% BOF Sludge - 80% Ore Conc. (u'size) Test ID# AISI-38

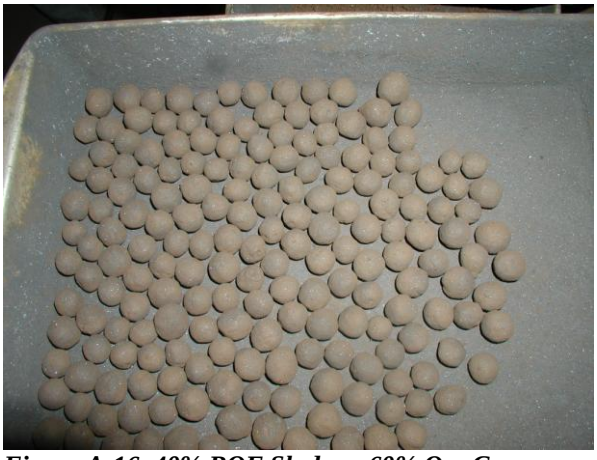

Figure A-16. 40% BOF Sludge - 60% Ore Conc. (+1/2") Test ID# AISI-39

Figure A-17. 40% BOF Sludge - 60% Ore Conc. (u'size) Test ID# AISI-39

Figure A-18. 50% BOF Sludge - 50% Pellet Fines (+1/2") Test ID# AISI-41

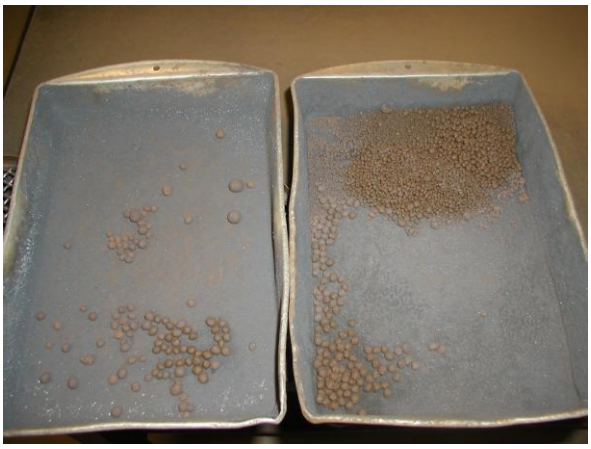

Figure A-19. 50% BOF Sludge - 50% Pellet Fines (u'size) Test ID# AISI-41

APPENDIX B Batch Balling Green Ball Data

Test	Iron Oxide	Coal	Binder	Binder	Seeds	Green Ball Quality						
						Moisture	Wet Drop #			Wet Comp	Dry Comp	Dry Comp
		%		%	g	%	18" std	18" Brick	36" Brick	lbs.	lbs.	24 hr. (lbs)
AISI-2	Minorca Mag Con	17.0	Bentonite	1.5	160	12.1	15.8	14.1	3.5	2.1	9.9	
AISI-4	Minorca Mag Con	17.0	CMC	0.5	150	13.2	28.2	22.5	6.8	1.4	20.6	
AISI-5	Minorca Mag Con	17.0	Polymer	0.5	150	14.1	N/A	N/A	N/A	N/A	N/A	
AISI-6	Minorca Mag Con	17.0	Wheat Starch	0.5	150	13.1	3.2	1.0	2.3	1.3	N/A	
AISI-7	Minorca Mag Con	17.0	Portland Cement	2.0	150	10.4	2.4	2.4	1.0	1.1	0.9*	
AISI-8	Minorca Mag Con	17.0	Lime/Molasses	2.0/3.0	150	9.9	7.0	6.4	2.0	2.2	12.1*	
AISI-9	Minorca Mag Con	17.0	CMC	0.25	150	12.0	14.1	14.9	4.0	1.5	12.3	
AISI-10	Minorca Mag Con	17.0	Polymer	0.125	150	12.9	3.7	3.9	1.0	1.0	1.9	
AISI-11	Minorca Mag Con	17.0	Polymer	0.3	150	N/A	N/A	N/A	N/A	N/A	N/A	
AISI-12	Minorca Mag Con	17.0	Hemicellulose Corn Starch	5.0	150	12.1	40.0	36.8	10.0	2.1	15.8	
AISI-13	Minorca Mag Con	17.0	Hemicellulose Corn Starch (2)	5.0	150	12.0	45.0	N/A	N/A	N/A	22.6	
AISI-14	Minorca Mag Con	17.0	Wheat Starch	1.8	150	12.3	4.8	3.7	1.8	1.2	5.8	
AISI-15	Minorca Mag Con	17.0	Wheat Starch (2)	1.8	150	11.5	3.5	3.0	1.0	1.2	1.7	
AISI-16	Minorca Mag Con	17.0	CMC	1.0	150	14.4	29.3	28.6	7.2	1.1	21.1	
AISI-17	Minorca Mag Con	17.0	Lime/Molasses	5.0/5.0	150	10.8	17.5	16.2	6.0	2.1	18.9*	
AISI-18	Minorca Mag Con	17.0	CMC	0.5	150	13.3	25.2	22.1	9.5	1.6	18.4	
AISI-19	Minorca Mag Con	17.0	CMC	0.25	150	12.1	18.3	16.8	2.6	1.3	11.0	9.2
AISI-20	Minorca Mag Con	17.0	CMC	0.25	140	12.2	16.4	16.7	4.0	1.7	10.7	10.4
AISI-21	Minorca Mag Con	17.0	CMC	0.25	128	12.2	12.3	11.6	3.0	2.0	13.7	13.1
AISI-22	Minorca Mag Con	17.0	CMC	0.35	128	13.2	52.5	48.6	6.7	1.5	15.1	14.4
AISI-23	Minorca Mag Con	17.0	CMC	0.35	128	13.3	49.5	41.6	9.7	1.7	17.5	13.4
AISI-24	Minorca Mag Con	17.0	Hemicellulose Corn Starch	2.50	128	11.9	8.9	NES	NES	NES	14.3	NES
AISI-25	Minorca Mag Con	17.0	Corn Starch	0.90	128	10.6	3.2	3.1	1.0	0.8	2.2	N/A
AISI-26	Minorca Mag Con	17.0	Corn Starch	1.80	128	11.1	2.9	2.1	1.0	1.1	2.6	N/A
AISI-27	Minorca Mag Con	17.0	CMC	0.25	128	11.9	17.0	12.6	4.0	1.8		
AISI-28	Minorca Mag Con	17.0	CMC	0.25	128	12.0	14.6	12.9	3.0	1.8	13.6	
AISI-29	Minorca Mag Con	17.0	CMC w/ High Intensity Mixing	0.25	128	12.1	17.5	15.8	3.9	1.7	13.6	
AISI-30	Minorca Mag Con	17.0	CMC	0.25	150 (+1/4")	12.3	20+				18.1	
AISI-31	Minorca Mag Con	17.0	Cooked Corn Starch	0.90	150 (+1/4")	12.3	6.2	N/A	N/A	N/A	21.9	N/A
AISI-32	Minorca Mag Con	17.0	Cooked Corn Starch	1.80	150 (+1/4")	12.5	20+	N/A	N/A	N/A	46.0	N/A

N/A = Not Available

NES = Not Enough Sample

* Extended drying time was allowed, (overnight approx 24 hrs.)

(2) Following the binder description, indicates a second variety or variation of these binder types

APPENDIX B Batch Balling Green Ball Data

Test	Iron Oxide	Coal	Binder	Dry Drop #			Green Ball Sizing, %				
		%		6" Brick	12" Brick	18" Brick	+3/4"	+1/2"	-1/2" +7/16"	-7/16" +3/8"	-3/8"
AISI-1	Minorca Mag Con	17.0	Bentonite				N/A	3.2	25.9	42.2	28.7
AISI-2	Minorca Mag Con	17.0	Bentonite				N/A	9.3	39.3	16.2	35.2
AISI-3	Minorca Mag Con	17.0	Bentonite				N/A	23.3	34.6	9.9	32.2
AISI-4	Minorca Mag Con	17.0	CMC				N/A	43.1	15.4	5.2	36.3
AISI-5	Minorca Mag Con	17.0	Polymer				N/A	N/A	N/A	N/A	N/A
AISI-6	Minorca Mag Con	17.0	Wheat Starch				N/A	4.1	23.7	28.5	43.7
AISI-7	Minorca Mag Con	17.0	Portland Cement				N/A	9.3	38.3	17.4	35.0
AISI-8	Minorca Mag Con	17.0	Lime/Molasses				N/A	26.7	34.5	18.0	20.8
AISI-9	Minorca Mag Con	17.0	CMC				N/A	17.8	43.5	8.0	30.7
AISI-10	Minorca Mag Con	17.0	Polymer				N/A	20.3	32.3	15.8	31.6
AISI-11	Minorca Mag Con	17.0	Polymer				N/A	N/A	N/A	N/A	N/A
AISI-12	Minorca Mag Con	17.0	Hemicellulose Corn Starch				N/A	23.6	19.9	18.0	38.6
AISI-13	Minorca Mag Con	17.0	Hemicellulose Corn Starch (2)				N/A	22.6	5.0	24.2	48.3
AISI-14	Minorca Mag Con	17.0	Wheat Starch				N/A	12.0	43.6	15.3	29.2
AISI-15	Minorca Mag Con	17.0	Wheat Starch (2)				N/A	22.8	41.5	8.2	27.4
AISI-16	Minorca Mag Con	17.0	CMC				N/A	22.9	23.7	13.7	39.7
AISI-17	Minorca Mag Con	17.0	Lime/Molasses				N/A	17.6	11.9	33.8	36.7
AISI-18	Minorca Mag Con	17.0	CMC				N/A	47.6	14.5	3.1	34.7
AISI-19	Minorca Mag Con	17.0	CMC				N/A	4.3	24.3	24.3	47.1
AISI-20	Minorca Mag Con	17.0	CMC				N/A	6.8	35.3	15.5	42.4
AISI-21	Minorca Mag Con	17.0	CMC				N/A	47.3	11.6	1.8	39.3
AISI-22	Minorca Mag Con	17.0	CMC				N/A	22.1	28.2	6.7	43.1
AISI-23	Minorca Mag Con	17.0	CMC				N/A	21.0	27.4	10.0	41.6
AISI-24	Minorca Mag Con	17.0	Hemicellulose Corn Starch				N/A	3.8	12.3	24.4	59.5
AISI-25	Minorca Mag Con	17.0	Corn Starch				N/A	18.1	25.1	16.0	40.8
AISI-26	Minorca Mag Con	17.0	Corn Starch				N/A	28.0	26.9	8.3	36.8
AISI-27	Minorca Mag Con	17.0	CMC				0.0	40.4	20.5	3.0	36.1
AISI-28	Minorca Mag Con	17.0	CMC			2.8	0.0	23.9	30.0	8.1	38.0
AISI-29	Minorca Mag Con	17.0	CMC w/ High Intensity Mixing			2.7	0.0	34.1	24.4	3.9	37.6
AISI-30	Minorca Mag Con	17.0	CMC	16.5	3.4	2.9	0.0	94.1	1.2	1.6	3.1
AISI-31	Minorca Mag Con	17.0	Cooked Corn Starch	18.8	5.2	3.0	0.0	98.0	0.6	0.7	0.7
AISI-32	Minorca Mag Con	17.0	Cooked Corn Starch	20+	20+	18.0	0.0	99.4	0.0	0.3	0.3

(2) Following the binder description, indicates a second variety or variation of these binder types

APPENDIX B Batch Balling Green Ball Data

Test	Iron Oxide	Coal	Binder	Binder	Seeds	Green Ball Quality					
						Moisture	Drop #	Dry Comp		Dry Drop #	
		%		%	g	%	*18" std*	lbs.	*6" Brick*	*12" Brick*	*18" Brick*
AISI-34**	Dried BOF Sludge	17.0	Cooked Corn Starch	1.8	150 (+20M)	20.9	20+	19.7	20+	20+	17.2
AISI-36**	Dried BOF Sludge	17.0	CMC	0.25	150 (+1/4")	16.9	20+	7.8	16.0	4.4	2.3
AISI-37**	Dried BOF Sludge	17.0	CMC	0.25	150 (+1/4")	16.9	20+	14.1	9.8	2.8	1.6
AISI-38	Dried BOF Sludge(20%) Mag Con (80%)	17.0	CMC	0.25	150 (+1/4")	13.0	20+	15.9	11.2	4.2	2.0
AISI-39	Dried BOF Sludge(40%) Mag Con (60%)	17.0	CMC	0.25	150 (+1/4")	14.6	20+	14.1	12.5	5.3	2.8
AISI-40**	Dried BOF Sludge	17.0	CMC	0.25	150 (+1/4")	15.8	20+	11.6	9.6	2.8	1.8
AISI-41	Dried BOF Sludge(50%) Pellet Fines (50%)	17.0	CMC	0.25	150 (+1/4")	16.2	20+	13.7	15.8	8.8	2.6

** See Appendix A for sample preparation methodology / techniques relating to variation between individual tests

Test	Iron Oxide	Coal	Binder	Green Ball Sizing, %				
		%		+3/4"	+1/2"	-1/2" +7/16"	-7/16" +3/8"	-3/8"
AISI-33	Minorca Mag Con	18.0	Cooked Corn Starch	3.9	93.2	1.8	0.4	0.7
AISI-34**	Dried BOF Sludge	17.0	Cooked Corn Starch	0.0	55.9	7.1	2.0	35.1
AISI-35	Minorca Mag Con	16.0	Cooked Corn Starch	3.5	95.1	1.1	0.2	0.2
AISI-36**	Dried BOF Sludge	17.0	CMC	0.0	12.7	28.9	14.6	43.8
AISI-37**	Dried BOF Sludge	17.0	CMC	6.7	66.4	9.2	8.3	9.4
AISI-38	Dried BOF Sludge(20%) Mag Con (80%)	17.0	CMC	0.0	88.3	4.0	2.5	5.2
AISI-39	Dried BOF Sludge(40%) Mag Con (60%)	17.0	CMC	0.0	98.6	0.0	0.8	0.5
AISI-40**	Dried BOF Sludge	17.0	CMC	0.0	81.8	12.8	1.9	3.5
AISI-41	Dried BOF Sludge(50%) Pellet Fines (50%)	17.0	CMC	0.0	96.8	0.4	0.1	2.7

Appendix B: PAIRED STRAIGHT HEARTH FURNACE SIMULATION USING A TWO ZONE BOX FURNACE (Coleraine Minerals Research Laboratory) April 17, 2014

UMD Natural Resources Research Institute

University of Minnesota Duluth

Driven to Discover

Paired Straight Hearth Furnace Simulation

using a

Two-Zone Box Furnace

Part A: Pellets made with Magnetite Concentrate

conducted for the

American Iron and Steel Institute

under

DOE Contract DE-FG36-08GO18133

Paired Straight Hearth Furnace-

Transformational Ironmaking Process

COLERAINE MINERALS RESEARCH LABORATORY

April 17, 2014

By: _____

Matt Mlinar – Research Coordinator

Approved by: _____

Richard Kiesel – Director Coleraine Minerals Research Laboratory

NRRI/TR-2013/43

Natural Resources Research Institute
University of Minnesota – Duluth
5013 Miller Trunk Highway
Duluth, Minnesota 55811

Coleraine Minerals Research Laboratory
P O Box 188
One Gayley Avenue
Coleraine, Minnesota 55722

This material is based upon work supported by the U.S. Department of Energy under Award Number DE-FG36-08GO18133.

Executive Summary

The United States Department of Energy (DOE) issued contract number DE-FG36-08GO18133, Paired Straight Hearth Furnace-Transformational Ironmaking Process in September, 2008, to be administered through the American Iron and Steel Institute (AISI) for continued investigation of the Paired-Straight-Hearth (PSH) furnace concept developed at McMaster University under a previous DOE grant.[1] The PSH concept utilizes two parallel pusher furnaces operating in opposite directions with gas transfer between them. The process is designed to make metallized iron pellets from iron oxide-coal pellets in a bed with a depth of up to 120 mm (4.72 inches). The iron oxide source can be iron oxide concentrates or residual iron oxide wastes from iron and steel making. In this study, magnetite taconite concentrate was used as the iron oxide source.

As part of the present DOE contract, a study of the kinetics of the reactions occurring in the PSH process was conducted in a two-part program at the Coleraine Minerals Research Laboratory (CMRL) of the Natural Resources Research Institute (NRRI), University of Minnesota-Duluth (UMD). The first part was construction of a two-zone, electrically heated box furnace of sufficient internal height to accept a crucible of up to 120 mm in height. In the PSH process, the iron oxide-coal pellets are heated first to 1200° C for a short time and then to about 1500° C for a period of forty minutes or more depending upon the depth of bed. The furnace was designed with two heated zones where the retention times could be varied.

Pellets of nominal size 16-19 mm (5/8 to 3/4 inch) diameter were made from fine magnetite concentrate sourced from a taconite operation in northern Minnesota. The pellets were made with about 20 percent weight of a finely ground high volatile coal typically used for pulverized coal injection in a blast furnace in northwest Indiana. Pellets were made using conventional batch balling methods with either cooked starch or bentonite clay as binder. Pellets were placed in fused magnesium oxide crucibles 125 mm (5 inches) high by 100 mm (4 inches) in diameter inside of a retainer block 200 mm by 230 mm (8 inches by 9 inches) made from insulating firebrick so that the heat transfer and reduction reaction proceeded in one dimension from top to bottom.

Tests were conducted in two phases. In Phase I, the effect of various furnace temperatures was investigated. In Phase II, the effect of bottom heating was investigated by placing the crucible and retainer block on a sliding refractory plate that could be preheated to various temperatures. Pellets were metalized at several temperatures from 1200° C to 1500° C and the metallized pellets were analyzed in five layers. Samples were photographed from the top both before and after reaction and the vertical shrinkage of the sample was recorded. In addition to measuring total Fe, metallic Fe, and ferrous Fe, at CMRL, the apparent densities and pellet shrinkage were determined at ArcelorMittal Global R&D-East Chicago. Hearth production data was also calculated.

The experiments demonstrated that high metallizations of 95 percent and over one kilogram per square meter per minute production rates are possible from the top of the pellet bed to the bottom depending upon the temperature of the furnace, reaction time, and the degree of preheating of the bottom sliding plate. The experiments provide quantitative information for developing a kinetic model to describe the pellet shrinkage, heat transfer, and gas evolution to aid in scale-up and for development of a CFD (Computational Fluid Dynamics) model of the process. Future programs should be conducted with waste iron oxides as well.

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Introduction

The Coleraine Minerals Research Laboratory (CMRL) of the Natural Resources Research Institute (NRRI), University of Minnesota Duluth (UMD) has conducted a study for the American Iron and Steel Institute (AISI) funded under DOE contract DE-FG36-08GO18133, Paired Straight Hearth Furnace-Transformational Ironmaking Process to evaluate and assess the quality of Direct Reduced Iron (DRI) pellets produced from deep bed heating and reduction of iron oxide-coal pellets in a batch furnace. The furnace was designed to simulate the PSH process as envisioned in a preliminary study by McMaster University, Hamilton Ontario, Canada.[1]

The objective of this study was to obtain data to help understand the heat transfer and kinetic characteristics for metallization of iron oxide-coal pellets in a deep bed for the design and construction of a pilot plant prior to the commercialization of PSH technology. This required the metallization of DRI pellets in a manner closely related to a commercial furnace. The resultant pellet chemistry and change in volume could then be evaluated as they transition in the bed. A deep bed (120mm) of dry pellets, prepared with iron oxides and coal provided by U. S. Steel, were heated and reduced in a two-zone electrically heated furnace designed to simulate top down radiant heating.

Pellets were exposed to a temperature of 1200° C for five minutes, then were exposed to a temperature of from 1425° C to 1500° C for residence times varied between 10 and 65 minutes. The change in height was determined by measuring the vertical shrinkage of the bed. The change in diameter of the pellets was recorded by photography of the top of the bed of reduced pellets. The composition of the gases evolved was measured as a function of time.

The mass of reduced pellets was divided into five horizontal layers for quality assessment. Each layer of the DRI pellets bed was analyzed for metallic iron (Fe^{o}), total iron (Fe_T), ferrous iron (Fe^{+2}), carbon (C), and sulfur (S) contents. In addition, the apparent density and average pellet diameter was measured on each layer by ArcelorMittal Global R&D-East Chicago, Indiana, to evaluate the rate of shrinkage of the pellets and the changes in density.

Two testing phases were conducted during this project. In the first testing phase, iron oxide-coal pellets were made with a cooked starch binder. The procedure used heating of the pellet crucible and holder from the top only with the assembly placed on the hot furnace floor. The second testing phase utilized a bentonite clay binder in place of the cooked starch binder. The procedure used heating of the pellet crucible and holder from the top and, in addition, a preheated fire brick plate was inserted below the sample assembly to provide controlled initial bottom heat. A light firebrick was utilized as the heating medium for the first eight tests of the second testing phase, and a dense refractory brick was used below the crucible and sample holder for the four remaining tests of the second phase.

Phase I Green Ball Components and Chemistry

The green ball chemistry was based on a molar carbon to oxygen ratio of exactly one. This resulted in a 20.2% pulverized coal addition based upon the chemistries found below. The iron ore concentrate composition, pulverized coal ultimate analysis, and pulverized coal proximate

analysis can be seen in Table 1, Table 2, and Table 3, respectively. Cooked starch was used as a binder at a 1.3% addition by weight. Green ball data can be seen in Table 4.

Table 1: Iron Ore Concentrate Composition[1]

Component	%wt. (Dry basis)
Fe_2O_3	64.42
FeO	29.96
MnO	0.13
MgO	0.28
CaO	0.39
MgO	0.28
SiO_2	3.8
Al_2O_3	0.06
TiO_2	0.02
K_2O	0.01
Na_2O	0.01
S	0.01
	99.37
Total Fe (calc)	68.31
Total Fe (direct)	68.43

Table 2: Pulverized Coal Ultimate Analysis[2]

Component.	%wt. (Dry basis)
C	76.92
H	5.18
N	1.51
O	8.31
S	0.94
Ash	7.14
	100.00
BTU/lb	13,803

[1] Analysis conducted at Acme Labs with the exception of total iron (TFe conducted at NRRI CMRL
[2] Analysis conducted at Acme Labs

Table 3: Pulverized Coal Proximate Analysis[3]

Component	%wt. (As Received)
Moisture	1.43
Ash	7.04
Volatile Matter	36.17
Fixed Carbon	55.36
	100.00
LBS Sulfur per Million BTU	0.684

Table 4: Green Ball Data

Balling Test Number:	B11572		**Date:**	11/17/2011
Test Description:	AISI Green Pellets			

Concentrate:	Magnetite		**Addition**:	78.5 % by Wt.	**ID:**	NRRI-142-11
Binder:	Cooked Starch		**Addition:**	1.3% by Wt.	**ID:**	N/A
Additive:	Pulverized Coal		**Addition:**	20.2% by Wt..	**ID:**	NRRI-47-10

Green Ball Moisture:	13.7 %		**18" Drop No.:**	7.7
Green Ball Wet Compression:	N/A		**Dry Compression:**	21.7 lbs

Dry Drop No.:	
18"	3.1
36"	1.4

Surface Appearance (1=wet, 5=dry):	3

Balling Comments:	19 mm x 16 mm

[3] Analysis conducted at Acme Labs

Phase I Testing Procedure

Testing Apparatus and Construction

The goals of this testing program were to design and construct a furnace with electrical heating, capable of achieving 1600° C in each of two separate zones to simulate a deep bed heating and reduction of green pellets using the PSH furnace technology and produce representative DRI pellets. The initial nominal bed height of the deep bed was 120 mm (4.72 inches).

The proposal was submitted in two parts:

1) The design and fabrication of the laboratory-scale electric resistance heated DRI furnace, and,
2) The production and quality assessment of deep bed produced DRI pellets.

Furnace Design and Fabrication

The furnace used for testing at CMRL consisted of two heated zones with a combined feeding and cooling chamber for introducing and cooling pellets under neutral (nitrogen) atmosphere. The furnace concept is presented in Figure 1. The actual furnace and control panel at CMRL can be seen Figure 2. Electrically heated elements were placed horizontally over the bed of pellets designed to radiate heat energy down through the bed, as shown in Figure 3. Each zone of the furnace has capability for heating up to 1600^{o}C. Temperature in each zone is controlled with a type "R" thermocouple located directly above the center of the sample.

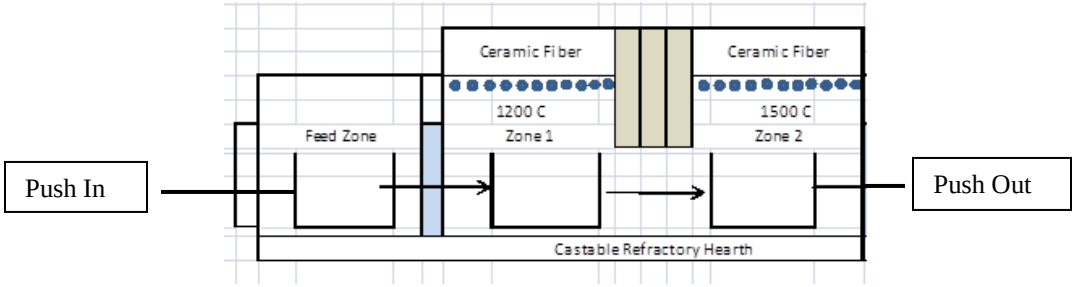


Figure 1: AISI PSH Furnace Concept

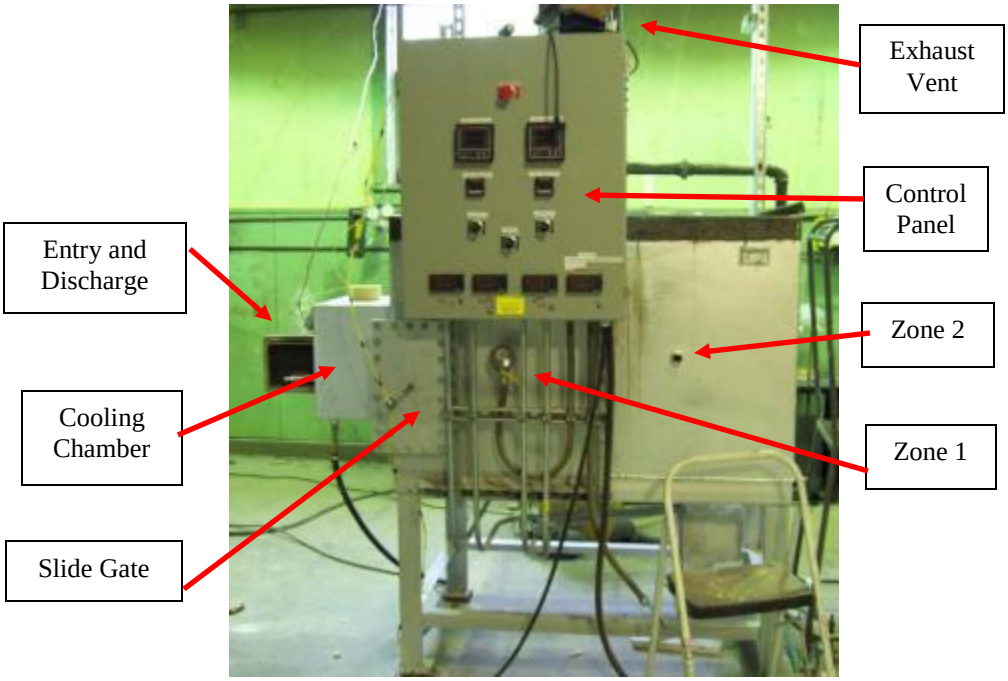


Figure 2: PSH Batch Furnace

Figure 3: Top of Furnace and Heating Elements

The bottom of the furnace contained a cast refractory hearth with a trough, designed to accommodate the manual movement of a ceramic crucible and mounting block from each of the zones using a ceramic push rod. Firebrick or ceramic fiber refractory was used on sidewalls and roof. The cooling chamber was water-jacketed and could be purged with nitrogen. Slide gate refractory technology (e.g., a moveable refractory brick) was used to separate the heated zones from the feeding and cooling chamber. The slide gate was manually operated using push rods for insertion and removal. Figure 4 displays the feeding/cooling chamber.

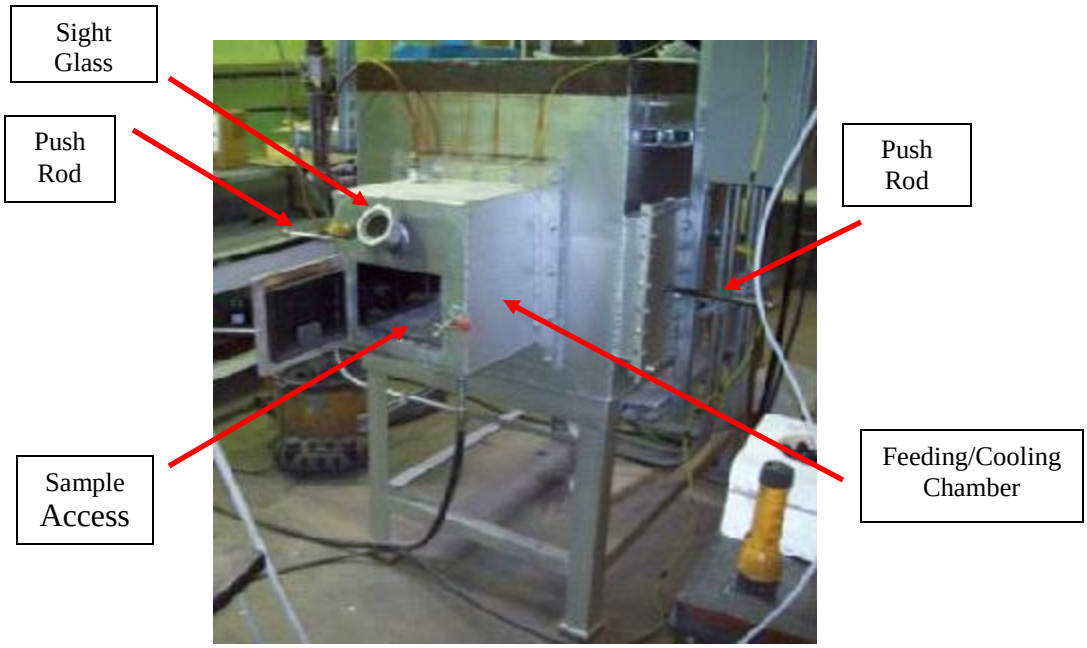


Figure 4: Feeder/Cooler end of PSH Furnace

Deep Bed DRI Production and Evaluation

Green pellets were prepared with dry iron oxide and coal according to recipes provided using the techniques previously determined (see the *Phase I Green Ball Components* and Chemistry section above). The green pellet size target was between 16 and 19 mm. A ceramic crucible containing the green pellets was manually moved sequentially from one zone to the next. The specified time interval in each zone was performed and the product pellets were quenched in the cooling chamber to stop the reaction and inhibit oxidation. The bed of DRI pellets produced were measured 3-dimensionally to record any change in volume, photographed and sectioned horizontally for quality assessment. Each segment of pellets produced were analyzed for metallic iron (Fe^{o}), total iron (Fe_{T}), carbon (C) and sulfur (S). A total of 44 tests were performed. The preheating in Zone 1 was operated at 1200^{o}C and the reduction heated in Zone 2 was operated at 1350^{o}C, 1425^{o}C, and 1500^{o}C. Preheating was conducted for five minutes and reduction was done in intervals of 10 minutes from 10 to 70 minutes total.

Sample Tray Preparation

Sample trays were constructed of high temperature ceramic firebricks with a magnesium oxide crucible inside to hold the green pellets. The trays were approximately 230mm (9 inches) long by 203mm (8 inches) wide, with the crucible having an outer diameter of 112mm (4.4 inches), inside diameter of 102mm (4 inches), and 120mm (4.72 inches) high. A metal mesh screen was attached to the bottom of each tray to hold the green pellets in the crucible during the test and also to be able to place a thermocouple at the bottom level of the sample. Approximately 1100 grams of green pellets were loaded into the crucible each test. This sample size was chosen because this amount of sample filled the crucible to nearly the 120mm mark (approximately 8-9 layers total). Figure 5 shows a fully constructed sample tray. Although this study was primarily conducted to investigate top-down heating of the sample, some degree of bottom heating occurred due to convective heating from the refractory brick through the mesh screen on the sample.

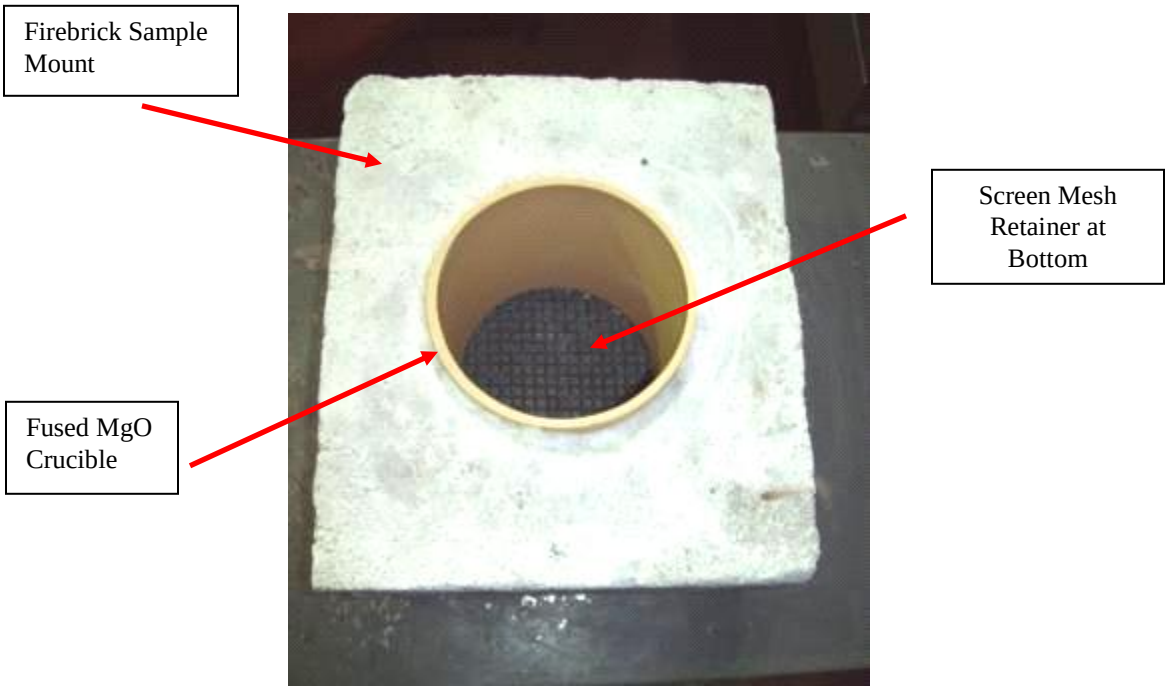


Figure 5: Sample Tray with Crucible Insert and Mesh Retainer

Temperature Profile Analysis

Temperature profiling was conducted on the full 70 minute tests via one of two methods. For the 1200°C Zone 2 temperature and 1350°C Zone 2 temperature runs, three traveling thermocouples were inserted into the sample at the 8mm (0.31 inch), 60mm (2.36 inch), and 112mm (4.41 inch) marks. These were designated as top ("TC1"), middle ("TC2"), and bottom ("TC3") thermocouples respectively. See below for a depiction of the thermocouple placements.

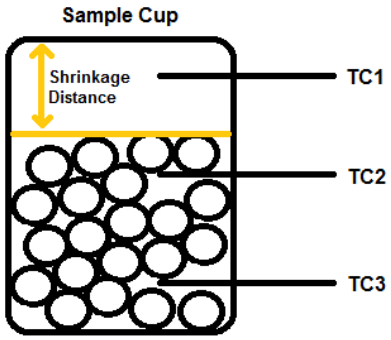


Figure 6: Thermocouple Placements for Low Temperature Runs

For the higher temperature runs (e.g., 1425°C and 1500°C Zone 2 temperatures), a hole was cut into the bottom of Zone 2 so a thermocouple couple be pushed into the bottom of the sample. This was denoted as the "bottom thermocouple" (see Figure 7).

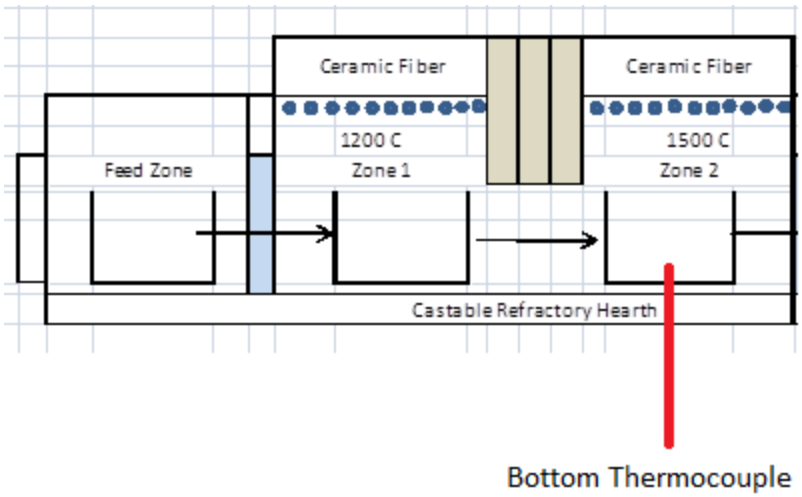


Figure 7: Thermocouple Placement for High Temperature Runs

Off-Gas Analysis

Two forms of gas analysis were conducted during the full 70 minute tests: (1) real-time gas analysis and (2) gas chromatography analysis. These two methods were conducted on different 70 minute tests but with the same operating parameters. These samples were taken above the sample cup in each zone. Figure 8, below, displays the gas sample locations on the outside of the furnace.

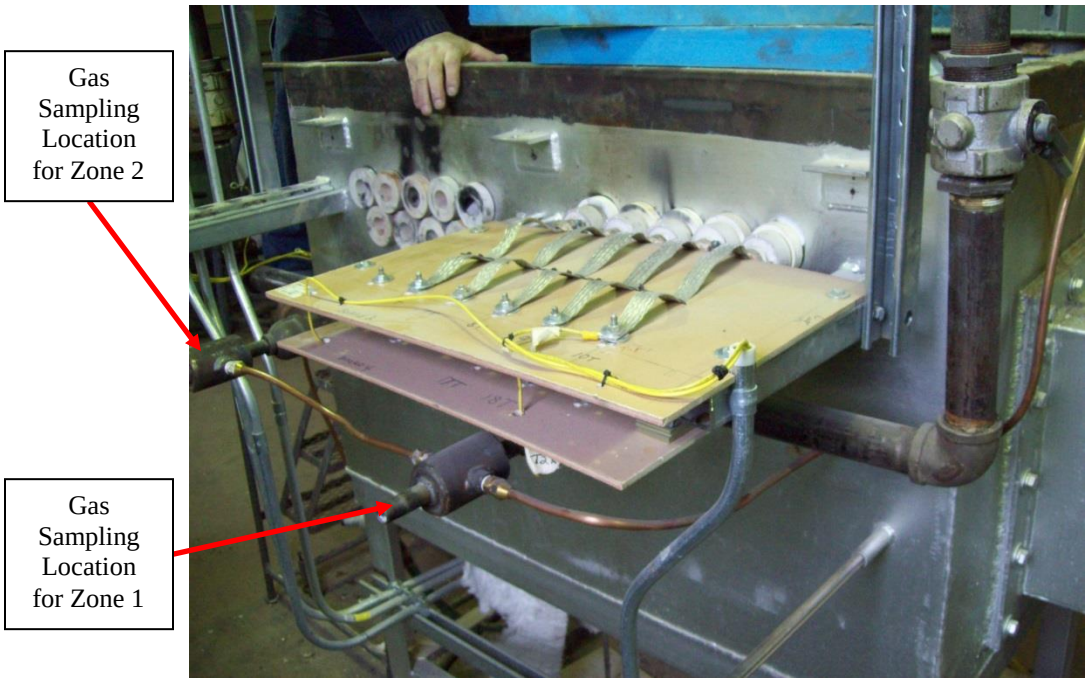


Figure 8: Gas Sampling Locations

Real-Time Gas Analysis

Real-time gas analysis was achieved by sampling the off-gas directly above the sample cup in both Zone 1 and Zone 2. An online gas analyzer was attached to the sample port. Either the

Testo 350XL or UEI AGA5000 was used for gas sampling. A three-data-point moving average was applied to each gas composition graph to filter out the high degree of sampling noise in the data.

Gas Chromatography Analysis

Gas chromatography analysis was also conducted in conjuncture with the on-line gas sampling. The UMD Natural Resources Research Institute would like to credit and thank Dr. Andriy Khotkevych for his gas chromatography work throughout this study. The gas chromatography equipment and procedure are described below.

Gas Sampling During Test Runs

The Chemglass™ 125 ml Gas Sampling Tube was connected to the gas sampler outlet, equipped with water jacketed cooling coil, particle filter and refillable moisture trap. The gas was aspired through the tube during 1 minute at 1.5 l/min. constant flow rate using the Air One™ Model TI-004 sampling pump, than the tube has been sealed and transferred for GC identification/quantification.

Gas Chromatography Analyses

Identification and quantification of the gas components was made on two Gow-Mac™ TCD Gas Chromatographs, connected to the MS Excel-compatible data logger. Three separate operations made for each gas probe:

a) Column: SS ø1/8"×6' packed with Hayesep D™. Carrier Gas: He, 8 ml/min. Isothermal, T = 85 °C. Used for quantification of CO_2. (Both N_2 and CO appear as a single peak at these conditions).
b) Column: SS ø1/8"×3' packed with Molsieve 5A. Carrier Gas: He, 8 ml/min. Isothermal, T = 85 °C. Used for quantification of CO and N_2. (CO_2 does not appear as a peak at these conditions).
c) Column: SS ø1/8"×6' packed with Hayesep D™. Carrier Gas: N_2, 5 ml/min. Isothermal, T = 85 °C. Used for quantification of H_2 against the external reference. (All other components show negligible response at these conditions).

Figure 9 shows a photograph of the gas sampling equipment used during the testing phase of this project.

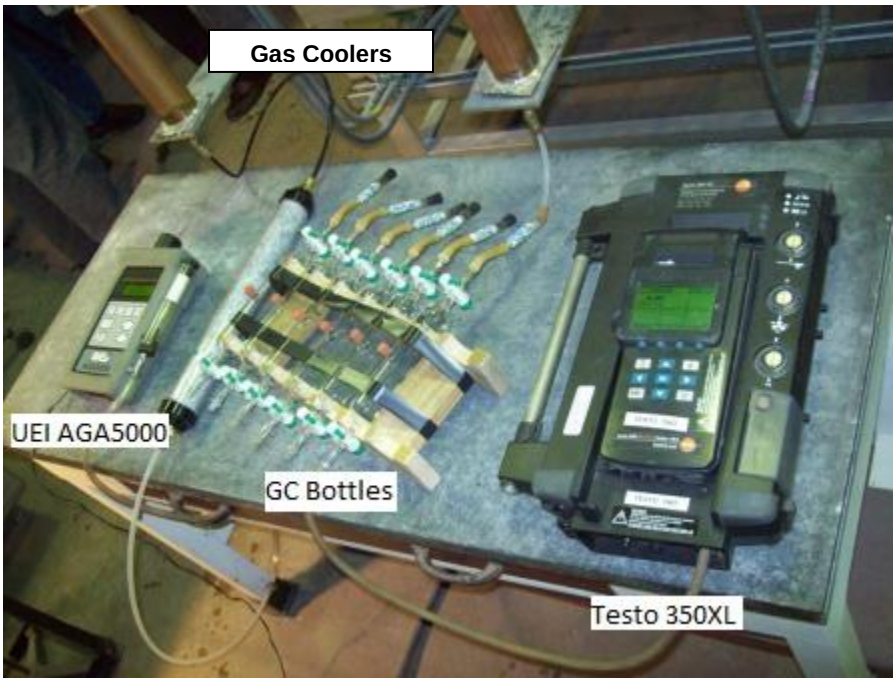


Figure 9: Gas Sampling Equipment

Chemical Analysis

At the completion of each test the DRI pellets were broken into five horizontal layers. Each of the five layers for every test were analyzed for carbon, sulfur, total iron, metallic iron, and ferrous iron; ferric iron was found by difference of the total iron and the metallic and ferrous iron components. This was done to show the reduction through the deep bed of pellets. Figure 10 displays how the sample crucible was divided into five layers.

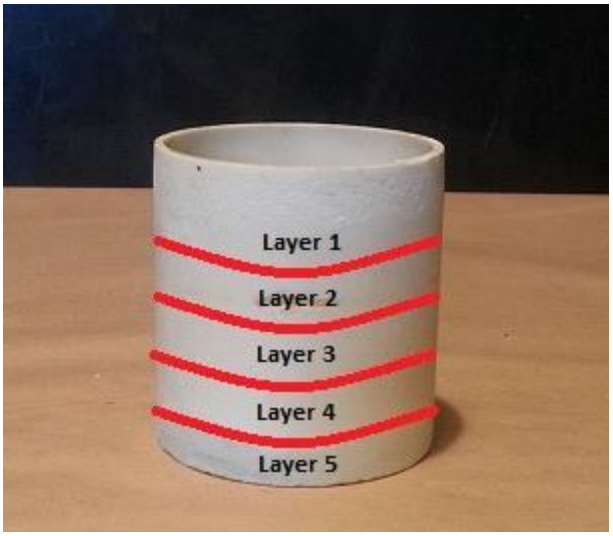


Figure 10: Sample Crucible Partitioned into Five Layers for Analysis

Metallization was also calculated for each layer, and was defined as:

$$\%\, Metallization = 100 * \frac{Metallic\ Iron}{Total\ Iron}$$

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

The standard crucible height was measured so that it could be compared to the vertical shrinkage during each run. After each run the height from the top center of the pellets to the top of the crucible was measured. The vertical shrinkage ratio was calculated and defined as:

$$\%\, Vertical\ Shrinkage = 100 * \frac{Shrinkage\ Level\ Measured\ (inches)}{Crucible\ Height\ (inches)}$$

Apparent or envelope density was determined on both dry pellets and partially reduced or reduced pellets. Individual pellets were used and pellets in clusters were separated prior to measurement. Measurements were made on a Micromeritics GeoPyc 1360 compact bench-top unit that consists of a console and measurement chamber, an analyzer, a microprocessor, and a keypad and LCD display. The envelope density emulates tap density using a fine particulate medium dryflow® which is a mixture of a small amount of natural graphite and ceramic microspheres. The measurement chamber used was 50.8 mm diameter.

The dryflow was placed in the chamber and inserted into the device. There was a piston on one end that advances into the chamber to compact the dryflow or the dryflow and sample. First, the dryflow alone is placed in the cylinder which rotates slowly and the piston advances to compact the dryflow to a minimum volume. Some trial and error is needed to determine the right number of pellets to place in the chamber. The manufacturer's recommendation is that the test material should occupy about 30 percent of the total volume with a minimum of 25 percent. The force applied to the piston is designed to move the material to the end of the chamber, but not compact or crush the material.

The cycle was repeated five times. Subsequently, the sample was introduced into the chamber and the process was repeated. The sample weight, and for these tests, the number of ball or pellets was counted for each test. The piston is calibrated so the difference in volume is known from the procedure. The cycle was repeated five times with the pellets or pellets immersed in the dryflow medium. The average result was calculated and printed along with other test conditions. Total procedure time was about 15 minutes.

Standard pellets were used as the calibration and reference size. All five layers of pellets for each run were analyzed for the average apparent volume and compared to the standard pellet volume. In the results for each test, a positive percentage means the pellet was smaller than the standard, i.e., the pellet shrunk; a positive number means the pellets were larger than the standard, i.e., the pellet swelled.

Weight loss was also recorded for each test using the starting weight (~1100-1200 grams) and the ending weight. The ending weight was found as the sum of the weights of each level after

preparing the sample for the chemical laboratory. Weight loss was then calculated and defined as:

$$\%\ Weight\ Loss = \ 100 * \left(1 - \frac{End\ Weight\ (g)}{Start\ Weight\ (g)}\right)$$

Hearth Productivity

Hearth productivity was calculated for the Phase I and II portion of this project. Hearth productivity was defined as the sum of the metallic iron in each DRI bed layer divided by area and time. More specifically, the below equations define how hearth productivity was calculated.

$$Metallic\ Iron\ in\ a\ Layer = Single\ Layer\ Weight\ (g) * Total\ Fe\ (\%) * Metallization\ (\%)$$

$$Total\ Metallic\ Iron = Sum\ of\ the\ Metallic\ Iron\ in\ all\ Five\ Layers\ (g)$$

$$Hearth\ Productivity\ \left(\frac{g}{cm^2 * min}\right) = \frac{Total\ Metallic\ Iron\ (g)}{\pi * r^2 (cm^2) * Time\ (\text{minutes})}, and$$

$$Hearth\ Productivity\ \left(\frac{kg}{m^2 * min}\right) = 10 * Hearth\ Productivity\ \left(\frac{g}{cm^2 * min}\right),$$

$$Where\ r = radius\ of\ crucible = 5.08\ cm\ (2\ inch)$$

Sample Crucible Photographs

A photograph of each filled sample tray was taken before and after the testing procedure from the same height to compare the shrinkage level of the sample and also to compare the shrinkage between runs due to differences in time and temperature. A photograph was also taken of each level of the pellet sample when processing for chemical analysis. Figure 11 displays a depiction of the crucible cup and where the shrinkage distance is measured.

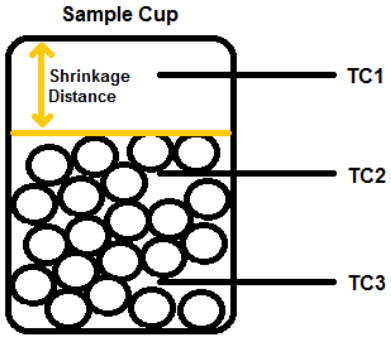


Figure 11: Crucible for Phase I Tests

Phase I Testing Program Results

The first testing phase consisted of 23 tests. The tests for Phase I are found below:

- 1200°C for 5 minutes
- 1200°C for 5 minutes, 1200°C for 65 minutes
- 1200°C for 5 minutes, 1350°C for 10, 20, 30, 40, 50, 60, and 65 minutes
- 1200°C for 5 minutes, 1425°C for 10, 20, 30, 40, 50, 60, and 65 minutes
- 1200°C for 5 minutes, 1500°C for 10, 20, 30, 40, 50, 60, and 65 minutes

Five Minutes in Zone 1 (1200°C), 0 Minutes in Zone 2 (1200°C) Test Results

This first test was used as a baseline for the five minute warm up for every other test throughout program.

Sample Temperature Profile

Figure 12 displays the temperature profile of the sample that was heated in Zone 1 at 1200°C for five minutes. The upper thermocouple approached 1200°C but the middle and lower were both below 500°C by the conclusion of the run. As in all of the following runs, the sample was receiving both top-down heating from the heating elements as well as bottom up heating from the furnace floor.

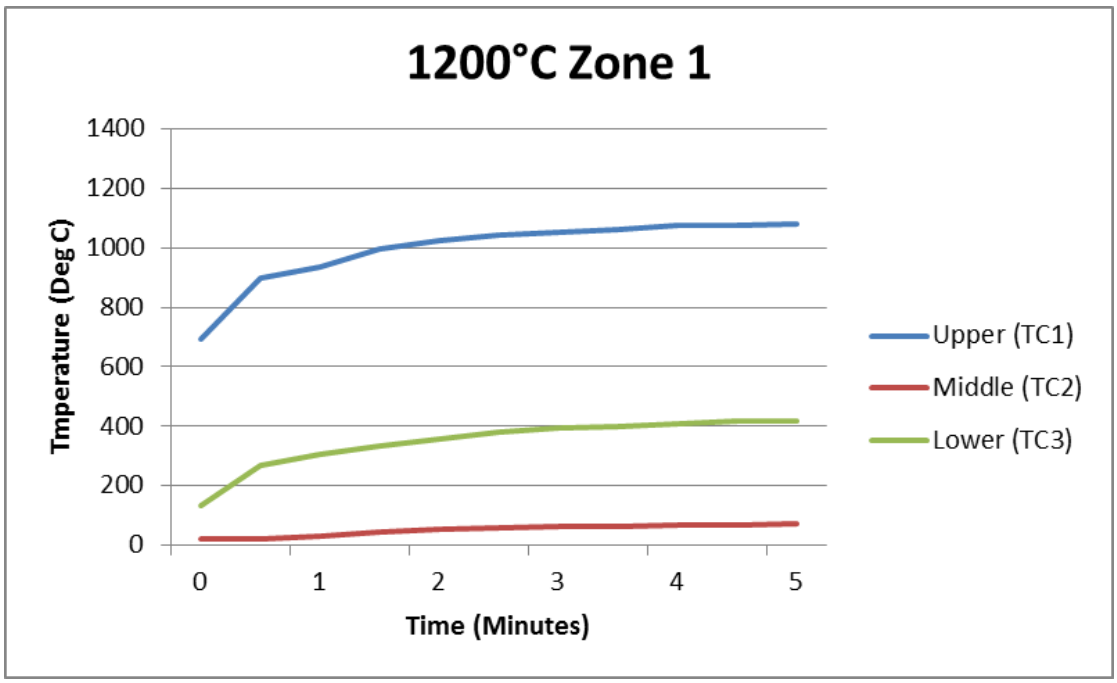


Figure 12: Phase I 1200°C Temperature Profile

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 13 displays the gas analysis of the sample that was heated in Zone 1 at 1200°C for five minutes. Very low carbon monoxide was detected with carbon dioxide increasing and oxygen decreasing throughout the run.

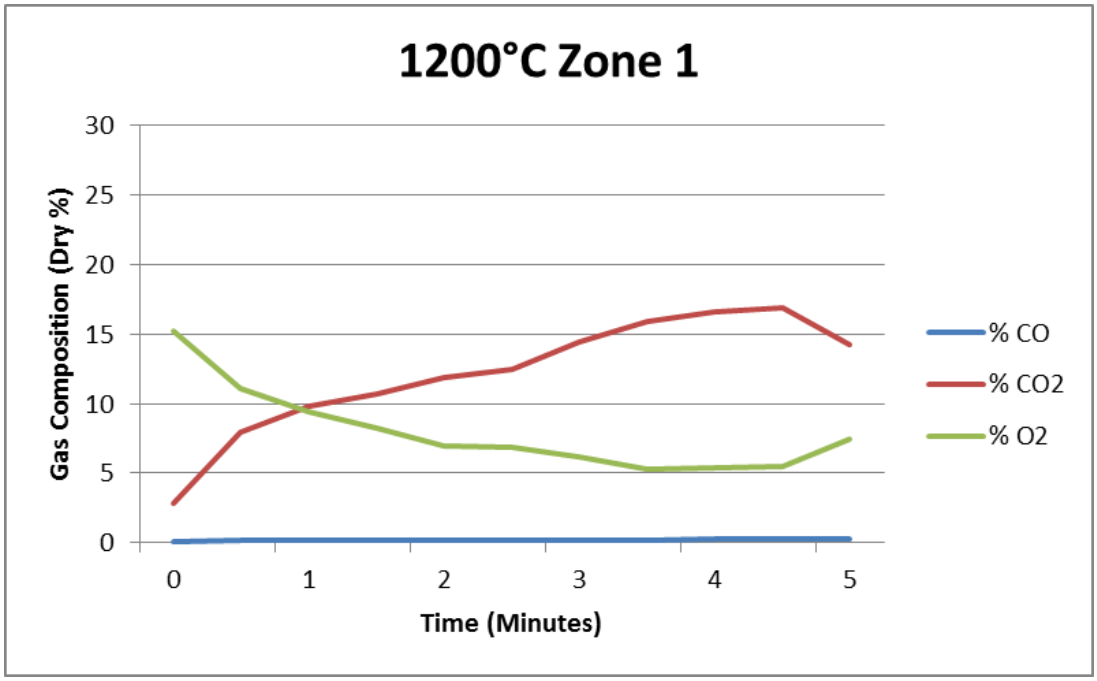


Figure 13: Phase I 1200°C Gas Composition

Chemical Analysis

The chemical analysis for the five minute warm up test can be found in Table 5 below. Metallization was very low throughout this test, with only Layer 1 above 10% metallized.

Table 5: Phase I 1200°C Chemical Analysis

Run Data			**Chemistry Data, Wt. %**						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1200	0	1	10.24	0.17	61.07	6.59	29.32	25.16	10.8
		2	14.07	0.18	51.22	1.33	14.89	35.00	2.6
		3	14.36	0.18	52.75	1.27	15.67	35.81	2.4
		4	14.49	0.19	51.42	1.13	13.83	36.46	2.2
		5	13.94	0.19	53.23	1.24	14.98	37.01	2.3

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 6 shows the shrinkage and weight loss data for the five minute test. Every pellet layer was swelled compared to the unfired pellet.

Table 6: Phase I 1200°C Shrinkage and Weight Loss Data

Run Data		**Shrinkage and Weight Data**			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage %	Weight Reduction, %
1200	0	1	-3.5	N/A	4.2
		2	-3.3		
		3	-0.2		
		4	-4.2		
		5	-0.7		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 3, page 90.

Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1200°C) Test Results

Sample Temperature Profile

Figure 14 displays the temperature profile of the sample that was heated in Zone 1 at 1200°C for five minutes and Zone 2 at 1200°C for 65 minutes. The upper thermocouple was nearly 1200°C for the majority of the test while the middle and lower thermocouples were leveling off at approximately 900°C and 800°C, respectively, by the end of the test.

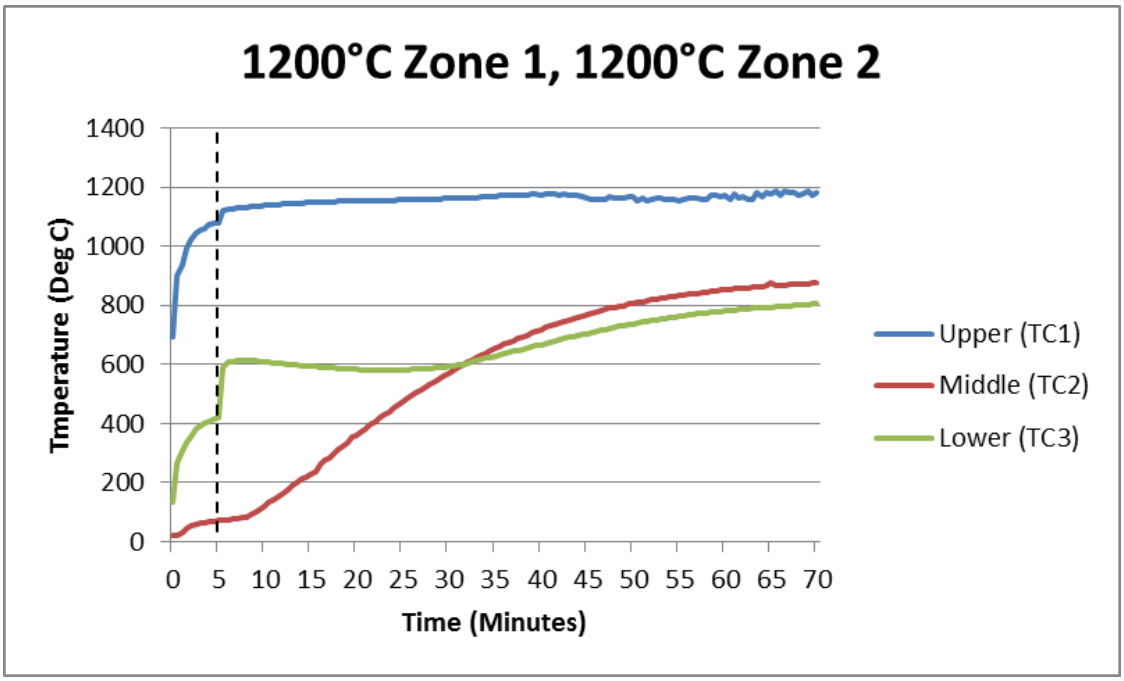


Figure 14: Phase I 1200°C/1200°C Temperature Profile

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 15 displays the gas analysis of the sample that was heated in Zone 1 at 1200°C for five minutes and Zone 2 at 1200°C for 65 minutes. Table 7 displays the gas chromatography data for this temperature profile.

Carbon monoxide was nearly zero throughout the run while oxygen and carbon dioxide were in the 10-15% range by the end of the test.

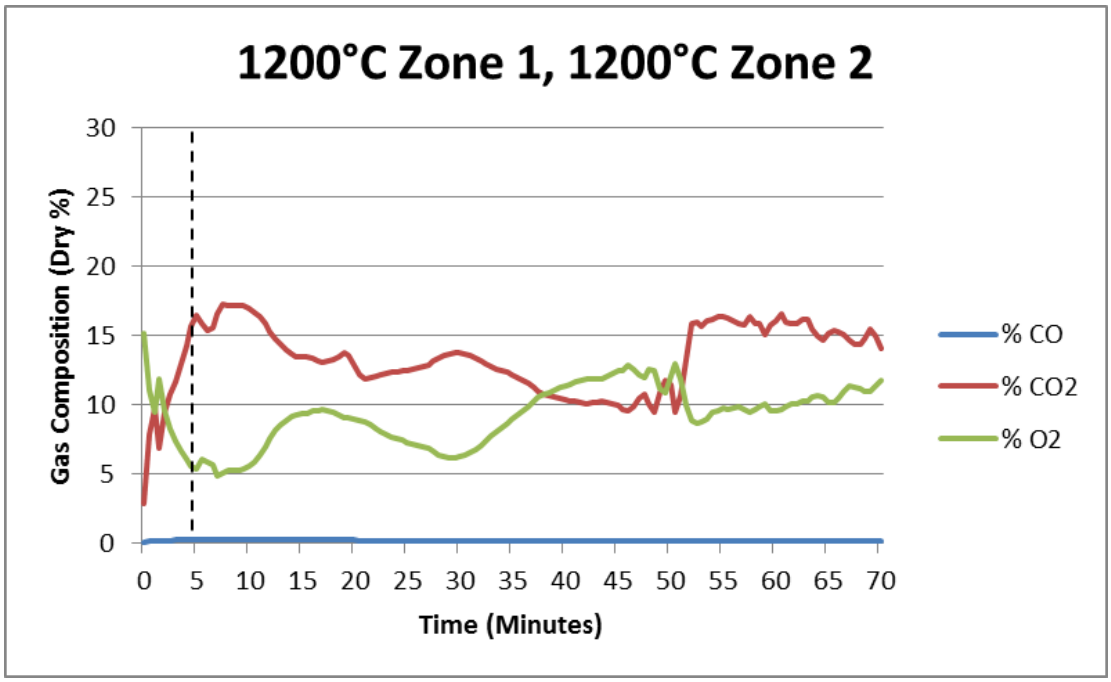


Figure 15: Phase I 1200°C/1200°C Gas Composition

Table 7: Phase I 1200°C/1200°C GC Data

Sample #	Zone	Sampling Time, min.		Moisture (vapors), %	Permanent Gases, %						
		Start	Stop		N2	CO2	CO	H2	O2	CH4	C2+
1	1	1	4	3.7	77.7	14.9	0.0	0.1	3.7	Not Found	Not Found
2	2	6	8	7.7	64.4	15.4	7.4	4.1	1.0	Not Found	Not Found
3	2	15	18	4.5	70.1	17.1	5.8	1.4	1.0	Not Found	Not Found
4	2	25	27	6.1	70.2	15.0	6.0	1.7	1.0	Not Found	Not Found
5	2	35	38	4.2	73.8	20.3	0.2	0.0	1.5	Not Found	Not Found
6	2	50	53	4.7	71.7	21.5	0.0	0.0	2.1	Not Found	Not Found

Chemical Analysis

Metallization for this test was above 80% in the first Layer, 63% in the second Layer, and low throughout levels 3-6.

Table 8: Phase I 1200°C/1200°C Chemical Analysis

Run Data			Chemistry Data, Wt. %						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1200	65	1	0.31	0.26	85.28	70.38	15.38	-0.48	82.5
		2	6.70	0.21	73.99	46.46	23.43	4.10	62.8
		3	10.75	0.19	61.43	5.69	45.23	10.51	9.3
		4	11.18	0.18	60.68	2.46	44.87	13.35	4.1
		5	11.83	0.18	59.12	1.30	37.10	20.72	2.2

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

The shrinkage and weight loss for this run can be found in Table 9 below.

Table 9: Phase I 1200°C/1200°C Shrinkage and Weight Loss Data

Run Data		Shrinkage and Weight Data			
Zone 2 Temperature, (deg C)	Zone 2 Time, (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage %	Weight Reduction, %
1200	65	1	11.6	23.8	22.2
		2	2.9		
		3	0.8		
		4	0.9		
		5	1.1		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 3, page 91.

Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1350°C) Test Results

Sample Temperature Profile

Figure 16 displays the temperature profile of the sample that was heated in Zone 1 at 1200°C for five minutes and Zone 2 at 1350°C for 65 minutes. The upper thermocouple was fairly constant at approximately 1300°C throughout the run. The middle thermocouple increased to approximately 1200°C by the end of the test, while the lower reached approximately 900°C.

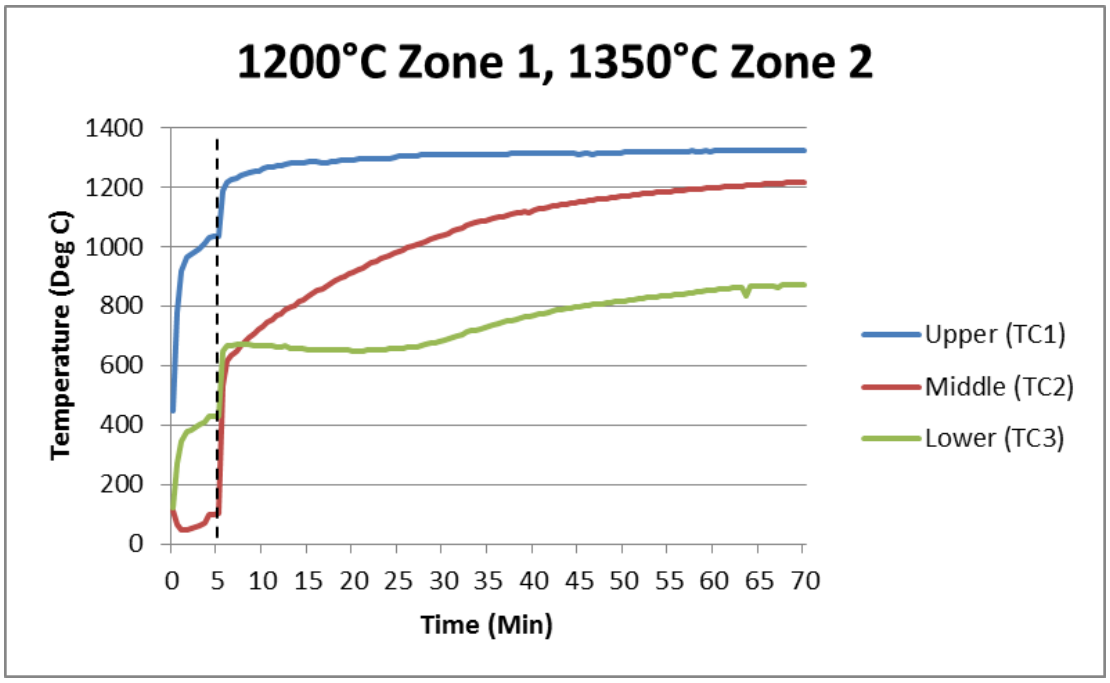


Figure 16: Phase I 1200°C/1350°C Temperature Profile

Off-Gas Analysis

Off-gas analysis was conducted with a Testo 350 XL. Figure 17 displays the gas analysis of the sample that was heated in Zone 1 at 1200°C for five minutes and Zone 2 at 1350°C for 65 minutes. Table 10 displays the GC data for this temperature profile.

Carbon dioxide was steadily rising and ending at approximately 23% while oxygen decreased to under 5% by the end of the run. The carbon monoxide, interestingly, showed two peaks of 6% and 12% at 18 minutes and 60 minutes, respectively.

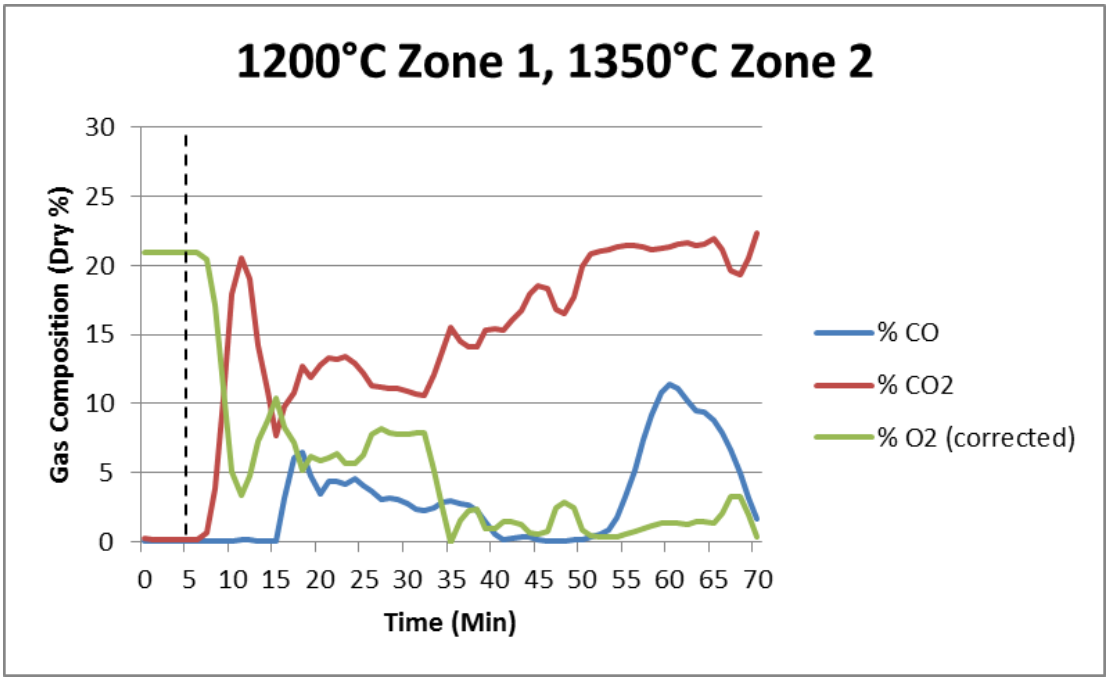


Figure 17: Phase I 1200°C/1350°C Gas Composition

Table 10: Phase I 1200°C/1350°C GC Data

Sample #	Zone	Sampling Time, min.		Moisture (vapors), %	Permanent Gases, %						
		Start	Stop		N2	CO2	CO	H2	O2	CH4	C2+
1	1	2	5	12.6	70.7	13.7	0.2	0.1	2.7	Not Found	Not Found
2	2	6	7.5	44.6	28.9	5.7	9.5	10	1.2	Not Found	Not Found
3	2	10	12	3.2	75.6	13.2	4.3	2.1	1.6	Not Found	Not Found
4	2	20	23	2.7	79.5	13.3	2.1	0.8	1.6	Not Found	Not Found
5	2	30	33	2.4	79.6	14.3	0.3	0.1	3.4	Not Found	Not Found
6	2	55	58	14.7	56.7	18.7	7.5	0.7	1.7	Not Found	Not Found

Chemical Analysis

The metallization for most of these runs were low, with only the 70 minute run having more than one layer above 90% metallized. Table 11 displays the chemical and metallization for the 1350°C Zone 2 temperature runs.

Table 11: Phase I 1200°C/1350°C Chemical Analysis

Run Data		Chemistry Data, Wt. %							
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1350	10	1	7.09	0.23	72.63	40.26	21.34	11.03	55.4
		2	5.89	0.14	66.33	11.63	21.25	33.45	17.5
		3	12.77	0.20	53.92	1.37	15.29	37.26	2.5
		4	13.13	0.21	53.24	1.26	14.10	37.88	2.4
		5	11.54	0.20	54.84	1.29	15.83	37.72	2.4
	20	1	9.20	0.21	69.93	37.64	22.28	10.01	53.8
		2	8.62	0.18	63.30	18.78	23.97	20.55	29.7
		3	10.90	0.18	56.40	4.97	16.61	34.82	8.8
		4	11.55	0.19	53.28	1.36	14.97	36.95	2.6
		5	10.99	0.19	55.21	1.17	17.27	36.77	2.1
	30	1	1.77	0.22	85.26	76.46	7.18	1.62	89.7
		2	7.92	0.22	67.31	30.30	24.35	12.66	45.0
		3	10.90	0.19	56.91	1.78	24.53	30.60	3.1
		4	10.63	0.19	57.08	3.45	23.25	30.38	6.0
		5	10.82	0.18	56.41	1.36	21.39	33.66	2.4
	40	1	0.75	0.19	86.95	78.64	7.43	0.88	90.4
		2	6.81	0.21	74.44	47.59	23.90	2.95	63.9
		3	8.69	0.19	64.21	17.16	36.09	10.96	26.7
		4	10.18	0.19	58.35	2.51	35.01	20.83	4.3
		5	13.08	0.19	57.01	3.50	28.23	25.28	6.1
	50	1	0.23	0.20	87.50	79.03	5.63	2.84	90.3
		2	3.65	0.23	83.68	73.75	9.50	0.43	88.1
		3	10.78	0.21	63.79	16.45	30.61	16.73	25.8
		4	11.37	0.21	61.91	10.49	34.64	16.78	16.9
		5	12.05	0.21	59.73	5.03	35.62	19.08	8.4
	60	1	0.08	0.28	86.08	74.86	9.95	1.27	87.0
		2	0.84	0.24	87.48	83.01	5.81	-1.34	94.9
		3	3.47	0.22	82.32	70.57	10.59	1.16	85.7
		4	9.84	0.19	65.83	19.67	38.53	7.63	29.9
		5	9.76	0.19	65.44	19.48	36.11	9.85	29.8
	65	1	0.12	0.20	86.33	79.10	5.11	2.12	91.6
		2	0.85	0.24	88.14	83.26	5.39	-0.51	94.5
		3	6.84	0.23	75.50	50.14	21.35	4.01	66.4
		4	8.96	0.21	66.75	26.33	38.65	1.77	39.4
		5	9.14	0.20	65.96	17.65	40.63	7.68	26.8

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 12, below, displays the shrinkage and weight loss for the 1350°C Zone 2 temperature runs.

Table 12: Phase I 1200°C/1350°C Chemical Analysis

Run Data		**Shrinkage and Weight Data**			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction, %
1350	10	1	11.9	N/A	9.9
		2	0.1		
		3	-0.4		
		4	1.1		
		5	0.4		
	20	1	9.7	N/A	13.3
		2	7.2		
		3	1.5		
		4	-2.8		
		5	4.7		
	30	1	22.3	23.8	17.3
		2	11.6		
		3	-1.1		
		4	4.3		
		5	1.9		
	40	1	21.2	23.8	22.0
		2	16.9		
		3	6.1		
		4	8.9		
		5	-0.6		
	50	1	25.3	23.8	24.1
		2	12.0		
		3	-1.7		
		4	4.9		
		5	5.0		
	60	1	26.2	34.4	32.1
		2	7.6		
		3	-9.1		
		4	1.1		
		5	1.3		
	65	1	30.2	29.1	31.8
		2	14.0		
		3	-1.0		
		4	1.7		
		5	2.3		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 3, pages 92 through 98.

Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1425°C) Test Results

Sample Temperature Profile

Figure 18 displays the temperature profile of the sample that was heated in Zone 1 at 1200°C for five minutes and Zone 2 at 1425°C for 65 minutes. Only the bottom thermocouple data could be acquired for this run due to the high temperatures in the hot zone (refer to the *Temperature Profile Analysis* section on page 7 for additional explanation). The bottom thermocouple shows that the temperature was nearing 1100°C by the end of this run.

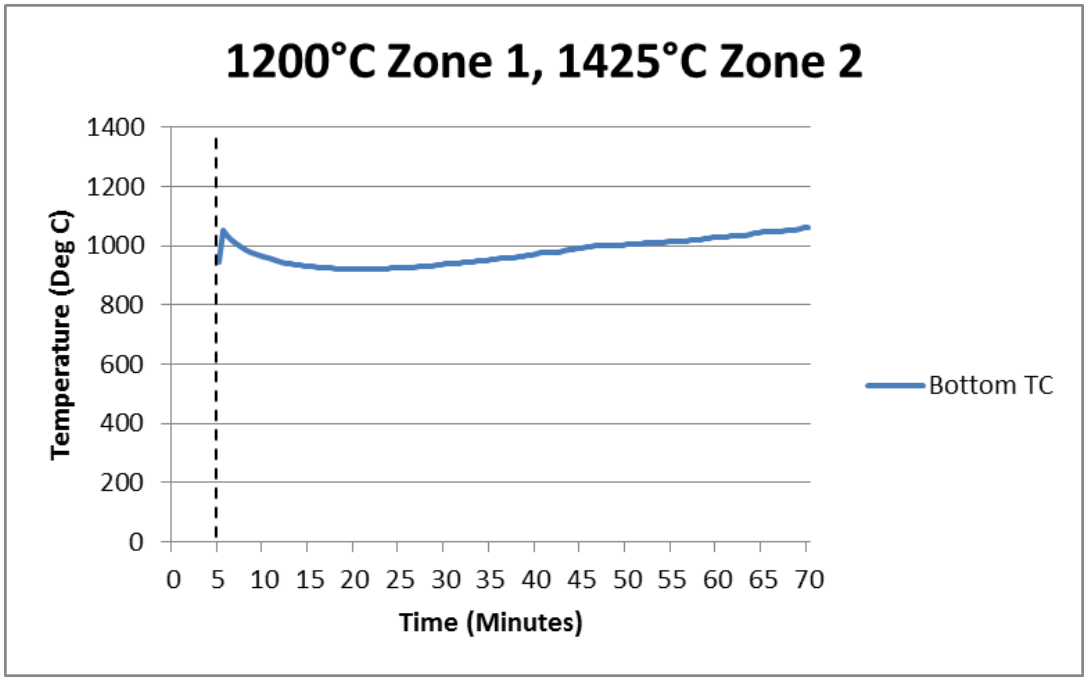


Figure 18: Phase I 1200°C/1425°C Temperature Profile

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 19 displays the gas analysis of the sample that was heated in Zone 1 at 1200°C for five minutes and Zone 2 at 1425°C for 65 minutes. Table 13 displays the GC data for this temperature profile.

Similar to the 1350°C run, the carbon dioxide was nearing 25% with little oxygen by the end of the run. The carbon monoxide, as before, had two distinct peaks at approximately 8 minutes and 47 minutes. The first peak was approximately 14% CO while the second peak was approximately 16%.

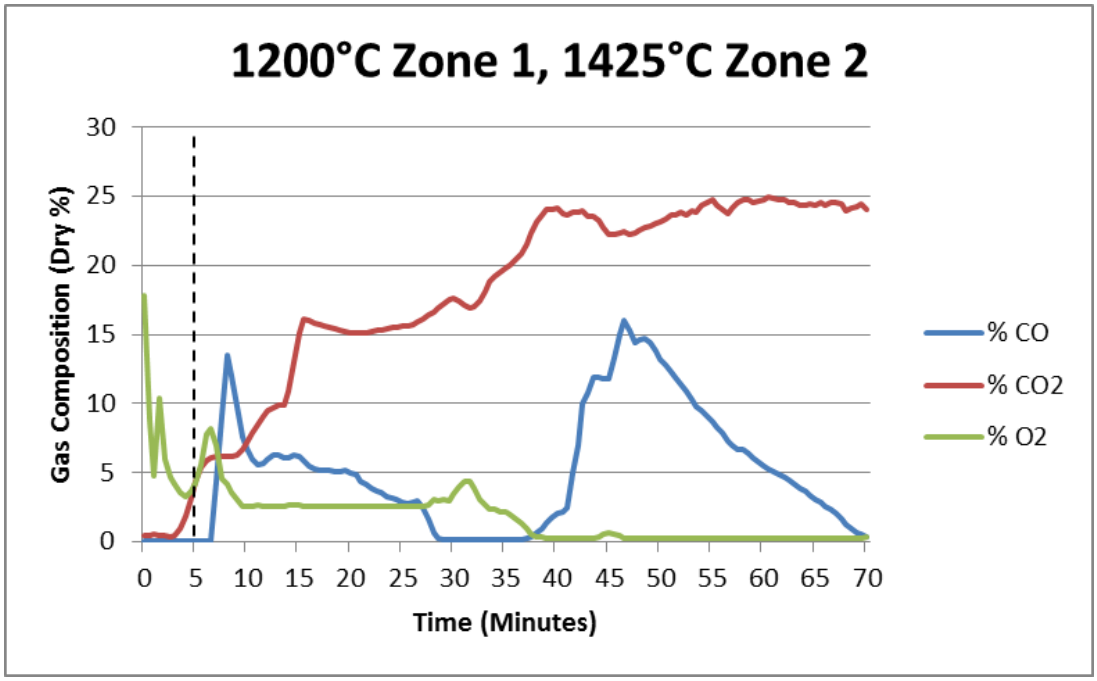


Figure 19: Phase I 1200°C/1425°C Gas Composition

Table 13: Phase I 1200°C/1425°C GC Data

Sample No.	Zone	Sampling Time, min.		Moisture (vapors), %	Permanent Gases, %						
		Start	Stop		N2	CO2	CO	H2	O2	CH4	C2+
1	1	2	5	3.4	82.5	7.8	0.0	0.2	6.2	Not Found	Not Found
2	2	7	10	5.4	71.4	11.1	5.9	2.8	3.4	Not Found	Not Found
3	2	15	18	4.5	79.4	11.1	1.9	0.8	2.3	Not Found	Not Found
4	2	25	29	4.4	79.8	14.0	0.8	0.2	0.9	Not Found	Not Found
5	2	40	44	4.7	61.8	16.7	15.0	0.9	0.8	Not Found	Not Found
6	2	55	59	5.3	56.1	18.1	18.9	0.8	0.9	Not Found	Not Found

Chemical Analysis

Metallization for these runs also were poor until the residence time in the second zone was greater than 50-60 minutes. For the test times of 65 and 70 minutes, the metallization for the top three layers were above 80%. The 70 minute test showed the highest metallization, with all layers having above 80% metallization with the exception of Layer 5 (69.7% metallization). Table 14 displays the chemical and metallization for the 1425°C Zone 2 temperature runs.

Table 14: Phase I 1200°C/1425°C Chemical Analysis

Run Data			Chemistry Data, Wt. %						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1425	10	1	7.83	0.22	67.61	35.73	17.82	14.06	52.8
		2	10.49	0.21	61.13	15.87	17.78	27.48	26.0
		3	12.58	0.20	55.39	7.18	14.19	34.02	13.0
		4	13.72	0.21	53.93	1.27	13.82	38.84	2.4
		5	13.06	0.20	54.32	1.21	17.08	36.03	2.2
	20	1	3.91	0.18	82.09	9.09	70.33	2.67	11.1
		2	11.31	0.19	63.15	26.91	20.64	15.60	42.6
		3	13.07	0.20	54.99	19.05	2.06	33.88	34.6
		4	13.15	0.21	53.31	19.12	1.26	32.93	35.9
		5	12.87	0.20	55.56	20.84	1.29	33.43	37.5
	30	1	1.34	0.22	85.83	77.03	7.58	1.22	89.7
		2	5.37	0.19	77.14	52.50	25.91	-1.27	68.1
		3	11.45	0.20	59.10	4.30	38.56	16.24	7.3
		4	11.93	0.19	57.88	1.14	23.74	33.00	2.0
		5	12.23	0.19	56.54	0.60	25.70	30.24	1.1
	40	1	0.20	0.18	87.95	82.21	5.52	0.22	93.5
		2	4.14	0.20	77.62	64.03	20.54	-6.95	82.5
		3	9.84	0.20	63.79	16.71	41.57	5.51	26.2
		4	11.94	0.19	57.11	1.94	34.87	20.30	3.4
		5	12.16	0.20	58.66	4.99	34.29	19.38	8.5
	50	1	0.05	0.18	88.27	82.79	5.19	0.29	93.8
		2	2.30	0.24	84.83	76.11	7.48	1.24	89.7
		3	8.02	0.24	67.93	33.39	31.38	3.16	49.2
		4	11.38	0.20	61.47	9.54	44.22	7.71	15.5
		5	11.35	0.21	60.03	7.62	44.82	7.59	12.7
	60	1	0.04	0.19	88.06	83.37	4.76	-0.07	94.7
		2	0.14	0.22	88.29	84.98	4.09	-0.78	96.3
		3	4.11	0.25	79.13	66.33	12.73	0.07	83.8
		4	8.11	0.25	69.98	37.16	27.94	4.88	53.1
		5	10.51	0.22	63.39	16.10	40.78	6.51	25.4
	65	1	0.14	0.23	87.52	78.67	7.16	1.69	89.9
		2	0.04	0.22	88.11	81.73	4.46	1.92	92.8
		3	0.43	0.25	88.42	85.42	1.81	1.19	96.6
		4	4.12	0.24	81.36	70.17	10.24	0.95	86.2
		5	6.13	0.23	75.25	52.45	20.17	2.63	69.7

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 15 displays the shrinkage and weight loss data for the 1425°C Zone 2 temperature runs.

Table 15: Phase I 1200°C/1425°C Shrinkage and Weight Loss Data

Run Data		Shrinkage and Weight Data			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction, %
1425	10	1	13.8	29.1	11.6
		2	8.5		
		3	1.2		
		4	4.6		
		5	7.8		
	20	1	16.3	26.5	16.2
		2	3.7		
		3	4.1		
		4	3.1		
		5	-2.5		
	30	1	20.1	23.8	20.5
		2	7.6		
		3	2.4		
		4	2.6		
		5	4.9		
	40	1	28.6	29.1	24.6
		2	13.0		
		3	2.7		
		4	5.3		
		5	3.3		
	50	1	27.4	31.7	30.2
		2	12.7		
		3	0.5		
		4	3.4		
		5	4.5		
	60	1	31.2	29.1	35.2
		2	23.7		
		3	2.5		
		4	-2.5		
		5	-3.0		
	65	1	29.3	42.3	37.5
		2	24.0		
		3	13.7		
		4	-6.4		
		5	-2.4		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 3, pages 99 through 105.

Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1500°C) Test Results

Sample Temperature Profile

Figure 20 displays the temperature profile of the sample that was heated in Zone 1 at 1200°C for five minutes and Zone 2 at 1500°C for 65 minutes. The temperature surpassed the 1200°C at approximately 68th minute. As in the 1425°C run, the bottom thermocouple formed a concave temperature curve throughout the run. The beginning temperature readings may have been biased due to the thermocouple being forced through the preheated furnace and into the sample cup.

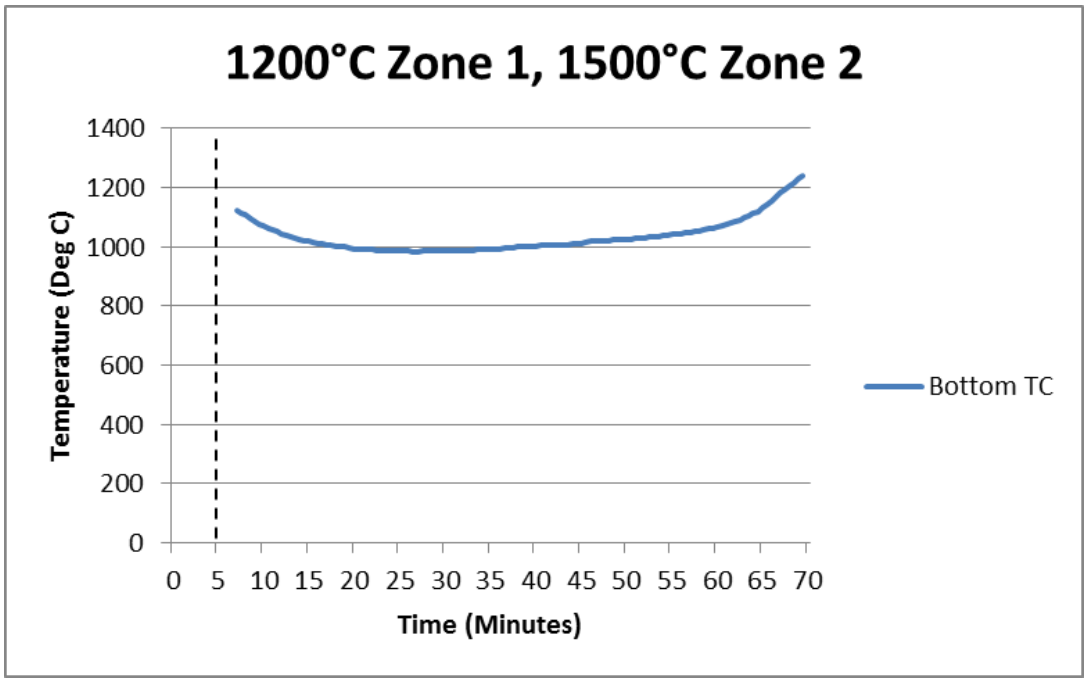


Figure 20: Phase I 1200°C/1500°C Temperature Profile

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 21 displays the gas analysis of the sample that was heated in Zone 1 at 1200°C for five minutes and Zone 2 at 1500°C for 65 minutes. Table 16 displays the gas chromatography data for this temperature profile.

The carbon dioxide was in the 20-25% range throughout much of the run, while the oxygen was very minimal from 8 minutes to the end of the run. The carbon monoxide, however, showed three distinct peaks at approximately 8, 33, and 58 minutes. The percentages at each peak were 28%, 15%, and 20%, respectively.

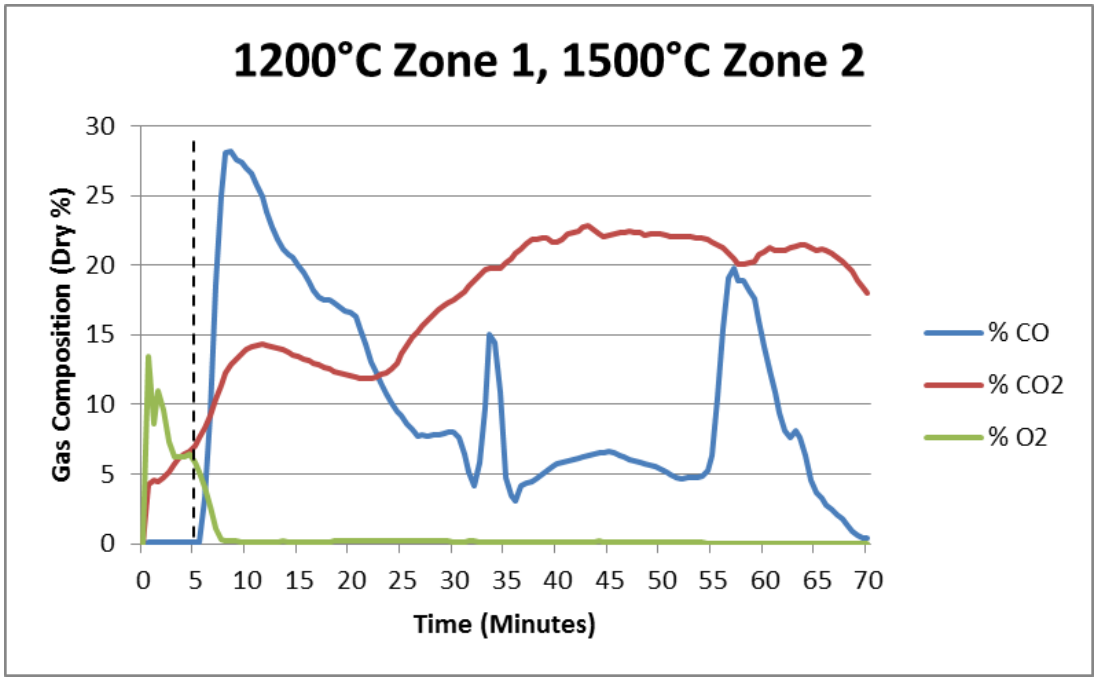


Figure 21: Phase I 1200°C/1500°C Gas Composition

Table 16: Phase I 1200°C/1500°C GC Data

Sample No.	Zone	Sampling Time, min.		Moisture (vapors), %	Permanent Gases, %						
		Start	Stop		N2	CO2	CO	H2	O2	CH4	C2+
1	1	1	4	12.1	83.1	9.1	0.0	0.2	3.6	Not Found	Not Found
2	2	5.5	7	5.7	22.5	8.9	37.6	17.5	1.4	Not Found	Not Found
3	2	10	13	5.4	65.2	9.7	12.5	6.2	0.7	Not Found	Not Found
4	2	20	23	7.5	71.1	11.9	8.2	2.7	0.7	Not Found	Not Found
5	2	30	33	8.3	65.1	15.2	10.0	1.6	0.6	Not Found	Not Found
6	2	50	53	4.1	61.3	17.2	12.2	0.5	0.5	Not Found	Not Found

Chemical Analysis

Metallization for the 65 and 70 minute runs were high, with all of the layers for these runs above 83% metallized. The 70 minute run, however, had all five layers above 90% metallized. Table 17 displays the chemical and metallization for the 1500°C Zone 2 temperature runs.

Table 17: Phase I 1200°C/1500°C Chemical Analysis

Run Data			Chemistry Data, Wt. %						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1500	10	1	3.89	0.22	80.42	63.75	14.84	1.83	79.3
		2	10.92	0.22	62.46	14.50	36.34	11.62	23.2
		3	13.19	0.21	55.54	1.33	17.49	36.72	2.4
		4	12.57	0.21	54.67	4.89	19.18	30.60	8.9
		5	12.54	0.21	56.48	1.32	18.48	36.68	2.3
	20	1	0.41	0.18	87.94	84.75	3.15	0.04	96.4
		2	6.77	0.18	69.52	54.90	20.70	-6.08	79.0
		3	11.80	0.21	58.33	6.12	24.19	28.02	10.5
		4	12.24	0.19	55.72	1.72	19.60	34.40	3.1
		5	12.35	0.19	56.15	1.08	21.68	33.39	1.9
	30	1	1.20	0.19	85.99	77.60	6.49	1.90	90.2
		2	7.59	0.19	71.19	35.58	28.28	7.33	50.0
		3	11.32	0.19	60.32	4.35	40.03	15.94	7.2
		4	12.11	0.19	57.86	1.11	27.89	28.86	1.9
		5	12.56	0.18	57.95	1.13	33.57	23.25	1.9
	40	1	0.07	0.19	86.44	79.41	5.68	1.35	91.9
		2	3.87	0.23	80.61	63.49	14.42	2.70	78.8
		3	8.75	0.21	67.82	24.50	36.16	7.16	36.1
		4	9.94	0.19	64.33	14.27	42.04	8.02	22.2
		5	11.08	0.19	61.62	5.74	44.79	11.09	9.3
	50	1	0.02	0.21	88.24	82.31	5.47	0.46	93.3
		2	0.25	0.25	88.46	84.60	3.85	0.01	95.6
		3	3.91	0.24	80.48	65.21	13.96	1.31	81.0
		4	8.50	0.22	69.08	30.67	35.04	3.37	44.4
		5	9.56	0.21	65.18	19.89	39.34	5.95	30.5
	60	1	0.24	0.20	87.94	81.98	5.99	-0.03	93.2
		2	BDL[4]	0.23	88.06	82.56	5.62	-0.12	93.8
		3	0.09	0.26	88.34	85.87	1.40	1.07	97.2
		4	2.00	0.26	85.83	81.18	2.26	2.39	94.6
		5	4.42	0.24	78.67	65.79	10.60	2.28	83.6
	65	1	0.26	0.20	88.59	83.78	4.79	0.02	94.6
		2	0.22	0.21	87.27	80.83	7.73	-1.29	92.6
		3	0.06	0.23	88.37	84.48	4.05	-0.16	95.6
		4	0.44	0.26	89.00	88.02	0.77	0.21	98.9
		5	1.92	0.25	87.51	87.89	0.36	-0.74	100.4

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 18 below displays the shrinkage and weight loss data for this run.

[4] BDL: Below Detection Limit

Table 18: Phase I 1200°C/1500°C Shrinkage and Weight Loss Data

Run Data		Shrinkage and Weight Data			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction, %
1500	10	1	16.5	29.1	11.1
		2	-3.7		
		3	-2.6		
		4	0.6		
		5	0.9		
	20	1	24.3	29.1	17.0
		2	10.9		
		3	0.8		
		4	1.1		
		5	-2.4		
	30	1	23.8	23.8	22.9
		2	4.1		
		3	4.2		
		4	0.7		
		5	1.1		
	40	1	25.9	29.1	29.9
		2	2.3		
		3	4.6		
		4	-5.6		
		5	1.4		
	50	1	32.6	42.3	33.7
		2	18.8		
		3	1.6		
		4	1.1		
		5	2.8		
	60	1	38.7	45.0	39.7
		2	30.5		
		3	20.6		
		4	5.4		
		5	4.5		
	65	1	36.5	47.6	40.0
		2	31.6		
		3	29.7		
		4	23.7		
		5	11.9		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 3, pages 106 through 112.

Phase I Testing Data Analysis

Five layers of the sample bed were analyzed for carbon, sulfur, total iron, metallic iron, ferrous iron, and pellet shrinkage upon completion of each test. The assayed data was plotted against temperature and time to determine the effects of changing testing conditions. Layer 5 was used as a proxy for reaction through the deep bed; therefore, that layer is described in depth.

Bed Layer Analyses vs. Time

Metallization for Zone 2 Temperatures 1350°C, 1425°C, and 1500°C

For the 1350°C Zone 2 temperature runs, Layer 5 metallization stayed relatively stable throughout the run until 35 minutes then increased from 2% to 9% at 55 minute mark. From 55 minutes to 70 minutes the metallization climbed to approximately 30%. Figure 22 below displays the metallization for the 1350°C Zone 2 temperature over time.

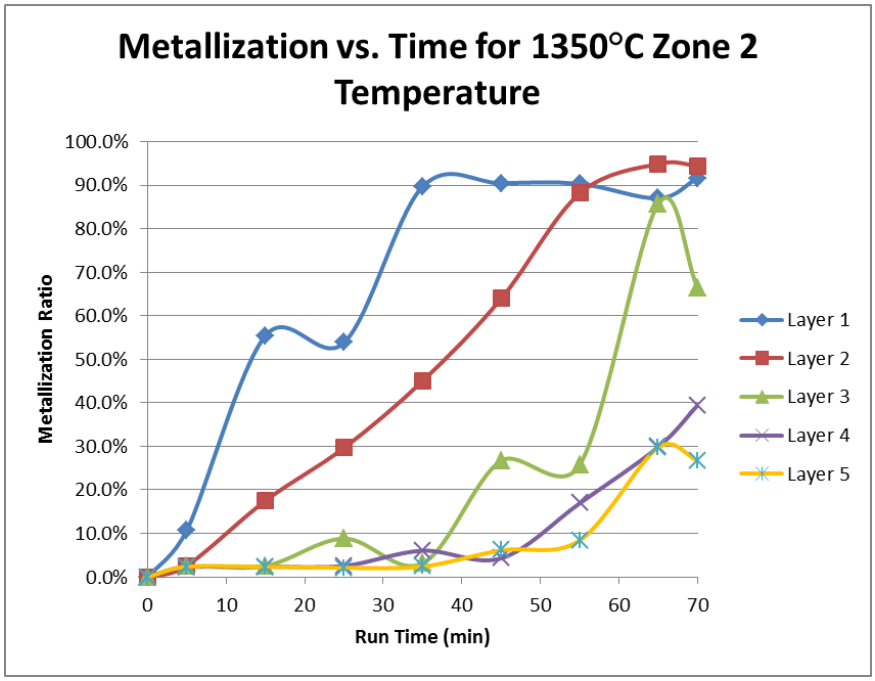


Figure 22: Phase I Metallization vs. Time for 1350°C for Zone 2 Temperature

For the 1425°C Zone 2 temperature runs, Layer 5 metallization remained low until the 25 minute mark, in which it peaked to 38%. Metallization returned to 1% at the 45 minute mark and then increased to approximately 70% at the conclusion of the 70 minute test. Figure 23 below displays the metallization for the 1425°C Zone 2 temperature over time.

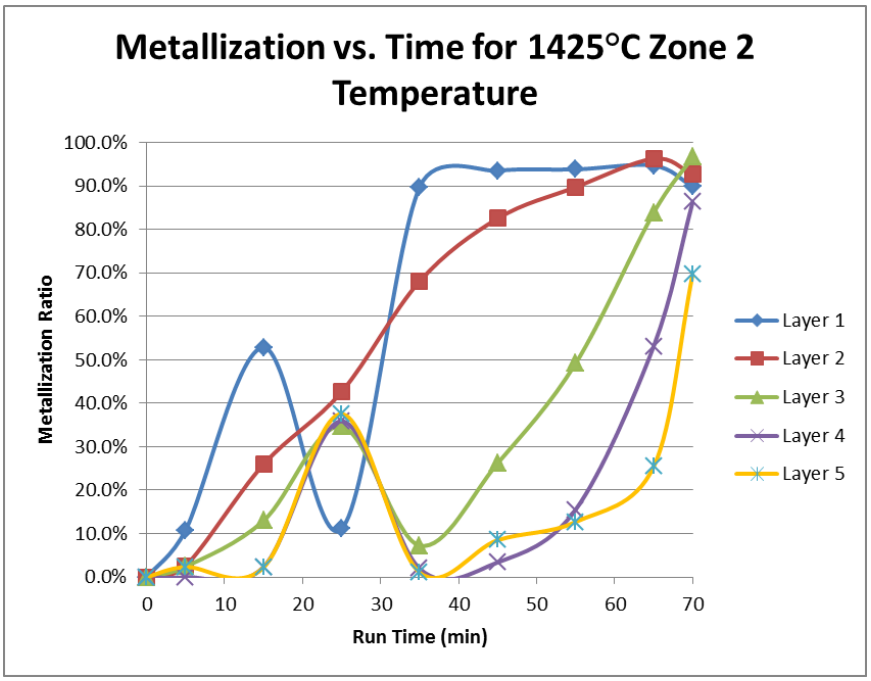


Figure 23: Phase I Metallization vs. Time for 1425°C for Zone 2 Temperature

For the 1500°C Zone 2 temperature runs, Layer 5 metallization stayed relatively stable at 2% until the 45 minute mark, in which it increased to 9%. From 45 minutes to 70 minutes, the metallization climbed to 100%. Figure 24 below displays the metallization for the 1500°C Zone 2 temperature over time.

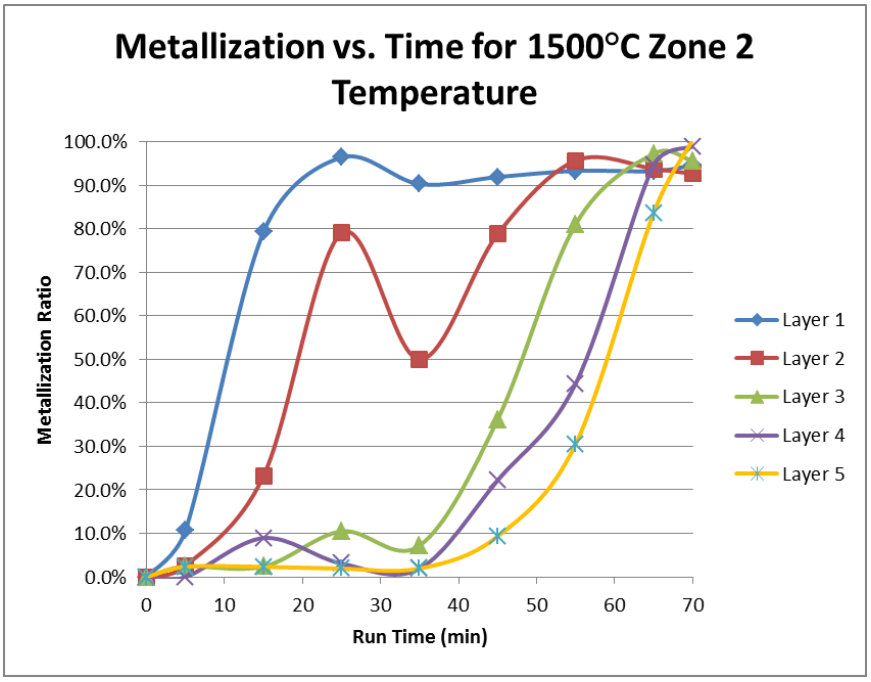


Figure 24: Phase I Metallization vs. Time for 1500°C for Zone 2 Temperature

Average Pellet Shrinkage for Zone 2 Temperatures 1350°C, 1425°C, and 1500°C

For the 1350°C Zone 2 temperature runs, Layer 5 pellets, on average, stayed relatively unchanged except at the 25 and 55 minute mark. For these two tests the pellets shrunk approximately 5%. Figure 25 below displays the average pellet shrinkage for the 1350°C Zone 2 temperature over time.

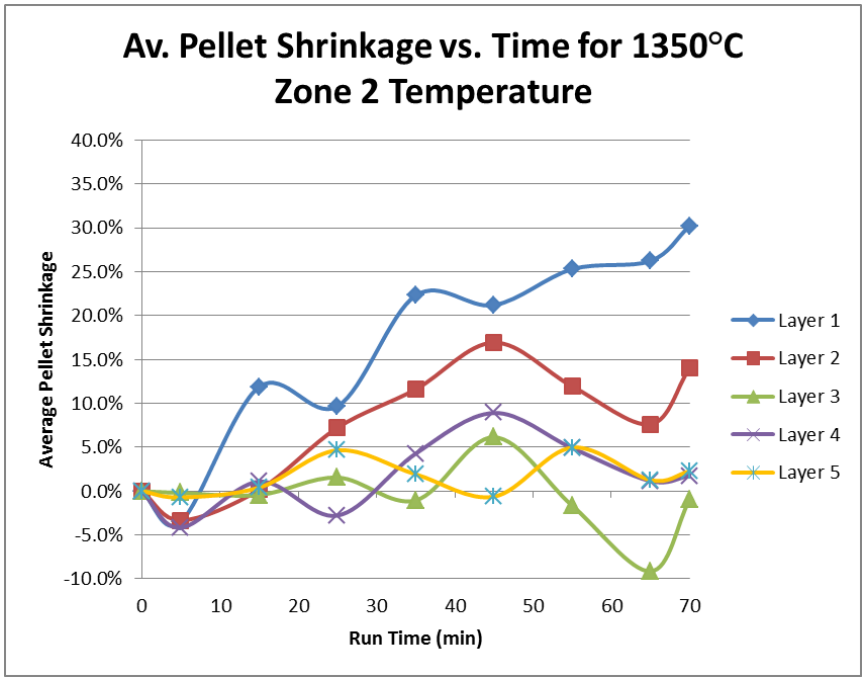


Figure 25: Phase I Average Pellet Shrinkage vs. Time for 1350°C for Zone 2 Temperature

For the 1425°C Zone 2 temperature runs, Layer 5 pellet shrinkage peaked during the 15 minute test at 8%, then returned to approximately 4% until the 65 minute mark. From 65 to 70 minutes the Layer 5 pellets swelled 2-3%. Figure 26 below displays the average pellet shrinkage for the 1425°C Zone 2 temperature over time.

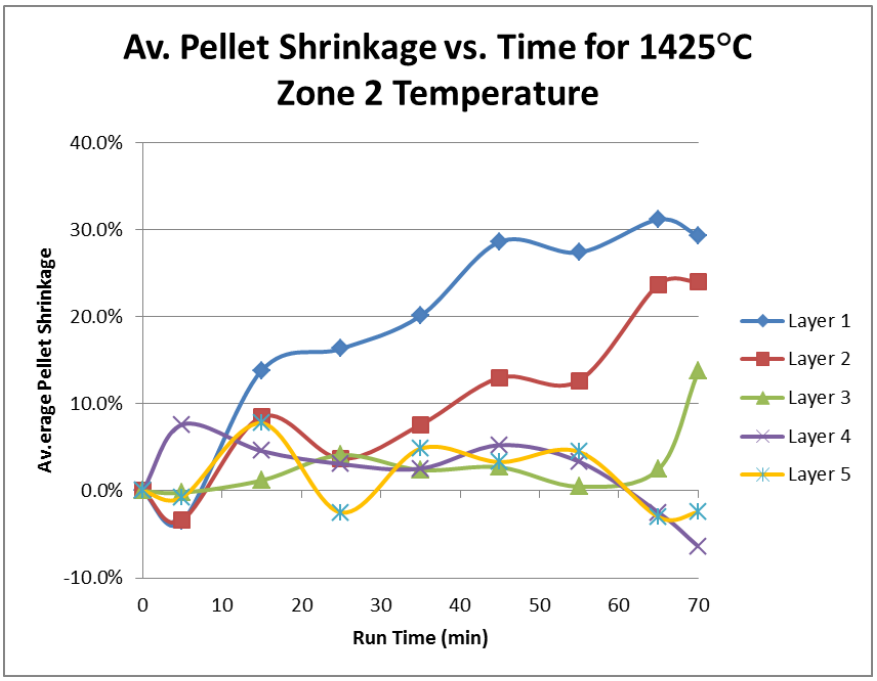


Figure 26: Phase I Average Pellet Shrinkage vs. Time for 1425°C for Zone 2 Temperature

For the 1500°C Zone 2 temperature runs, Layer 5 pellet shrinkage remained unchanged until the 25 minute mark, in which the average pellet swelled 2.4%. From the 25 minute to 65 minute mark average pellet shrinkage increased to 4.5%, and ultimately, to 12% at 70 minutes. Figure 27 below displays the average pellet shrinkage for the 1425°C Zone 2 temperature over time.

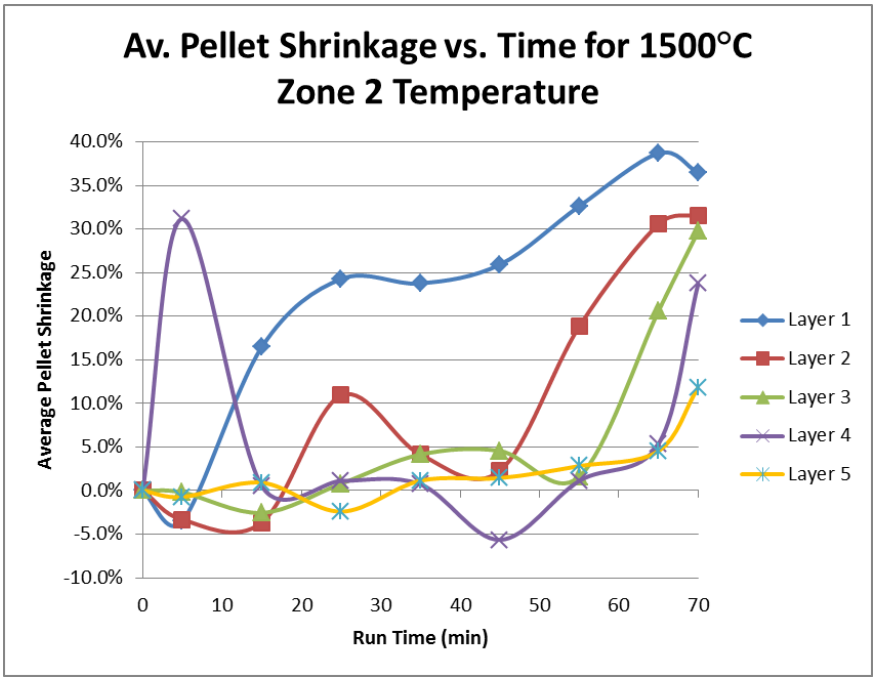


Figure 27: Phase I Average Pellet Shrinkage vs. Time for 1500°C for Zone 2 Temperature

Carbon for Zone 2 Temperatures 1350°C, 1425°C, and 1500°C

For the 1350°C Zone 2 temperature runs, Layer 5 carbon decreased from approximately 15% to 11% at 35 minutes, and then increased slightly to 13% at the 45 minute mark. Carbon decreased to approximately 9% by the end of the 70 minute test. Figure 28 below displays the average pellet shrinkage for the 1350°C Zone 2 temperature over time.

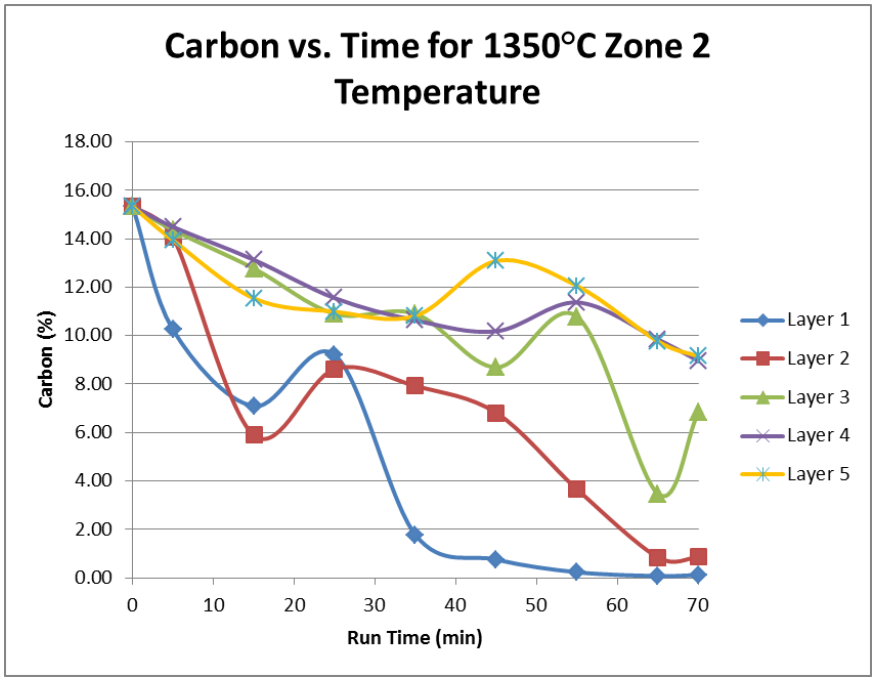


Figure 28: Phase I Carbon vs. Time for 1350°C for Zone 2 Temperature

For the 1425°C Zone 2 temperature runs, Layer 5 carbon decreased fairly linearly from approximately 15% to 11% by the 65 minute mark. From 65 to 70 minutes, carbon decreased from 11% to 6%. Figure 29 below displays the average pellet shrinkage for the 1425°C Zone 2 temperature over time.

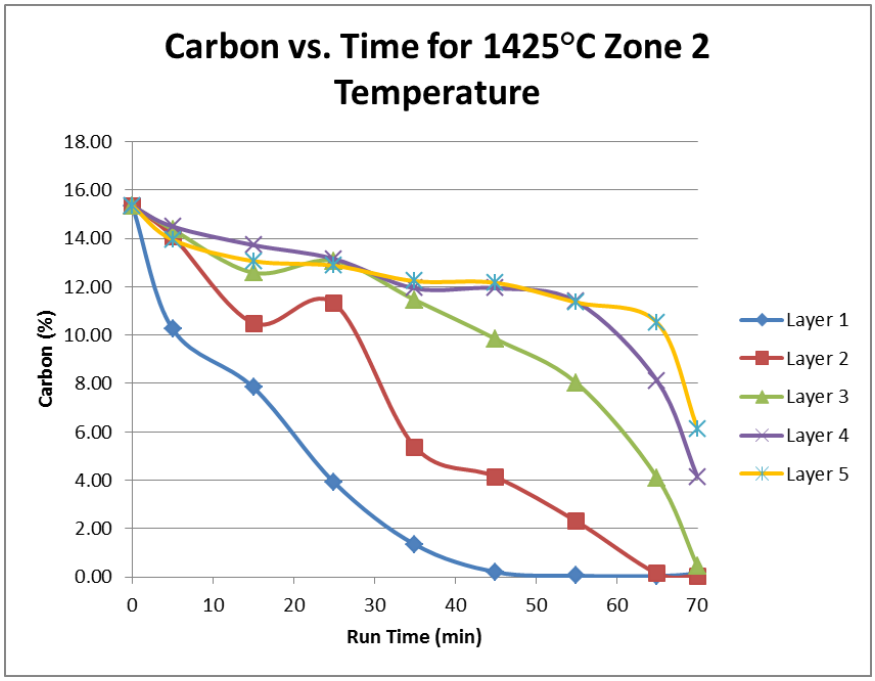


Figure 29: Phase I Carbon vs. Time for 1425°C for Zone 2 Temperature

For the 1500°C Zone 2 temperature runs, Layer 5 carbon decreased from approximately 15% to 11.5% by the 35 minute mark. From 35 to 55 minutes, carbon decreased from 11.5% to 9.5%, and then ultimately to 2% by the conclusion of the 70 minute run. Figure 30 below displays the average pellet shrinkage for the 1500°C Zone 2 temperature over time.

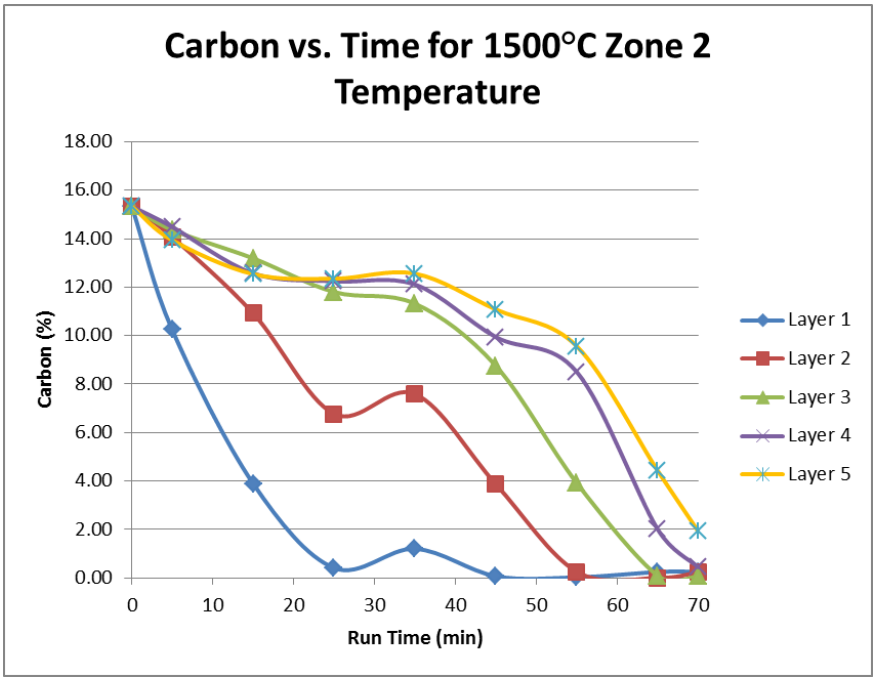


Figure 30: Phase I Carbon vs. Time for 1500°C for Zone 2 Temperature

Sulfur for Zone 2 Temperatures 1350°C, 1425°C, and 1500°C

For the 1350°C Zone 2 temperature runs, Layer 5 sulfur remained relatively constant and averaged 0.19%. Figure 31 below displays the percent sulfur for the 1350°C Zone 2 temperature over time.

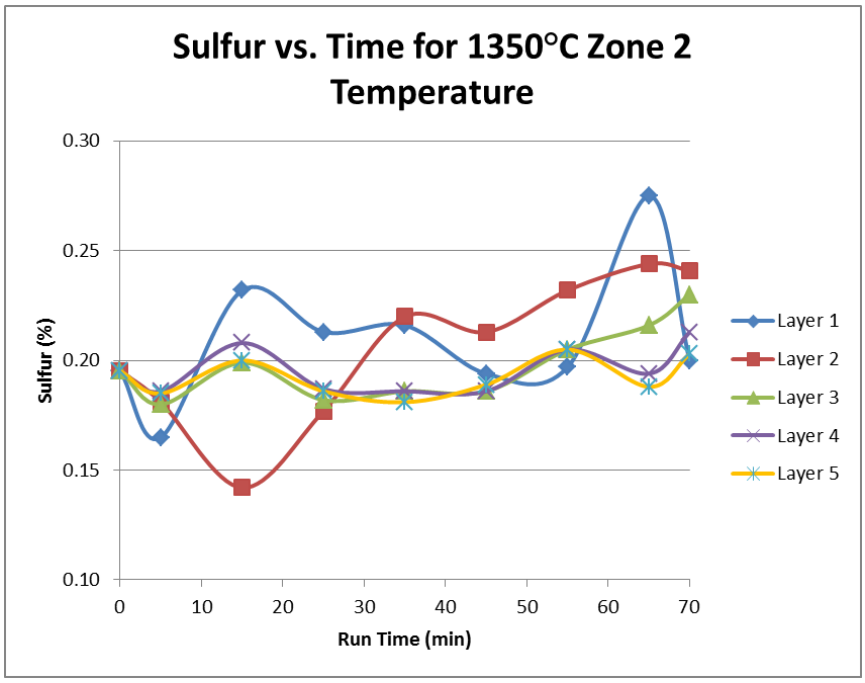


Figure 31: Phase I Sulfur vs. Time for 1350°C for Zone 2 Temperature

For the 1425°C Zone 2 temperature runs, Layer 5 sulfur remained relatively constant and averaged 0.20% until the 35 minute mark. From 35 minutes to 70 minutes, the percent sulfur increased from 0.19% to 0.23%. Figure 32 below displays the percent sulfur for the 1425°C Zone 2 temperature over time.

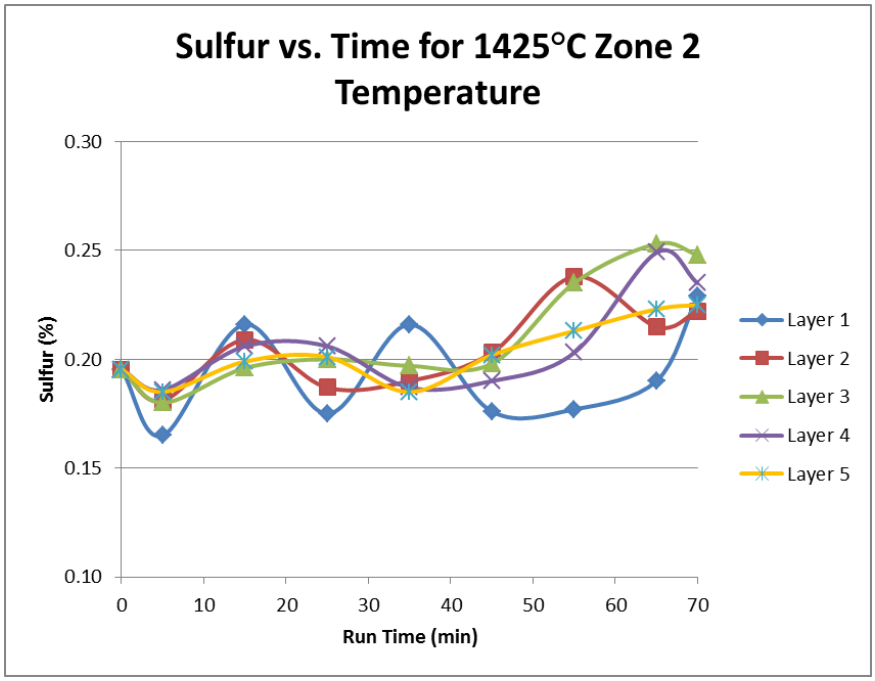


Figure 32: Phase I Sulfur vs. Time for 1425°C for Zone 2 Temperature

For the 1500°C Zone 2 temperature runs, Layer 5 sulfur remained relatively constant and averaged 0.19% until the 55 minute mark. From 55 minutes to 70 minutes, the percent sulfur increased from 0.19% to 0.25%. Figure 33 below displays the percent sulfur for the 1500°C Zone 2 temperature over time.

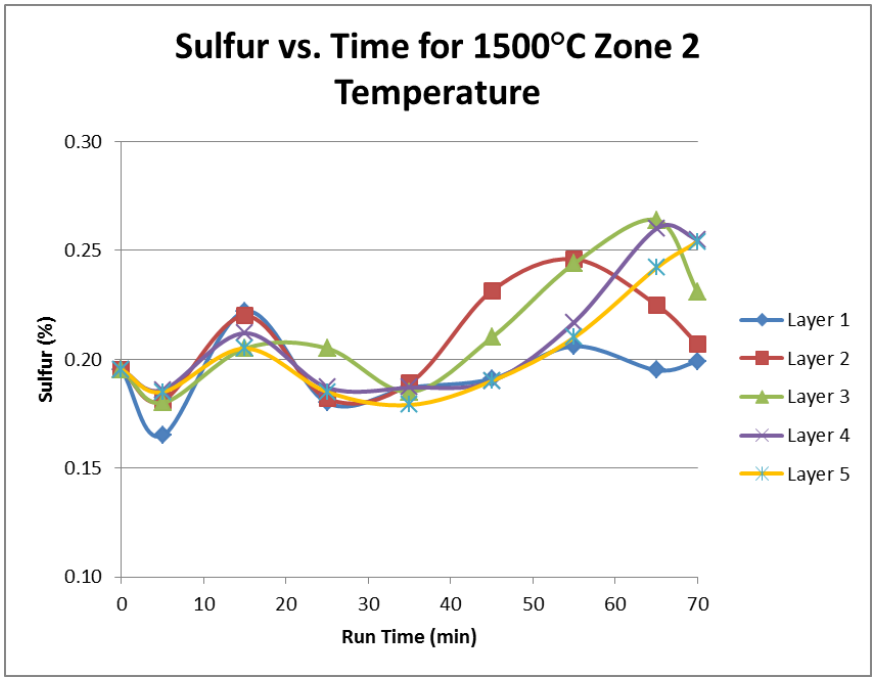


Figure 33: Phase I Sulfur vs. Time for 1500°C for Zone 2 Temperature

Ferrous Iron for Zone 2 Temperatures 1350°C, 1425°C, and 1500°C

For the 1350°C Zone 2 temperature runs, Layer 5 ferrous iron decreased from 24% to 16% from the start of the run to the 25 minute mark. From 25 minutes to the end of the 70 minute test the ferrous iron increased to approximately 40%. Figure 34 below displays the percent ferrous iron for the 1350°C Zone 2 temperature over time.

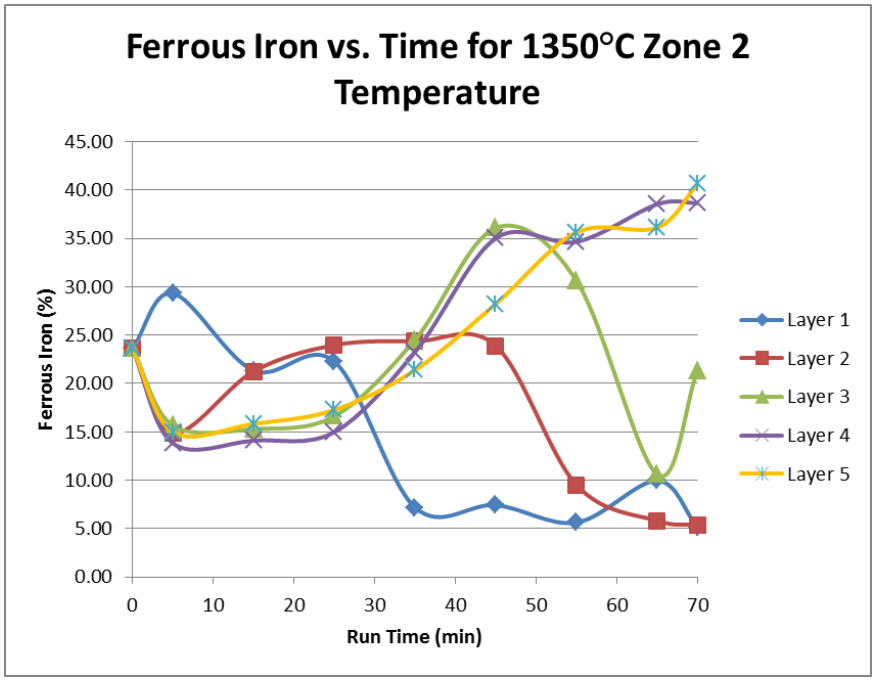


Figure 34: Phase I Ferrous Iron vs. Time for 1350°C for Zone 2 Temperature

For the 1425°C Zone 2 temperature runs, Layer 5 ferrous iron decreased from 24% to 1% from the start of the run to the 25 minute mark. From 25 minutes to 55 minutes the ferrous iron increased to approximately 44%, and was ultimately decreased to 20% by the 70 minute mark. Figure 35 below displays the percent ferrous iron for the 1425°C Zone 2 temperature over time.

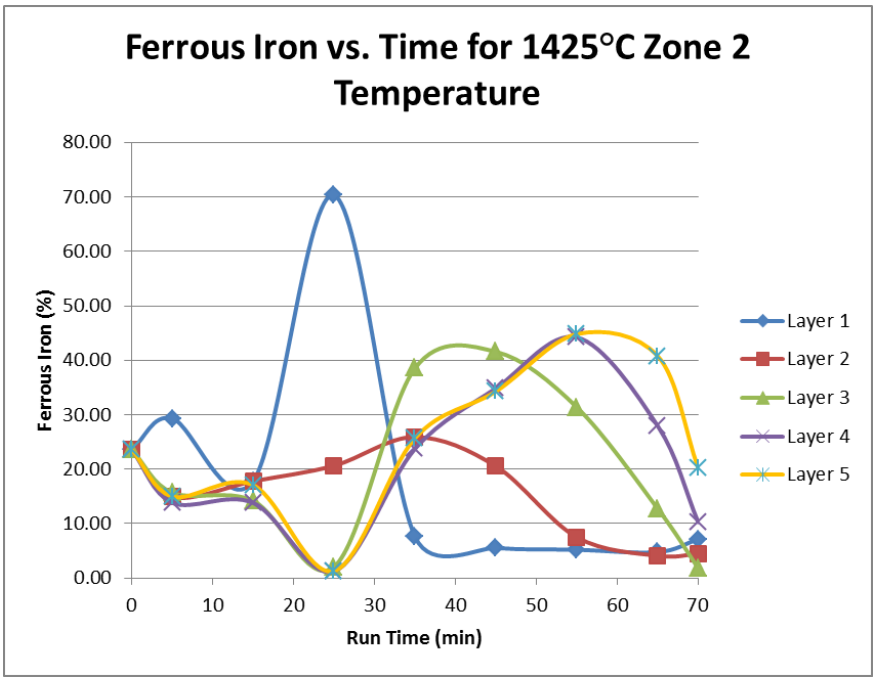


Figure 35: Phase I Ferrous Iron vs. Time for 1425°C for Zone 2 Temperature

For the 1500°C Zone 2 temperature runs, Layer 5 ferrous iron decreased from 24% to 18% from the start of the run to the 15 minute mark. From 15 minutes to 45 minutes the ferrous iron increased to approximately 45%. The ferrous iron decreased from 45% at 45 minutes to nearly zero by the end of the 70 minute run. Figure 36 below displays the percent ferrous iron for the 1500°C Zone 2 temperature over time.

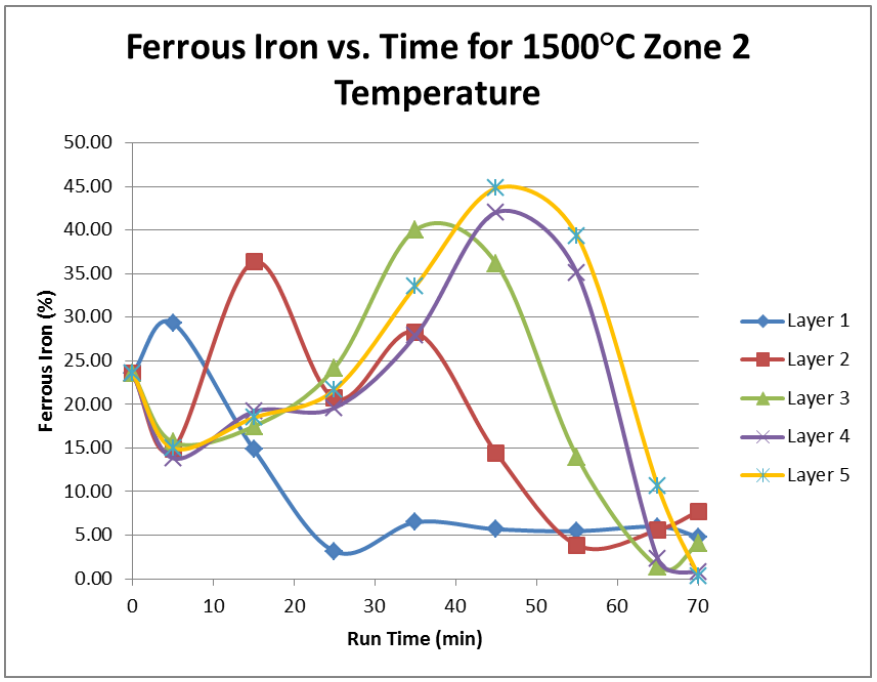


Figure 36: Phase I Ferrous Iron vs. Time for 1500°C for Zone 2 Temperature

Vertical Shrinkage vs. Time

The vertical shrinkage for the Zone 2 temperature of 1350°C increased approximately 24% at 35 minutes and leveled off until the 65 minute mark. From 65 minutes to 70 minutes the vertical shrinkage increased to approximately 32%. For both the 1425°C and 1500°C Zone 2 temperatures the vertical shrinkage increased approximately 30% at the 15 minute mark and then decreased to 22% by 35 minutes. From 35 minutes to 70 minutes the vertical shrinkage for the Zone 2 temperatures of 1425°C and 1500°C increased to 38% and 40%, respectively. Figure 37 displays the vertical shrinkage vs. time plot.

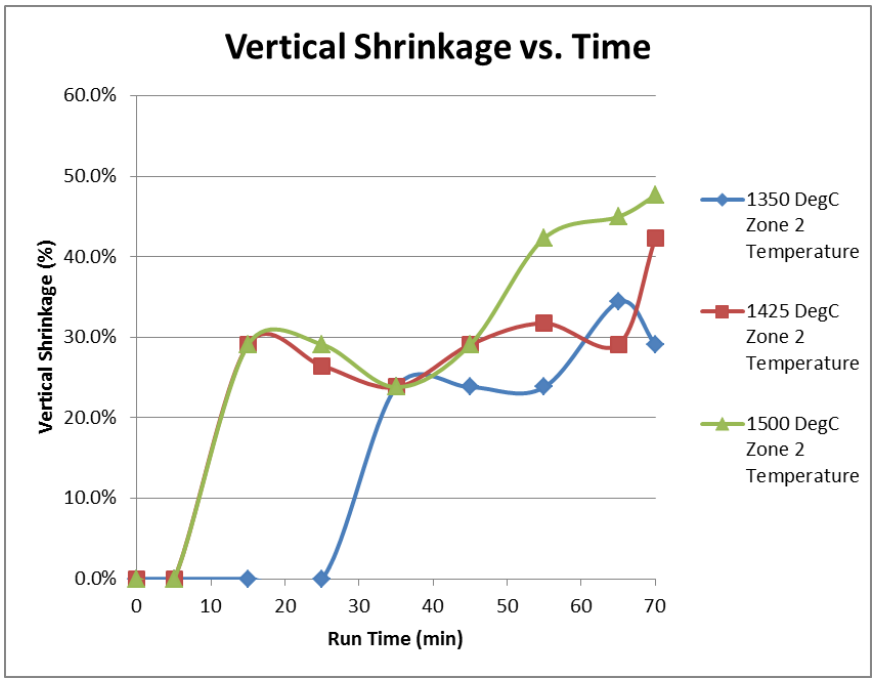


Figure 37: Phase I Vertical Shrinkage vs. Time

Weight Loss vs. Time

The total sample weight loss for the Zone 2 temperatures of 1350°C, 1425°C, and 1500°C were fairly linear. The linear approximation for weight losses versus time relationships were found to be:

1) $Weight\ Loss\ Percentage\ for\ 1350°C\ Zone\ 2\ Temperature = 0.4422 * Time + 1.7153$

2) $Weight\ Loss\ Percentage\ for\ 1425°C\ Zone\ 2\ Temperature = 0.5144 * Time + 2.0036$

3) $Weight\ Loss\ Percentage\ for\ 1500°C\ Zone\ 2\ Temperature = 0.5796 * Time + 1.7804,$

$Where\ Time\ is\ the\ total\ run\ time\ in\ minutes.$

Figure 38 displays the weight loss vs. time plot.

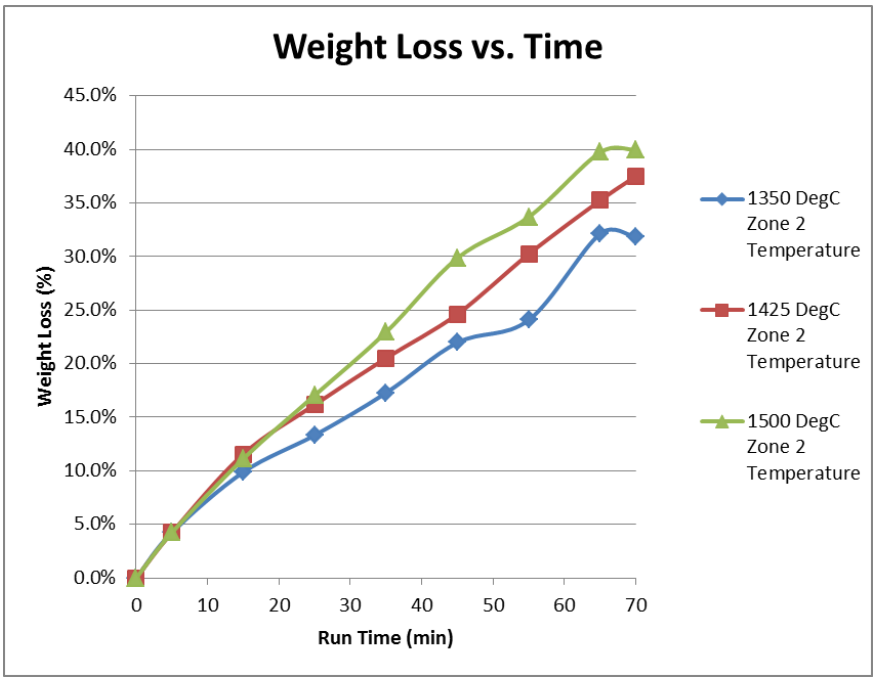


Figure 38: Phase I Weight Loss vs. Time

Bed Layer Analyses vs. Zone 2 Temperature

Layer 5 metallization increased from 2% to 27% between 1200°C and 1350°C, 27% to 70% between 1350°C and 1425°C, and from 70% to 100% from 1425°C to 1500°C. Figure 39 below displays the metallization versus time for the 70 minute run.

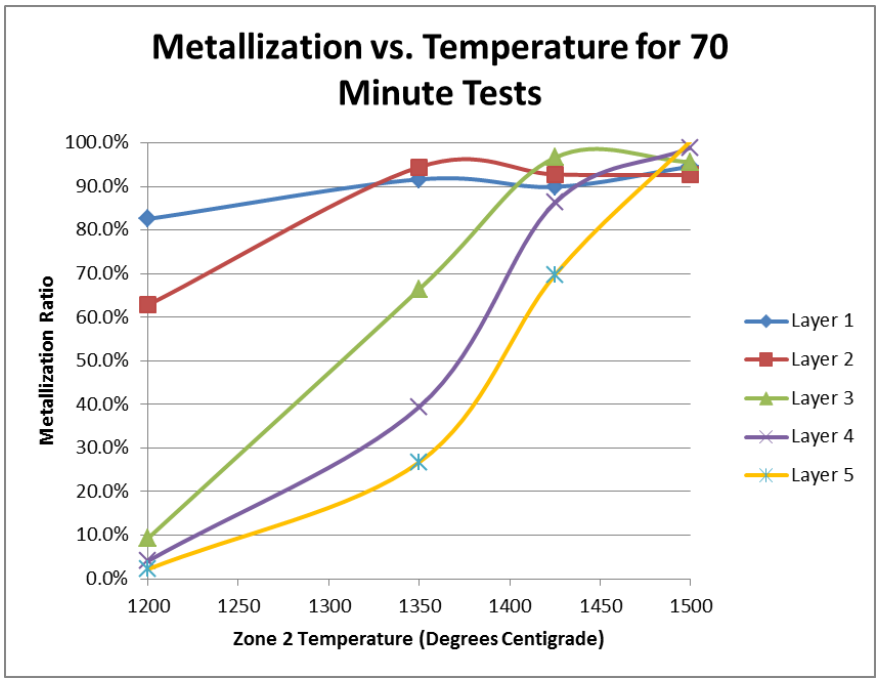


Figure 39: Phase I Metallization vs. Temperature 70 Minute Tests

The average Layer 5 pellet shrunk to 2.3% at 1350°C, swelled to 2.4% between 1350°C and 1425°C, and ultimately shrunk to 12% by 1500°C. Figure 40 below displays the average pellet shrinkage versus time for the 70 minute run.

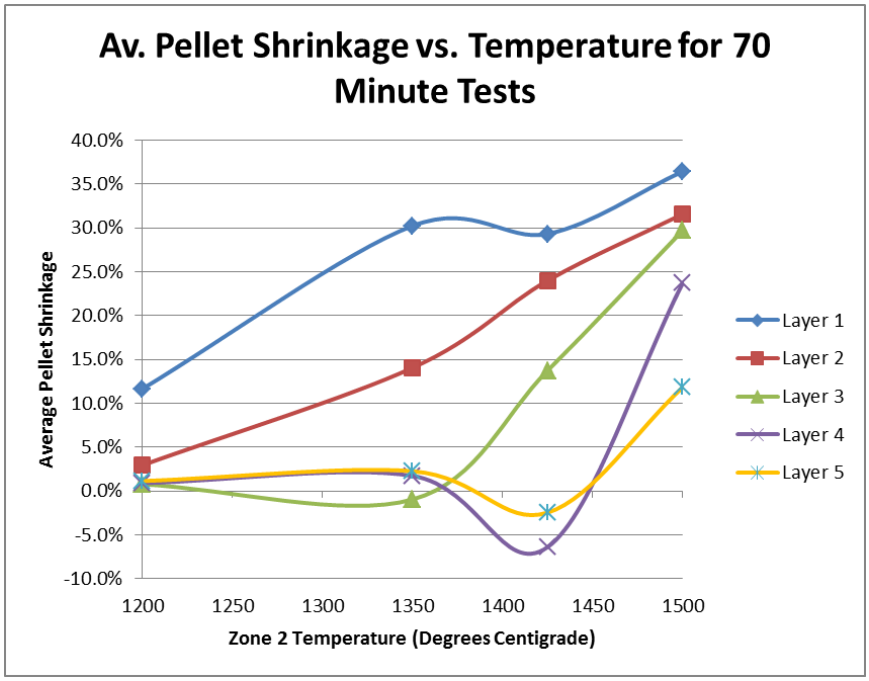


Figure 40: Phase I Average Pellet Shrinkage vs. Temperature 70 Minute Tests

Layer 5 total carbon decreased nearly linearly from 14% to 2% between the 1200°C to 1500°C temperature range. Figure 41 below displays the sulfur versus time for the 70 minute run.

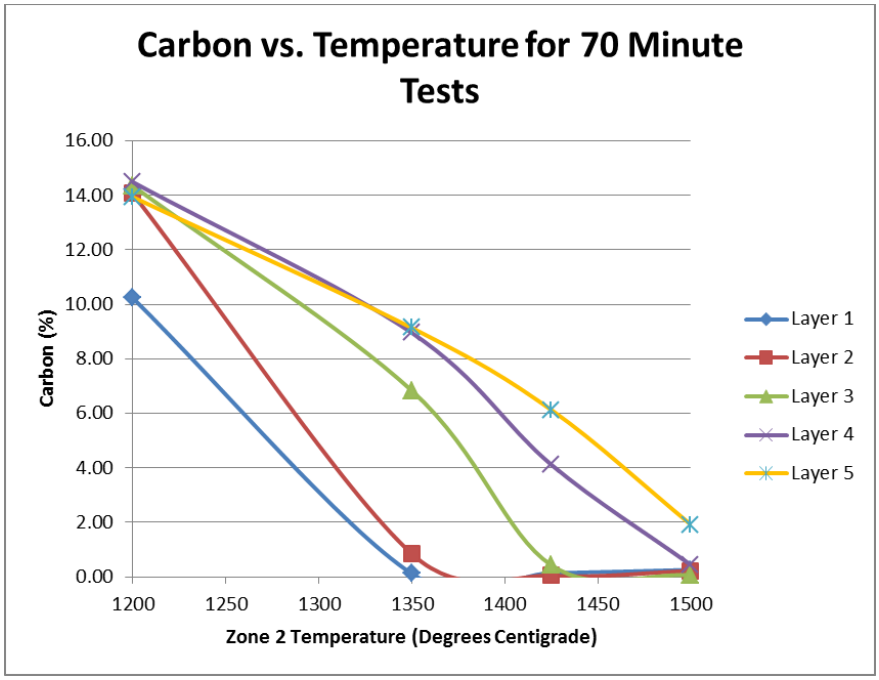


Figure 41: Phase I Carbon vs. Temperature 70 Minute Tests

Layer 5 sulfur increased to from 0.19% to 0.23% from 1200°C to 1350°C, and ultimately to 0.25% from 1350°C to 1500°C. Figure 42 below displays the sulfur versus time for the 70 minute run.

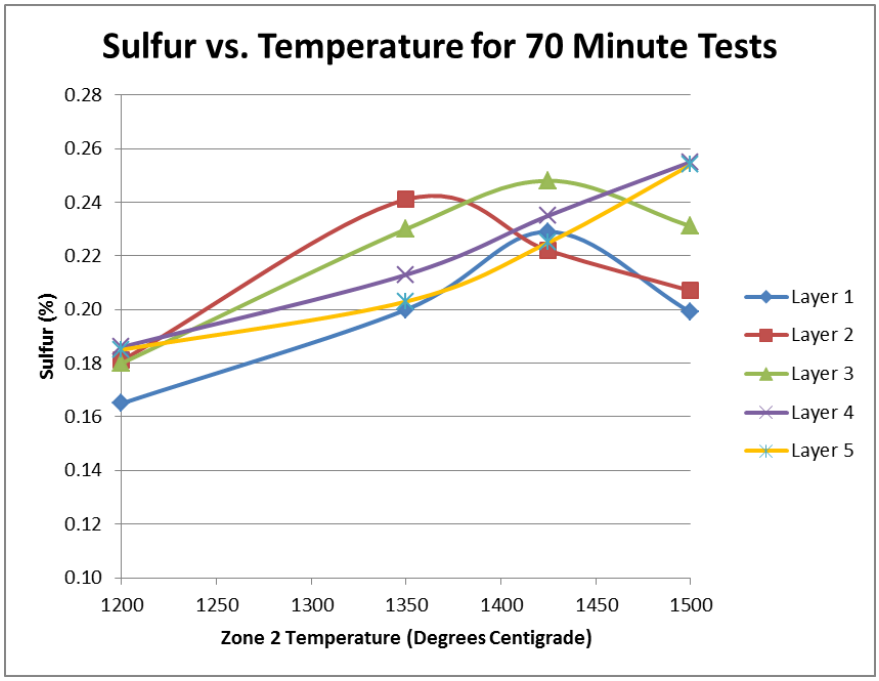


Figure 42: Phase I Sulfur vs. Temperature 70 Minute Tests

Layer 5 ferrous iron increased approximately 3.5%, from 37.1%-40.6%, in the 1200°C to 1350°C temperature range. The ferrous iron percentage then decreased approximately 20% every 150°C, ultimately being nearly zero at 1500°C. Figure 43 below displays the sulfur versus time for the 70 minute run.

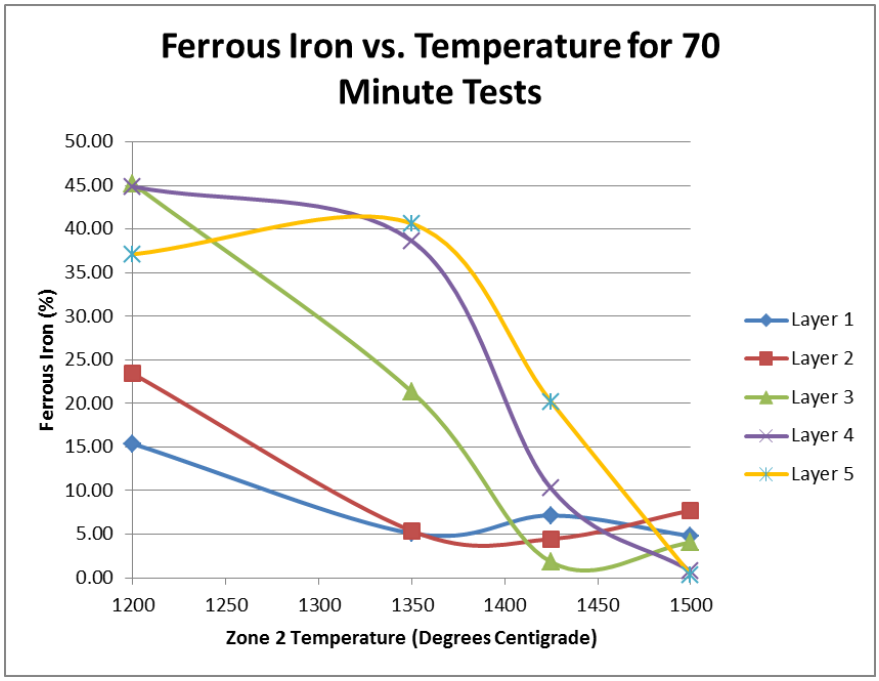


Figure 43: Phase I Ferrous Iron vs. Temperature 70 Minute Tests

Vertical Shrinkage vs. Temperature

Vertical shrinkage increased from 24% at 1200°C to 29% at 1350°C, and then from 42% to 48% from 1425°C to 1500°C. Figure 44 displays the vertical shrinkage vs. temperature plot for the 70 minute tests.

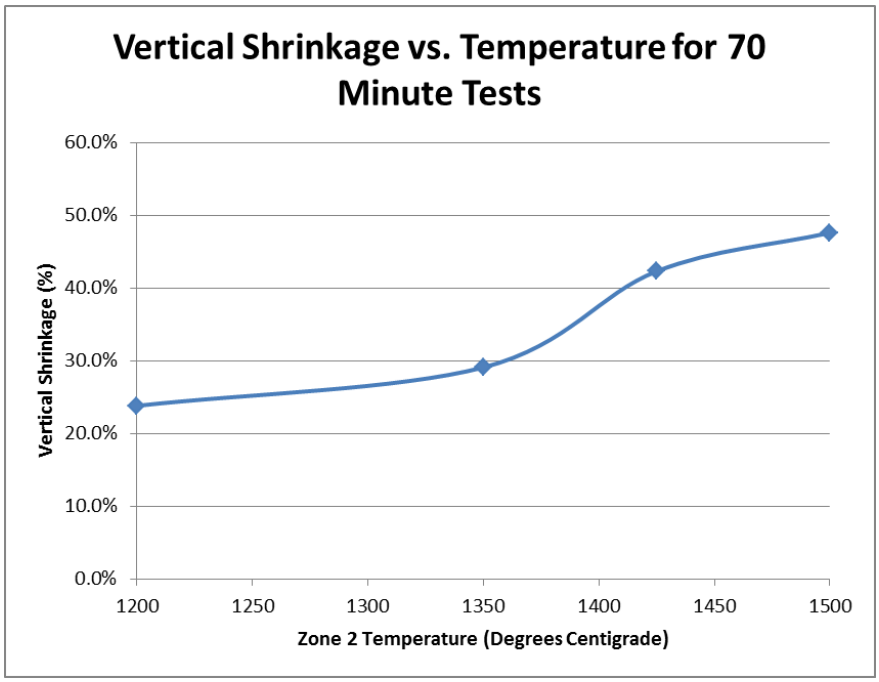


Figure 44: Phase I Vertical Shrinkage vs. Temperature

Weight Loss vs. Temperature

The total sample weight loss over temperature was fairly linear for the temperature ranges 1200°C to 1425°C. The approximation for weight losses versus temperature in this temperature range were found to be:

$$Weight\ Loss\ Percentage = 0.0675 * Temperature - 58.861,$$

$$Where\ Temperature\ is\ the\ temperature\ in\ degrees\ Centigrade\ (valid\ from\ 1200°C\ to\ 1425°C).$$

From 1425°C to 1500°C, the weight loss increased only an additional 2.5%. Total weight loss at 1500°C was approximately 40%. Figure 45 displays the weight loss vs. temperature plot.

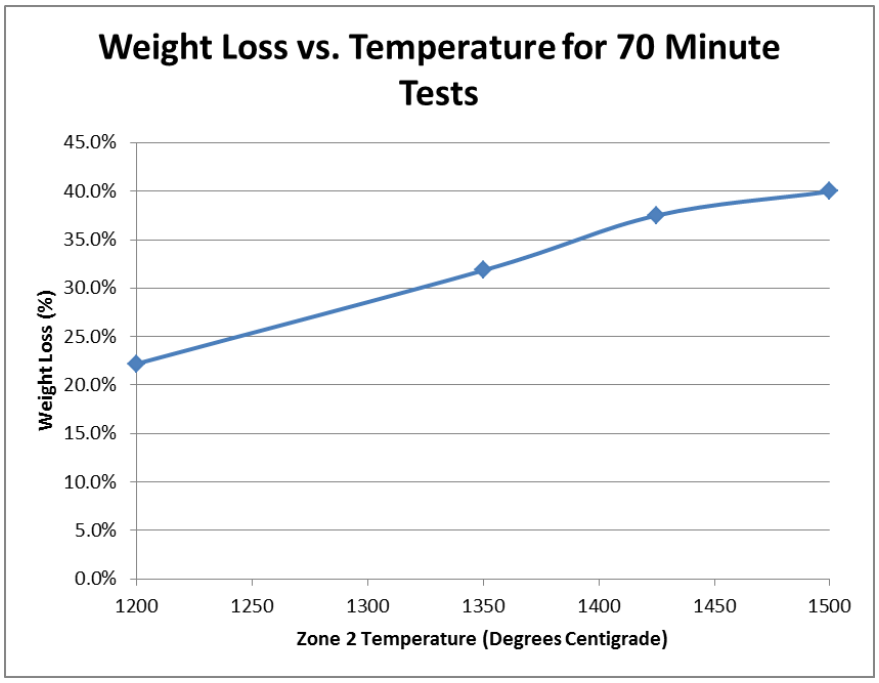


Figure 45: Phase I Weight Loss vs. Temperature

Time vs. Temperature Metallization Relationship

To achieve 90% or greater metallization for Layer 5, data show a minimum of 1500°C for 67 minutes is required. Figure 46 displays the time vs. temperature metallization relationship for 90% metallization.

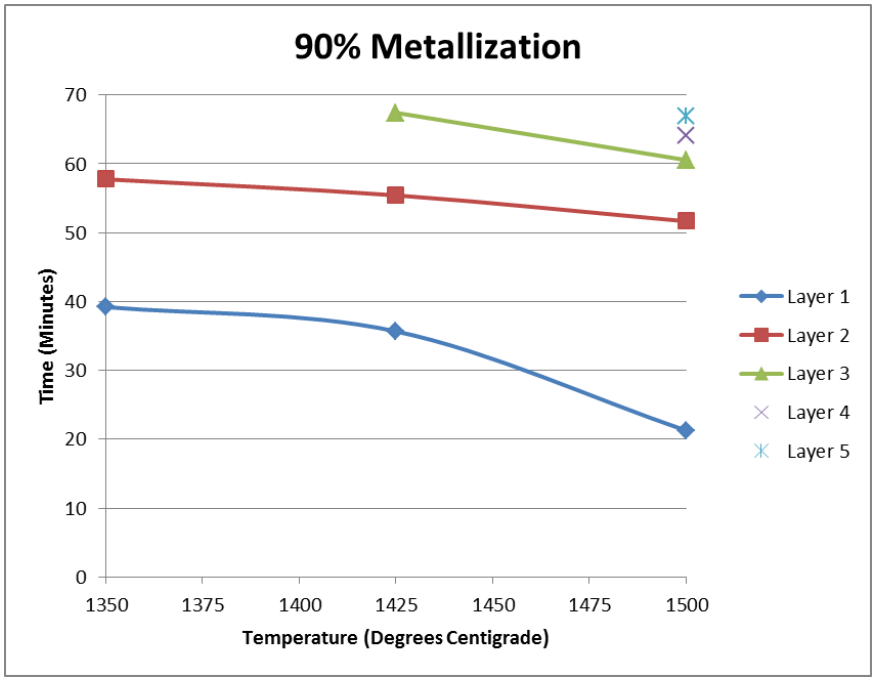


Figure 46: Phase I Time vs. Temperature Relationship for 90% Metallization

To achieve 95% or greater metallization for Layer 5, a minimum of 1500°C for 68 minutes is required. Figure 47 displays the time vs. temperature metallization relationship for 95% metallization. Note that Layer 1 approached, but never achieved, 95% metallization throughout Phase I. At 1425°C and 1500°C the highest metallization for Layer 1 was 94.7% and 94.6%, respectively.

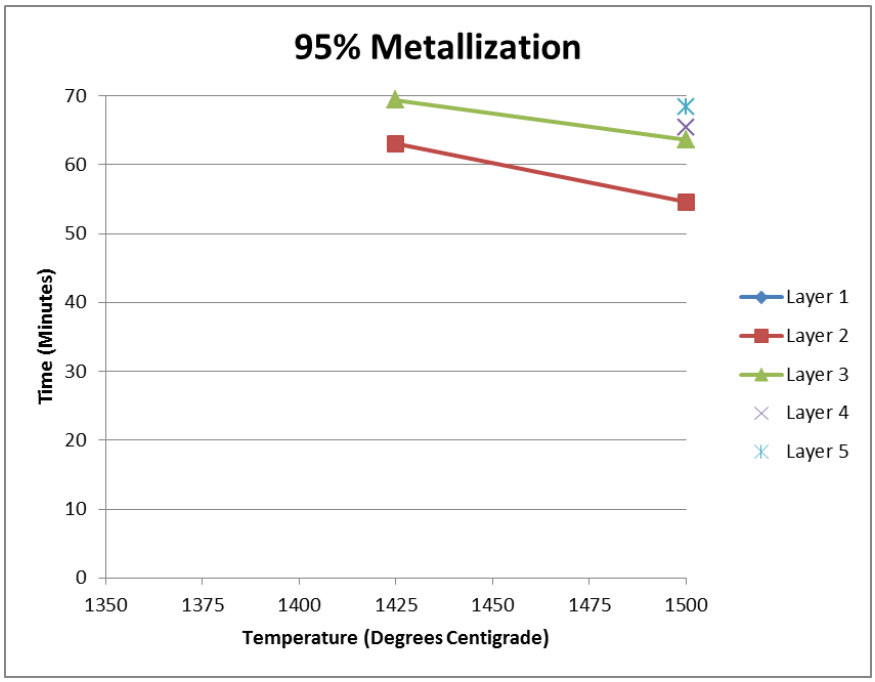


Figure 47: Phase I Time vs. Temperature Relationship for 95% Metallization

Hearth Productivity

Table 19, Figure 48, and Figure 49 below display the hearth productivity data from Phase I testing. From investigation of Figure 48 and Figure 49 it is evident that the production of metallic iron increases with temperature but not necessarily with time. Figure 48 shows that hearth productivity decreases from the ten minute mark until approximately the 30-40 minute mark, and then increases up until the 60-65 minute mark.

Table 19: Phase I Hearth Productivity Data

Zone 2 Temp (deg C)	Zone 2 Time (min)	Total Metallic Iron Produced (g)	Hearth Productivity (g/cm2-min)	Hearth Productivity (kg/m2-min)
1200	0	22.88	N/A	N/A
1200	65	203.47	0.04	0.39
1350	10	N/A	N/A	N/A
1350	20	119.50	0.07	0.74
1350	30	155.34	0.06	0.64
1350	40	196.83	0.06	0.61
1350	50	273.15	0.07	0.67
1350	60	424.32	0.09	0.87
1350	65	466.70	0.09	0.89
1425	10	104.13	0.13	1.28
1425	20	189.95	0.12	1.17
1425	30	200.97	0.08	0.83
1425	40	267.05	0.08	0.82
1425	50	361.31	0.09	0.89
1425	60	443.22	0.09	0.91
1425	65	513.92	0.10	0.98
1500	10	107.68	0.13	1.33
1500	20	177.59	0.11	1.10
1500	30	234.22	0.10	0.96
1500	40	333.24	0.10	1.03
1500	50	434.82	0.11	1.07
1500	60	532.72	0.11	1.10
1500	65	558.85	0.11	1.06

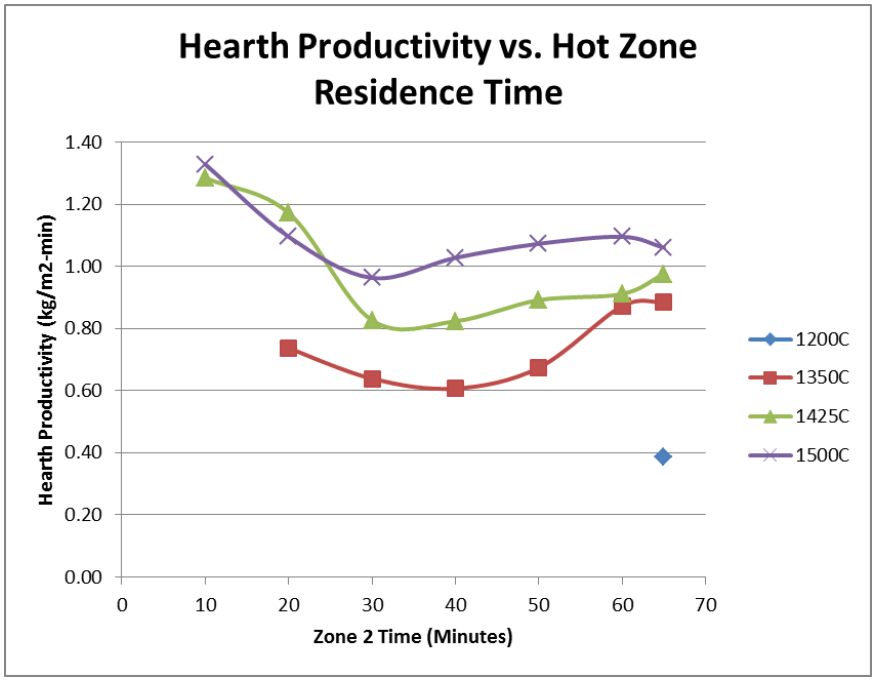


Figure 48: Phase I Hearth Productivity vs. Hot Zone Residence Time

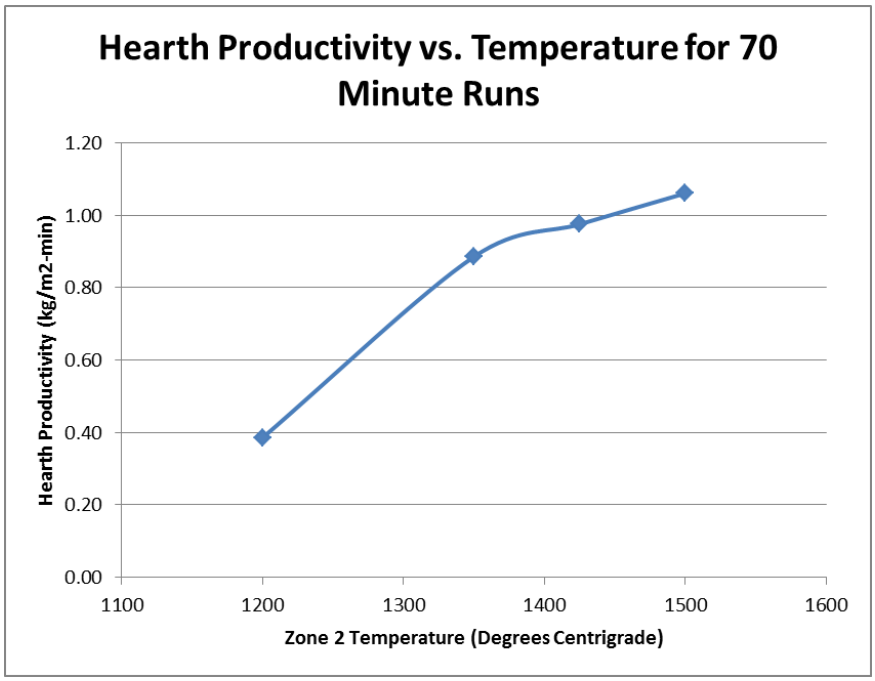


Figure 49: Phase I Hearth Productivity vs. Temperature for 70 Minute Runs

Metallization and Hearth Productivity

From Figure 46 and Figure 47 it was found that to reduce all five layers it would require approximately 65 minutes at 1500 degrees centigrade. When comparing this information to Figure 48, this shows that the hearth productivity would be approximately 1.06 kg/m^2-minute.

Phase II Green Ball Components and Chemistry

The green balls for the Phase II testing were made with the same components and ratios as in Phase I, however, the starch binder was not used. In place of starch, a bentonite binder was used at a 1.3% addition rate.

Phase II Testing Procedure

The testing procedure for the second phase of testing was similar to the first with the exception of an additional fire brick below the sample tray. This fire brick was utilized to create a more representative hot refractory bed of a moving car in a continuous production system.

Two different types of bricks were used; Runs 1-8 used a light firebrick and Runs 9-12 used a dense refractory brick. Each brick was notched on the bottom corners to allow movement of the trays and bricks through the furnace. Figure 50 and Figure 51 display an example fire brick with notches cut into the block. A "fork" was fabricated to aid the movement of sample trays through the furnace (see Figure 52 and Figure 53).

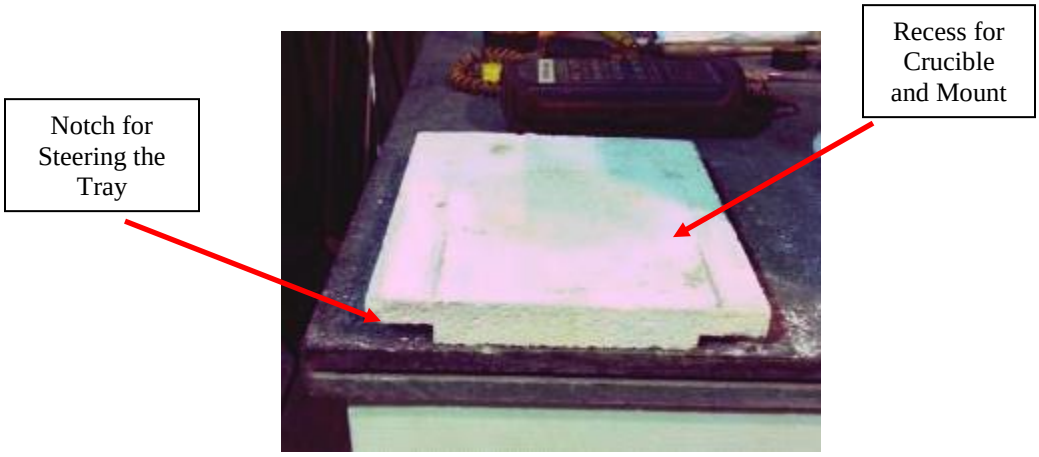


Figure 50: Phase II Firebrick tray for under crucible and mount

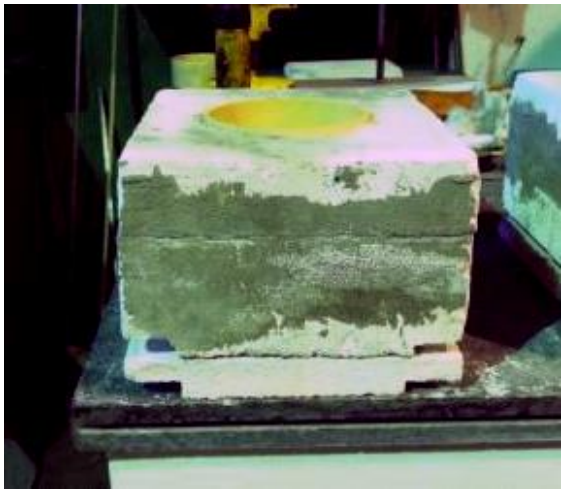


Figure 51: Phase II Sample Tray on Firebrick

Figure 52: Fork Tool for Moving Sample Tray

Figure 53: Moving Sample Tray through Furnace

Temperature in the second zone was taken from below the furnace, as in the high temperature tests in the first phase of testing (known as the bottom thermocouple or "Bottom TC"). Gas analysis was conducted through the end of the furnace (see Figure 54). Gas analysis was conducted by use of an online gas analyzer and/or six discreet samples for gas chromatography. Some tests were run twice with the same operating parameters to allow for different gas analyses. Figure 54, below, shows the sampling point locations for both temperature and gas analyses.

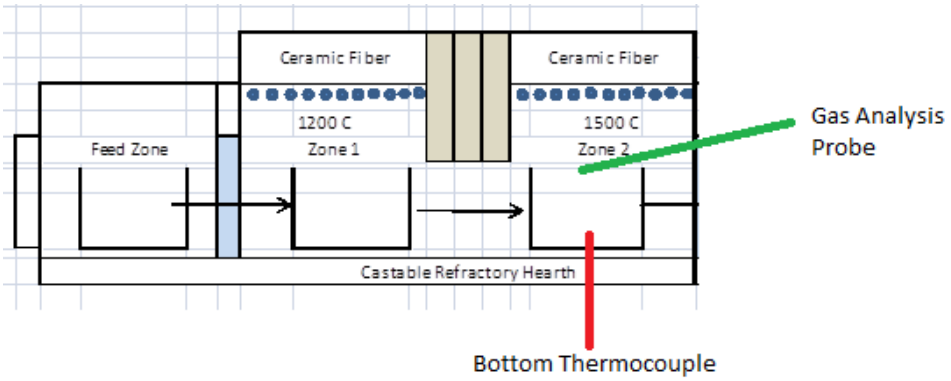


Figure 54: Phase II Temperature and Gas Sampling Points

Phase II Testing Program Results

The second testing phase consisted of 12 tests. The first eight tests in this series utilized a light firebrick below the sample tray; the next four utilized a dense refractory brick. The tests for Phase II are found below:

- Two runs of 1200°C for 5 minutes, 1425°C for 65 minutes (light firebrick)
- Two runs of 1200°C for 5 minutes, 1450°C for 65 minutes (light firebrick)
- Two runs of 1200°C for 5 minutes, 1475°C for 65 minutes (light firebrick)
- Two runs of 1200°C for 5 minutes, 1500°C for 65 minutes (light firebrick)

- Two runs of 1200°C for 5 minutes, 1450°C for 65 minutes (dense refractory brick)
- One run of 1200°C for 5 minutes, 1475°C for 65 minutes (dense refractory brick)
- One run of 1200°C for 5 minutes, 1500°C for 65 minutes (dense refractory brick)

Light Firebrick: Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1425°C) Test Results

Sample Temperature Profile

Figure 55 displays the average temperature of the bottom thermocouple in Zone 2 for Run 1 and 2. Each run was similar in that they started at approximately 1150°C and leveled off at approximately 975°C.

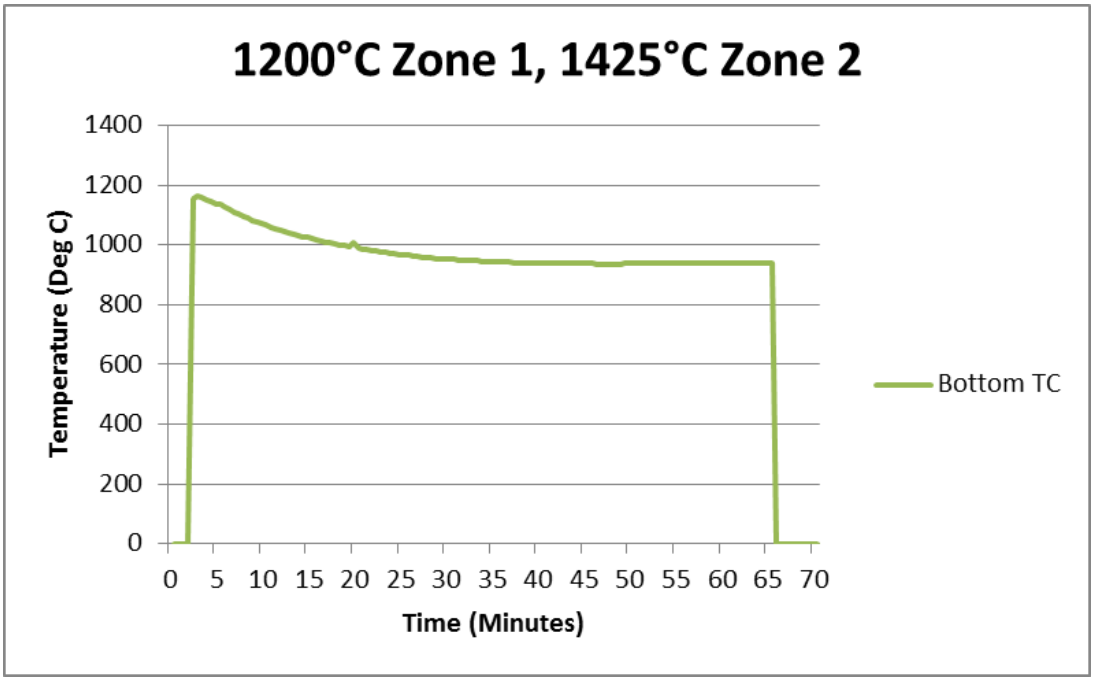


Figure 55: Phase II 1425°C Temperature Profile

Off-Gas Analysis

Off-gas analysis for this sample was conducted by gas chromatography. Table 20 displays the gas analysis for the second test. Carbon dioxide held fairly constant in the middle to high 40% range at the beginning and then decreased near the end of the test. Hydrogen, on the other hand, started at 22% and decreased to below 3% by the completion of the test.

Table 20: Phase II 1425°C Gas Composition Run 2

Sample #	Zone	Sampling Start Time, min.	Permanent Gases, %			
			N2	CO2	CO	H2
1	2	1	19.6%	10.0%	48.1%	22.3%
2	2	5	22.7%	10.0%	47.6%	19.7%
3	2	10	27.0%	9.6%	45.7%	17.6%
4	2	20	41.8%	8.6%	34.1%	15.6%
5	2	30	43.1%	11.6%	36.2%	9.1%
6	2	59	28.8%	12.7%	56.4%	2.1%

Chemical Analysis

Table 21 shows the metallization was greater than 80% for the top three layers for each run. Layers 4 and 5 dropped to below 72% and 60% for the first and second run, respectively.

Table 21: Phase II 1200°C/1425°C Chemical Analysis

Run Data			Chemistry Data, Wt. %						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1425	65	1	0.04	0.20	85.94	75.33	7.32	3.29	87.7
		2	0.05	0.20	86.44	79.46	8.99	-2.01	91.9
		3	2.22	0.27	82.49	73.32	10.27	-1.10	88.9
		4	4.90	0.22	76.65	54.93	17.22	4.50	71.7
		5	6.99	0.20	69.13	30.63	31.33	7.17	44.3
	65	1	0.01	0.21	86.56	77.87	10.62	-1.93	90.0
		2	0.28	0.21	86.49	79.52	8.71	-1.74	91.9
		3	0.77	0.23	85.93	79.07	7.51	-0.65	92.0
		4	6.28	0.21	73.61	43.71	26.90	3.00	59.4
		5	6.77	0.19	70.50	35.60	32.00	2.90	50.5

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 22 displays the shrinkage and weight loss data for both Run 1 and 2.

Table 22: Phase II 1200°C/1425°C Shrinkage and Weight Loss Data

Run Data		Shrinkage and Weight Data			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction (%)
1425	65	1	26.1	31.7	36.9
		2	28.3		
		3	13.8		
		4	2.4		
		5	1.9		
	65	1	32.9	31.7	34.0
		2	29.6		
		3	16.7		
		4	3.0		
		5	1.3		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 6, pages 118 and 119.

Light Firebrick: Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1450°C) Test Results

Sample Temperature Profile

Figure 56 displays the temperature of the bottom thermocouple in Zone 2 for Run 2. Starting temperature was slightly below 1200°C and decreased until ultimately finishing at approximately 950°C.

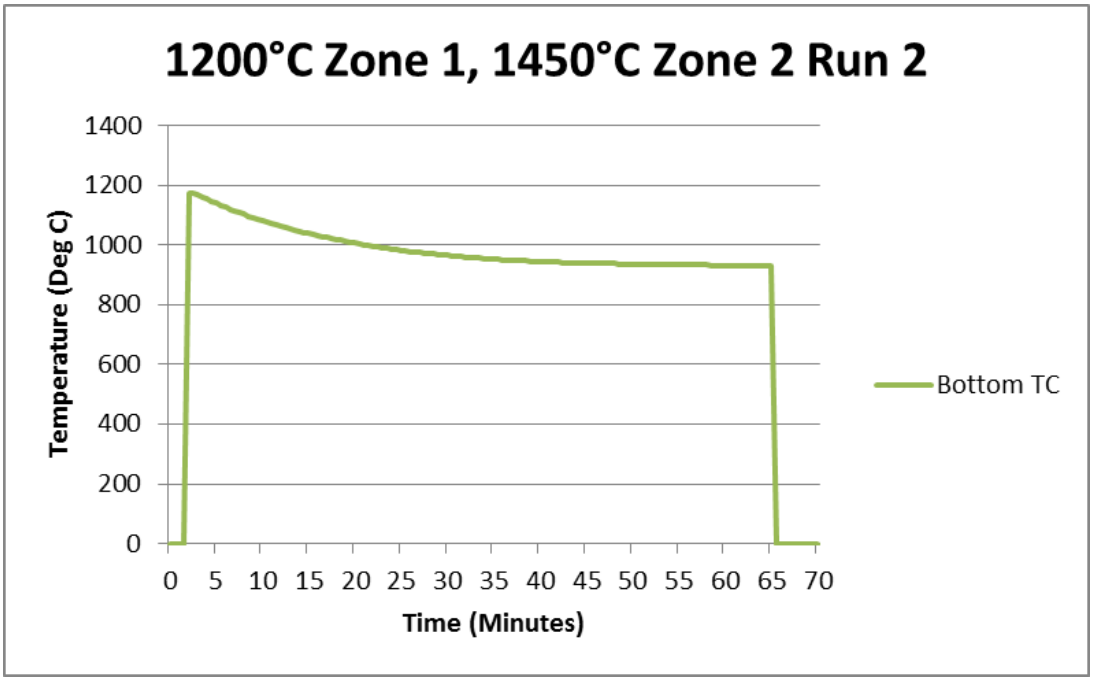


Figure 56: Phase II 1450°C Temperature Profile Run 2

Off-Gas Analysis

Off-gas analysis for carbon monoxide, carbon dioxide, and oxygen was conducted with a UEI AGA5000. Figure 57 displays the gas analysis for Run 1. Carbon monoxide was in the 25-30% range throughout most of the run, while carbon dioxide was approximately 15%. Oxygen was negligible throughout the run.

Hydrogen and nitrogen were analyzed via gas chromatography. Table 23 displays the gas analysis for Run 2. Hydrogen started at approximately 28% and decreased to nearly zero percent by the conclusion of the test.

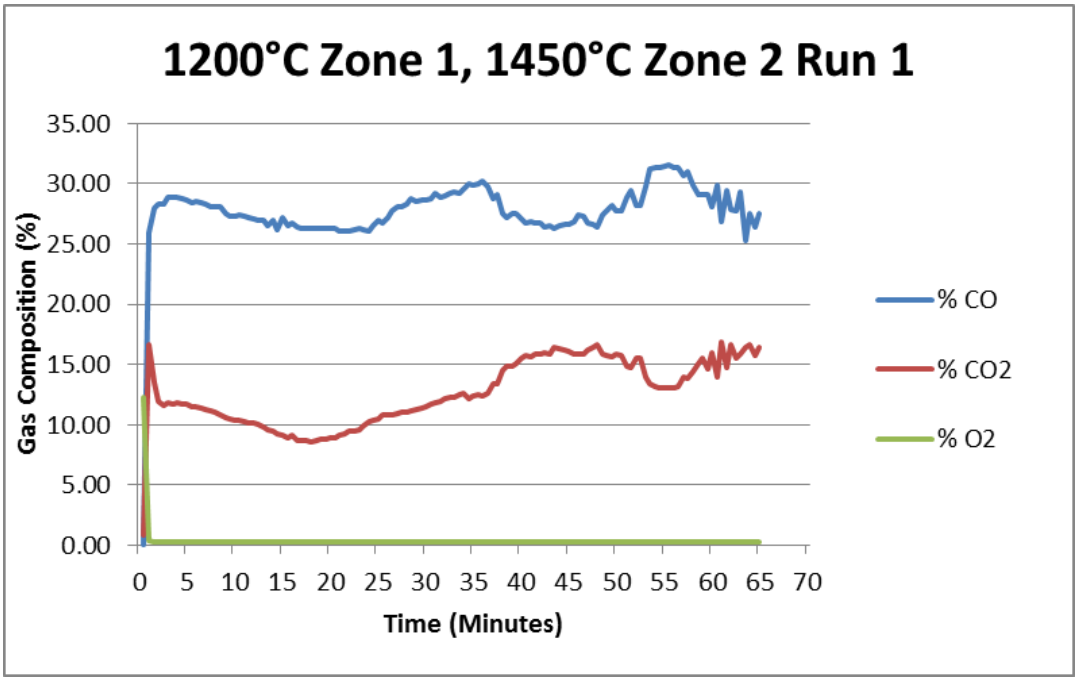


Figure 57: Phase II 1450°C Gas Composition Run 1

Table 23: Phase II 1450°C Gas Composition Run 2

Sample #	Zone	Sampling Start Time, min.	Permanent Gases, %	
			N2	H2
1	2	1	14.6%	27.7%
2	2	5	16.7%	25.5%
3	2	10	22.2%	22.5%
4	2	20	43.8%	13.8%
5	2	30	40.3%	7.7%
6	2	59	56.1%	0.5%

Chemical Analysis

The first run resulted in over 90% metallization in the upper three layers; run two the upper three layers only had 85% metallization. For each run, the bottom two layers were under 70% metallized.

Table 24: Phase II 1200°C/1450°C Chemical Analysis

Run Data			Chemistry Data, Wt. %						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1450	65	1	0.05	0.19	86.79	79.50	7.29	0.00	91.6
		2	0.04	0.21	87.06	80.84	6.81	-0.59	92.9
		3	0.41	0.24	87.24	82.80	3.81	0.63	94.9
		4	6.06	0.23	74.54	48.71	26.91	-1.08	65.3
		5	8.35	0.20	68.42	27.24	34.84	6.34	39.8
	65	1	0.02	0.19	86.66	75.72	9.87	1.07	87.4
		2	0.04	0.21	86.54	78.23	9.29	-0.98	90.4
		3	2.78	0.25	82.09	69.74	10.17	2.18	85.0
		4	6.52	0.19	72.36	41.14	23.82	7.40	56.9
		5	6.75	0.18	69.93	29.52	29.68	10.73	42.2

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Shrinkage and weight loss data can be found in Table 25 below.

Table 25: Phase II 1200°C/1450°C Shrinkage and Weight Loss Data

Run Data		Shrinkage and Weight Data			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage %	Weight Reduction (%)
1450	65	1	33.0	37.0	35.7
		2	29.5		
		3	18.0		
		4	4.2		
		5	3.7		
	65	1	33.1	37.0	35.1
		2	29.6		
		3	14.6		
		4	0.1		
		5	4.2		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 6, pages 120 and 121.

Light Firebrick: Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1475°C) Test Results

Sample Temperature Profile

Figure 58 displays the average temperature of the bottom thermocouple in Zone 2 for Run 1 and 2. Starting temperature was approximately 1200°C and decreased until ultimately finishing at approximately 1000°C.

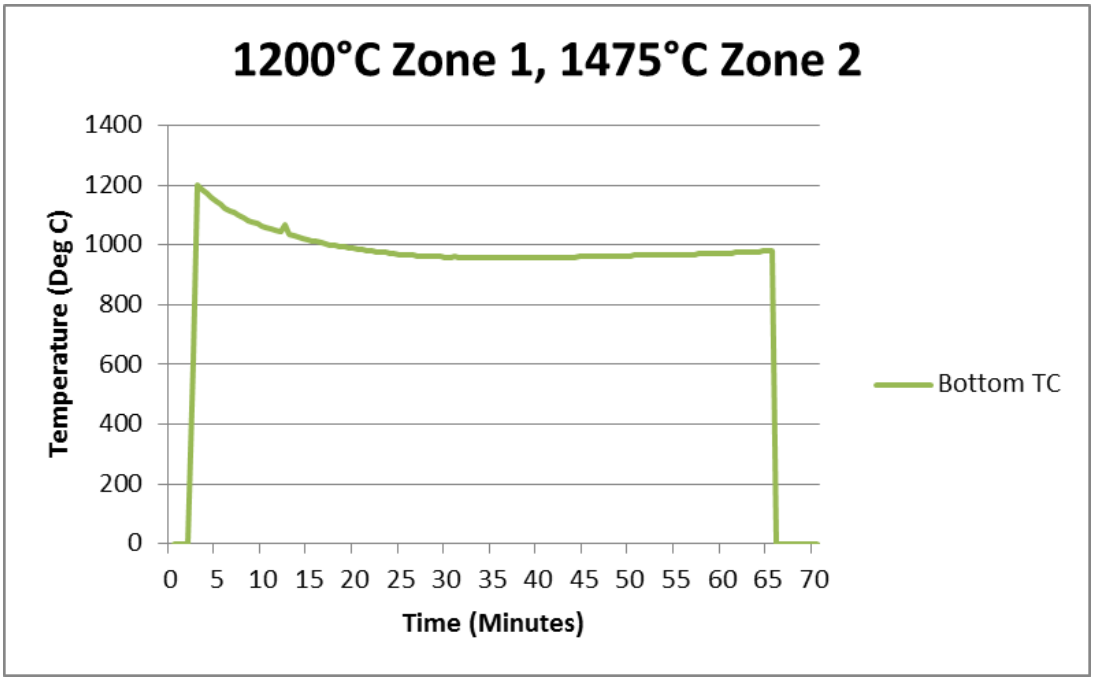


Figure 58: Phase II 1475°C Temperature Profile

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 59 displays the gas analysis for Run 1. Interestingly, the carbon monoxide had two peaks; one at approximately 4 minutes and the other at 36 minutes. The peak for each was approximately 30% and 26%, respectively. Carbon dioxide, in comparison, continued to increase from about 10% to 27% by the completion of the run. The hydrogen component, found via gas chromatography, was found to be approximately 20% at the beginning of the test and declined to under 1% by the conclusion. Table 26 displays the gas chromatography data for Run 2.

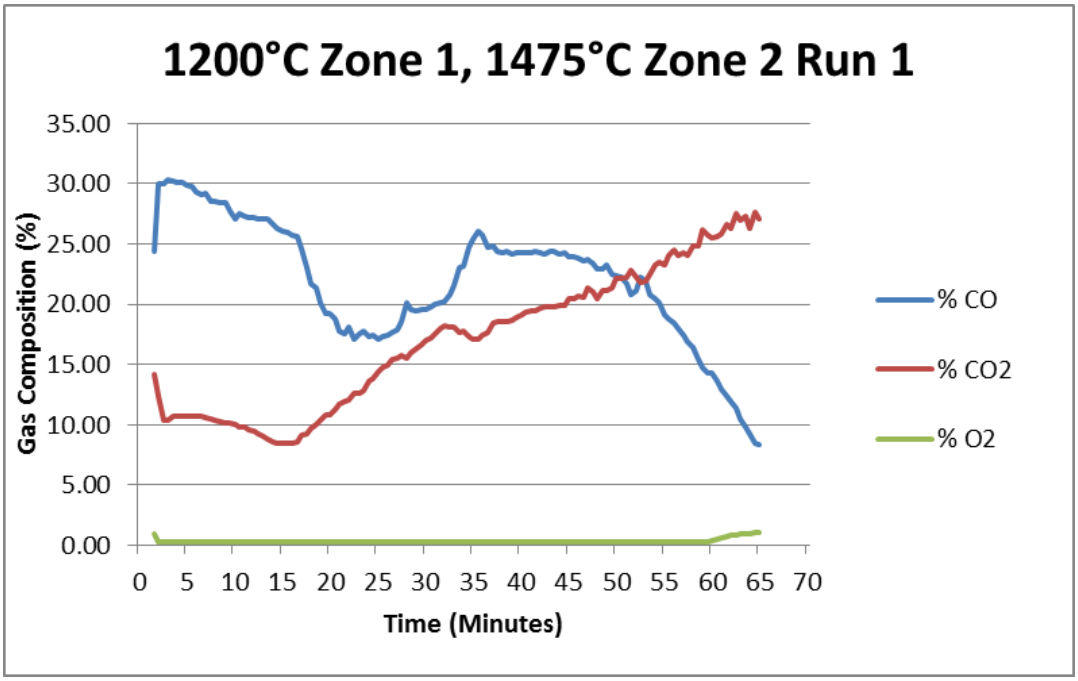


Figure 59: Phase II 1475°C Gas Composition Run 1

Table 26: Phase II 1475°C Gas Composition Run 2

Sample #	Zone	Sampling Start Time, min.	Permanent Gases, %	
			N2	H2
1	2	1	14.2%	19.9%
2	2	5	18.9%	20.9%
3	2	10	29.1%	17.0%
4	2	20	39.6%	16.0%
5	2	30	36.1%	9.2%
6	2	59	29.4%	0.9%

Chemical Analysis

Table 27: Phase II 1200°C/1475°C Chemical Analysis

Run Data			Chemistry Data, Wt. %						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1475	65	1	0.05	0.18	86.42	78.42	9.68	-1.68	90.7
		2	0.02	0.23	85.60	67.17	8.41	10.02	78.5
		3	0.24	0.25	86.51	81.70	7.02	-2.21	94.4
		4	2.56	0.23	81.26	67.76	10.75	2.75	83.4
		5	2.68	0.20	75.55	42.33	22.82	10.40	56.0
	65	1	0.01	0.20	87.43	78.39	7.49	1.55	89.7
		2	0.01	0.21	86.62	80.39	4.50	1.73	92.8
		3	1.12	0.24	85.71	80.17	4.52	1.02	93.5
		4	5.68	0.21	75.89	54.04	9.06	12.79	71.2
		5	7.19	0.18	71.41	37.42	27.53	6.46	52.4

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 28: Phase II 1200°C/1475°C Shrinkage and Weight Loss Data

Run Data		Shrinkage and Weight Data			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction, (%)
1475	65	1	35.7	37.0	37.4
		2	31.2		
		3	22.9		
		4	7.8		
		5	3.2		
	65	1	37.3	26.5	36.8
		2	29.1		
		3	12.0		
		4	-2.1		
		5	0.8		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 6, pages 122 and 123.

Light Firebrick: Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1500°C) Test Results

Sample Temperature Profile

Figure 60 displays the temperature of the bottom thermocouple in Zone 2 for Run 1. Starting temperature was slightly above 1200°C and decreased until ultimately settling at approximately 1000°C, very similar to the 65 Minutes in Zone 2 at 1475°C run.

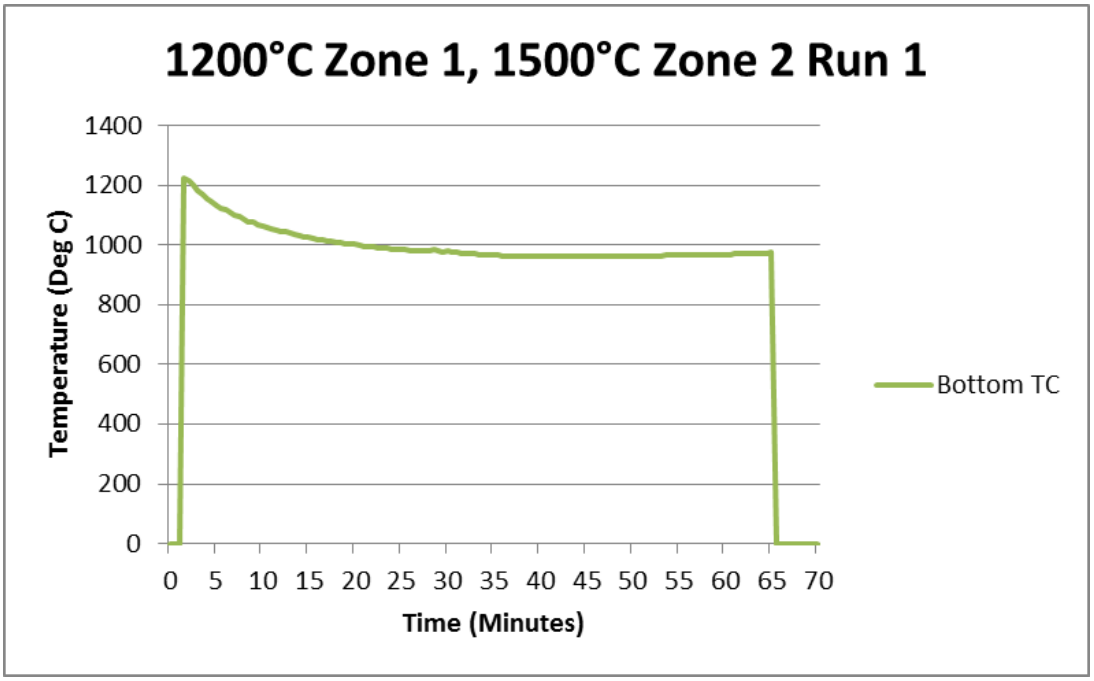


Figure 60: Phase II 1500°C Temperature Profile Run 1

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 61 displays the gas analysis for Run 1. Carbon monoxide stayed fairly constant at 26% until the 55 minute mark, in which it decreased to approximately 24%. Carbon dioxide fluctuated between 7-15%, while oxygen increased from zero to approximately 6% starting at the 26 minute mark. The hydrogen component, found via gas chromatography, was found to be nearly 30% at the beginning of the test and declined to under 1% by the conclusion. Table 29 displays the gas chromatography data for Run 2.

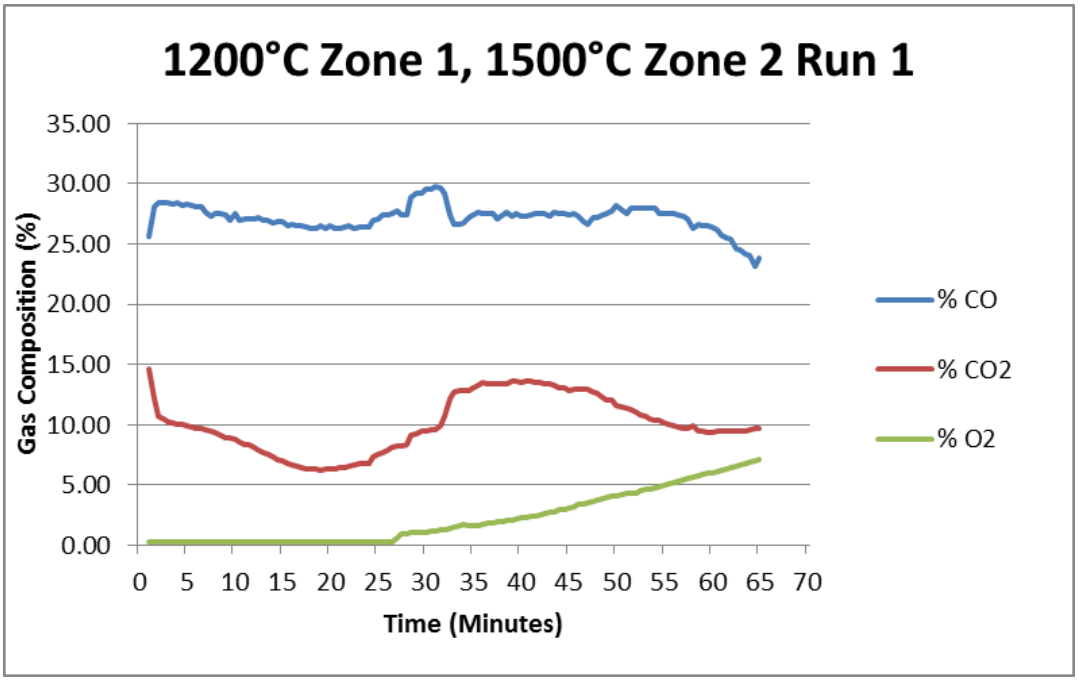


Figure 61: Phase II 1500°C Gas Composition Run 1

Table 29: Phase II 1500°C Gas Composition Run 2

Sample #	Zone	Sampling Start Time, min.	Permanent Gases, %	
			N2	H2
1	2	1	13.2%	28.2%
2	2	5	13.0%	27.5%
3	2	10	17.7%	25.9%
4	2	20	27.1%	19.1%
5	2	30	30.3%	6.8%
6	2	59	44.8%	0.8%

Chemical Analysis

Run 2 shows that the top four layers were over 90% metallized, with the bottom layer being 77.4% metallized. During Run 1 the bottom two layers were lost into the furnace, thus are not reported.

Table 30: Phase II 1200°C/1500°C Chemical Analysis

Run Data			Chemistry Data, Wt. %						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1500	65	1	0.01	0.17	87.61	78.87	6.09	2.65	90.0
		2	0.01	0.19	85.76	75.49	7.26	3.01	88.0
		3	0.01	0.22	85.05	74.72	6.85	3.48	87.9
		4	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		5	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	65	1	0.01	0.20	87.18	79.16	6.46	1.56	90.8
		2	0.02	0.19	86.35	78.40	5.67	2.28	90.8
		3	0.12	0.25	87.48	83.80	2.43	1.25	95.8
		4	1.37	0.23	85.59	80.97	2.92	1.70	94.6
		5	2.98	0.20	79.76	61.73	11.51	6.52	77.4

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 31 displays the shrinkage and weight loss data.

Table 31: Phase II 1200°C/1425°C Shrinkage and Weight Loss Data

Run Data		Shrinkage and Weight Data			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction, (%)
1500	65	1	35.4	N/A	N/A
		2	32.6		
		3	30.6		
		4	N/A		
		5	N/A		
	65	1	35.1	37.0	38.8
		2	32.4		
		3	27.1		
		4	12.1		
		5	7.6		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 6, pages 124 and 125.

Dense Refractory Brick: Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1450°C) Test Results

Sample Temperature Profile

Figure 62 displays the temperature of the bottom thermocouple in Zone 2 for Run 2. Starting temperature was approximately 1150°C and decreased until ultimately finishing at approximately 1050°C.

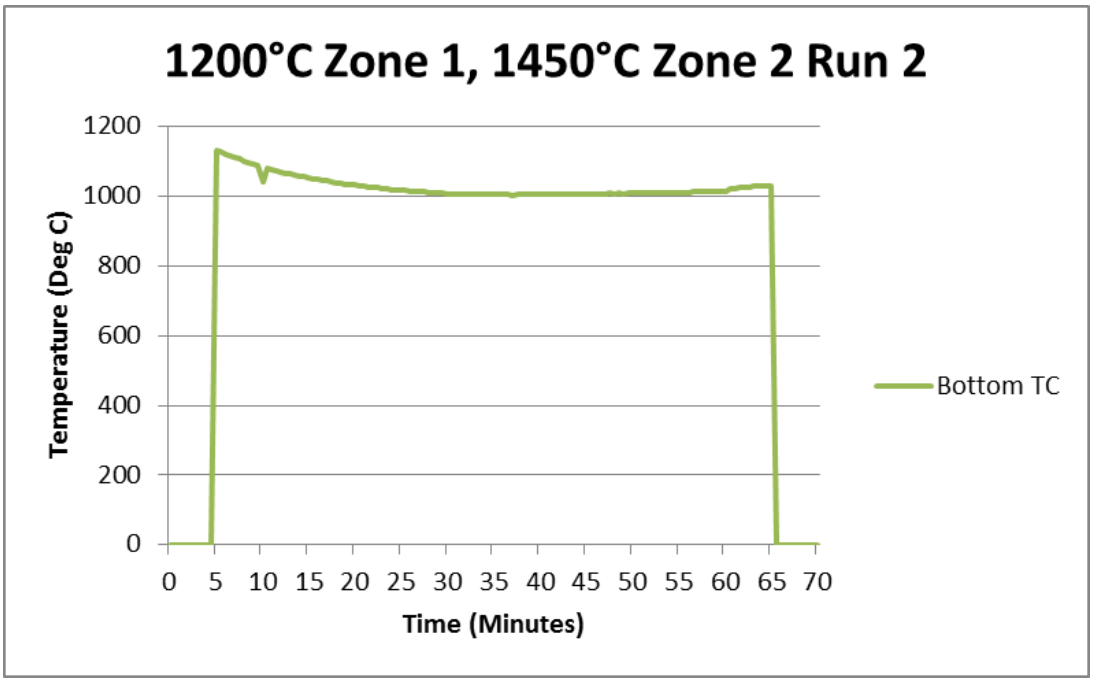


Figure 62: Phase II 1450°C Temperature Profile Run 2

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 63 displays the gas analysis for Run 2. Carbon monoxide increased from a fairly constant 25% to approximately 30% at the 27 minute mark, and ended by decreasing to approximately 26%. Carbon dioxide started at approximately 15% and ended at 17%, with a decrease to 10% at the 19 minute mark. Oxygen held at 1% or below the entire run.

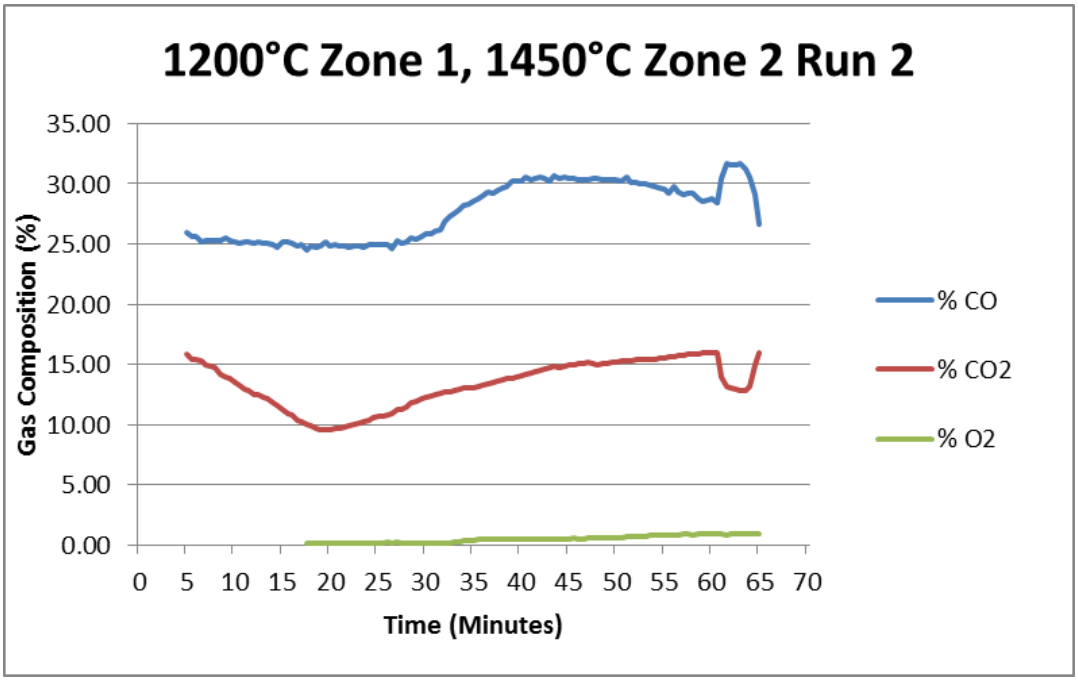


Figure 63: Phase II 1450°C Gas Composition Run 2

Chemical Analysis

Metallization was 80% or above for the top three layers in each run, however Run 1 had lower metallization throughout all of the layers. Run 1 only had one layer above 90% metallized while Run 2 had three.

Table 32: Phase II 1200°C/1450°C Chemical Analysis

Run Data			**Chemistry Data, Wt. %**						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1450	65	1	0.04	0.22	87.24	71.46	13.36	2.42	81.9
		2	0.02	0.27	84.14	71.39	11.11	1.64	84.8
		3	0.24	0.25	86.04	79.91	5.44	0.69	92.9
		4	6.05	0.24	68.96	40.60	26.46	1.90	58.9
		5	6.85	0.21	65.02	33.84	30.26	0.92	52.0
	65	1	0.03	0.20	87.04	80.23	6.25	0.56	92.2
		2	0.03	0.20	86.40	80.51	5.40	0.49	93.2
		3	1.05	0.24	85.22	76.61	5.01	3.60	89.9
		4	5.24	0.23	72.27	48.91	21.45	1.91	67.7
		5	2.51	0.22	77.46	52.63	21.68	3.15	67.9

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 33 displays the shrinkage and weight loss data for this test.

Table 33: Phase II 1200°C/1450°C Shrinkage and Weight Loss Data

Run Data		**Shrinkage and Weight Data**			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction, (%)
1450	65	1	24.7	31.7	34.2
		2	21.5		
		3	15.1		
		4	-1.1		
		5	-5.5		
	65	1	27.9	21.2	36.1
		2	22.4		
		3	5.7		
		4	-0.9		
		5	-7.9		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 7, pages 126 and 127.

Dense Refractory Brick: Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1475°C) Test Results

Sample Temperature Profile

Figure 64 displays the temperature of the bottom thermocouple in Zone 2. It started at approximately 1150°C and ended at approximately 1100°C.

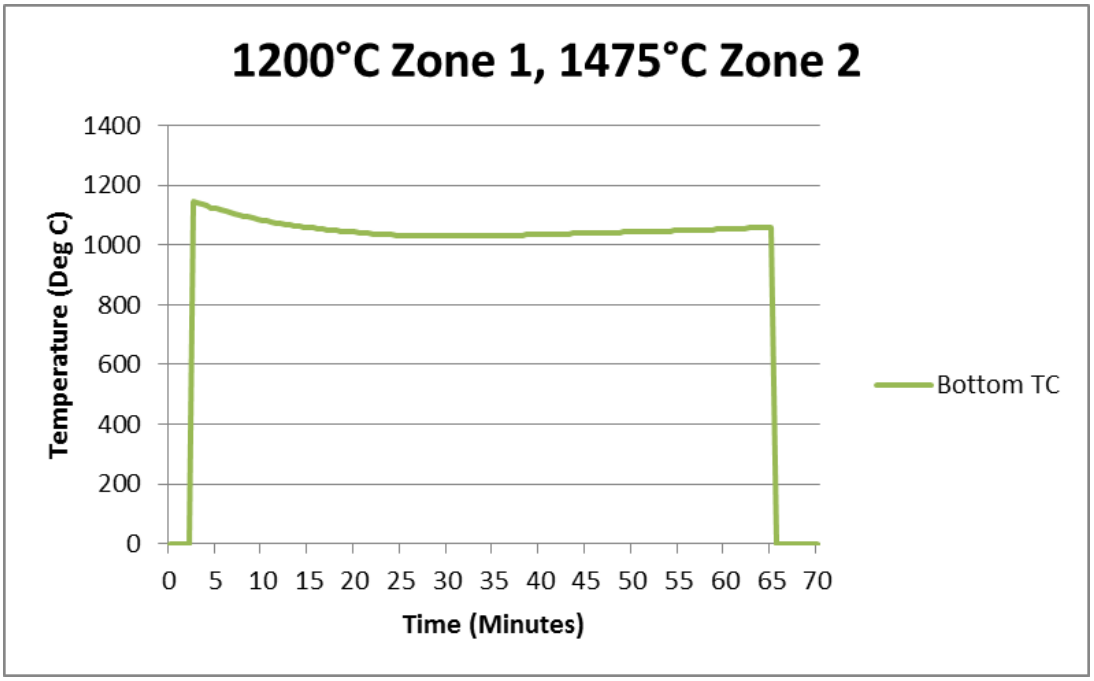


Figure 64: Phase II 1475°C Temperature Profile

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 65 displays the gas analysis during this run. Carbon monoxide started at approximately 30% and decreased to about 4% at the 24 minute mark. It then jumped up to approximately 8% and then ended at 5%. Carbon dioxide decreased to approximately 1% at 23 minutes before increasing to 11% by the end of the run. Oxygen remained high, starting at about 4% and peaking at 18% before dropping to 14% by the end of the run.

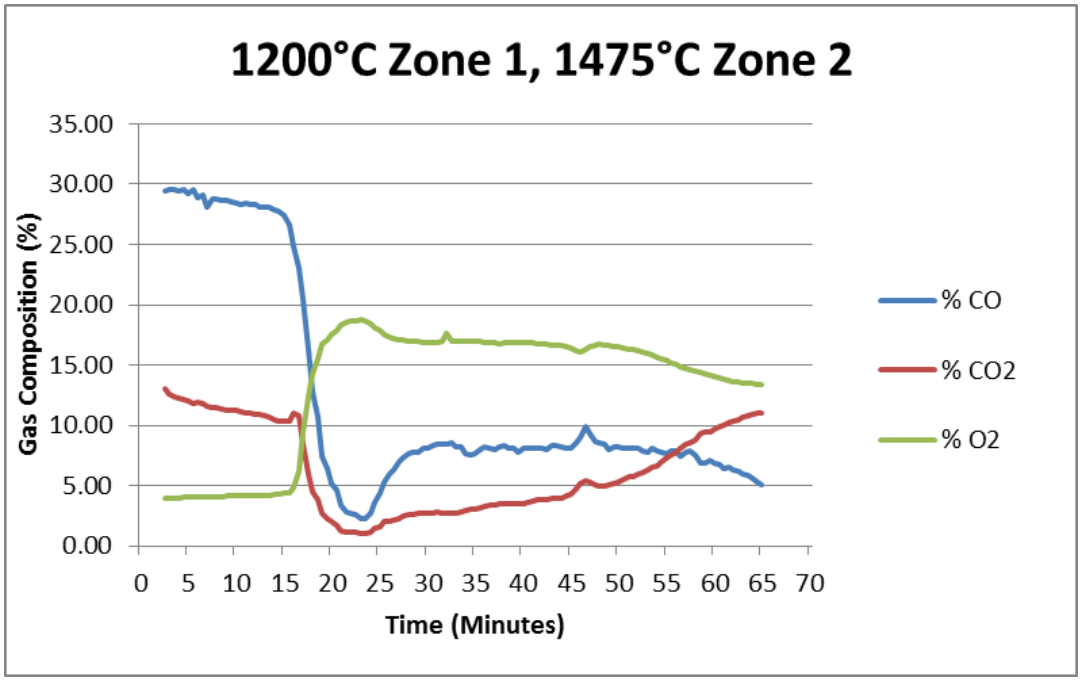


Figure 65: Phase II 1475°C Gas Composition

Chemical Analysis

All five layers were over, or nearly over, 90% metallized.

Table 34: Phase II 1200°C/1475°C Chemical Analysis

Run Data			**Chemistry Data, Wt. %**						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1475	65	1	0.01	0.24	88.37	80.44	7.07	0.86	91.0
		2	0.03	0.23	86.12	80.47	5.09	0.56	93.4
		3	0.03	0.24	86.45	81.73	4.23	0.49	94.5
		4	0.73	0.23	86.40	83.52	2.32	0.56	96.7
		5	1.91	0.23	82.93	74.32	6.53	2.08	89.6

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

The shrinkage and weight loss data can be seen below in Table 35.

Table 35: Phase II 1200°C/1475°C Chemical Analysis

Run Data		**Shrinkage and Weight Data**			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction, (%)
1475	65	1	30.7	37.0	39.4
		2	27.6		
		3	27.0		
		4	13.0		
		5	3.3		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 7, page 128.

Dense Refractory Brick: Five Minutes in Zone 1 (1200°C), 65 Minutes in Zone 2 (1500°C) Test Results

Sample Temperature Profile

Figure 66 displays the temperature of the bottom thermocouple in Zone 2. Temperature started at approximately 1150°C and ended at approximately 1100°C.

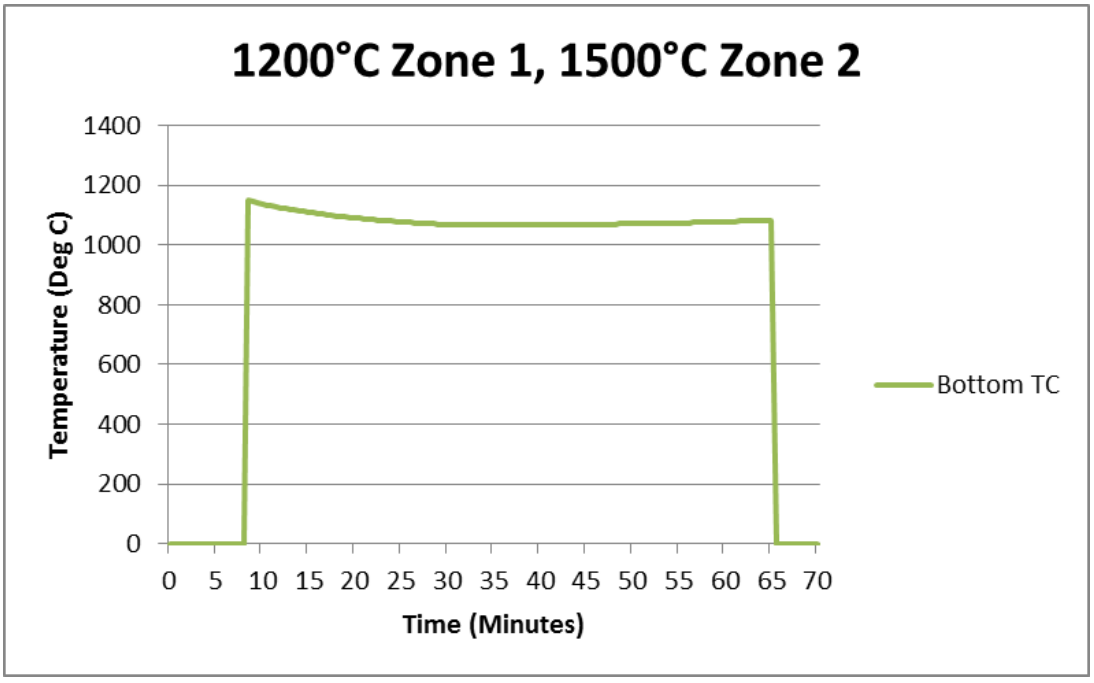


Figure 66: Phase II 1500°C Temperature Profile

Off-Gas Analysis

Off-gas analysis was conducted with a UEI AGA5000. Figure 67 displays the gas analysis during this run. Carbon monoxide started above 25% and ultimate decreased to 17% by the end of the run. There was, however, a peak back up to 25% at the 16 minute mark. Both carbon dioxide and oxygen started between 5-10% and ended up at 9% and 12%, respectively.

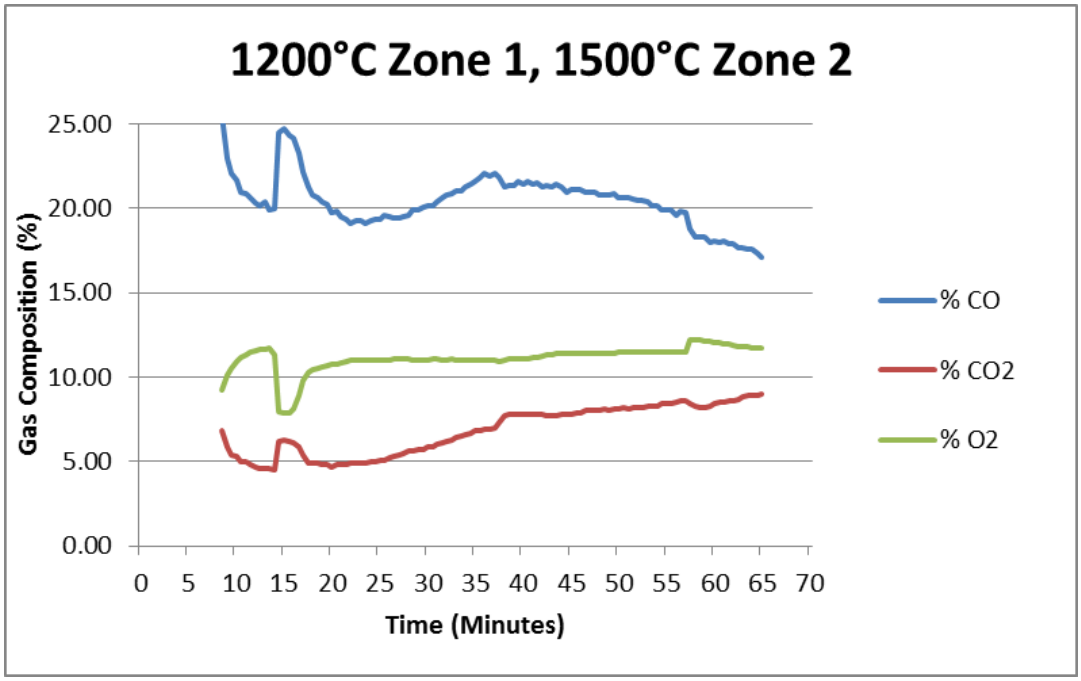


Figure 67: Phase II 1500°C Gas Composition

Chemical Analysis

All layers were above 91% metallized during this run.

Table 36: Phase II 1200°C/1500°C Chemical Analysis

Run Data			Chemistry Data, Wt. %						
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization
1500	65	1	0.02	0.22	88.36	81.16	6.11	1.09	91.9
		2	0.01	0.20	86.82	81.13	5.39	0.30	93.4
		3	0.01	0.21	86.62	79.69	5.97	0.96	92.0
		4	0.48	0.23	87.08	84.75	2.06	0.27	97.3
		5	1.22	0.22	85.32	81.15	2.53	1.64	95.1

Vertical Shrinkage, Average Pellet Shrinkage, and Weight Loss

Table 37 displays the shrinkage and weight loss data for this test.

Table 37: Phase II 1200°C/1500°C Shrinkage and Weight Loss Data

Run Data		Shrinkage and Weight Data			
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	Average Pellet Shrinkage, %	Vertical Shrinkage, %	Weight Reduction (%)
1500	65	1	35.4	37.0	40.1
		2	27.9		
		3	29.1		
		4	12.1		
		5	5.8		

Sample Cup Photographs

The sample cup photographs can be seen in Appendix 7, page 129.

Phase II Testing Data Analysis

Five layers of the sample bed were analyzed for carbon, sulfur, total iron, metallic iron, ferrous iron, and pellet shrinkage upon completion of each test. The assayed data was plotted against temperature and time to determine the effects of changing testing conditions. Layer 5 was used as a proxy for reaction through the deep bed; therefore, that layer is described in depth.

Light Firebrick: Bed Layer Analyses vs. Temperature

Layer 5 metallization was 47% at 1425°C, but the metallization during the 1450°C test dropped to 41%. From 1450°C to 1500°C, metallization increased from 41% to 77.4% at 1500°C. Figure 68 below displays the metallization versus time for the 70 minute run.

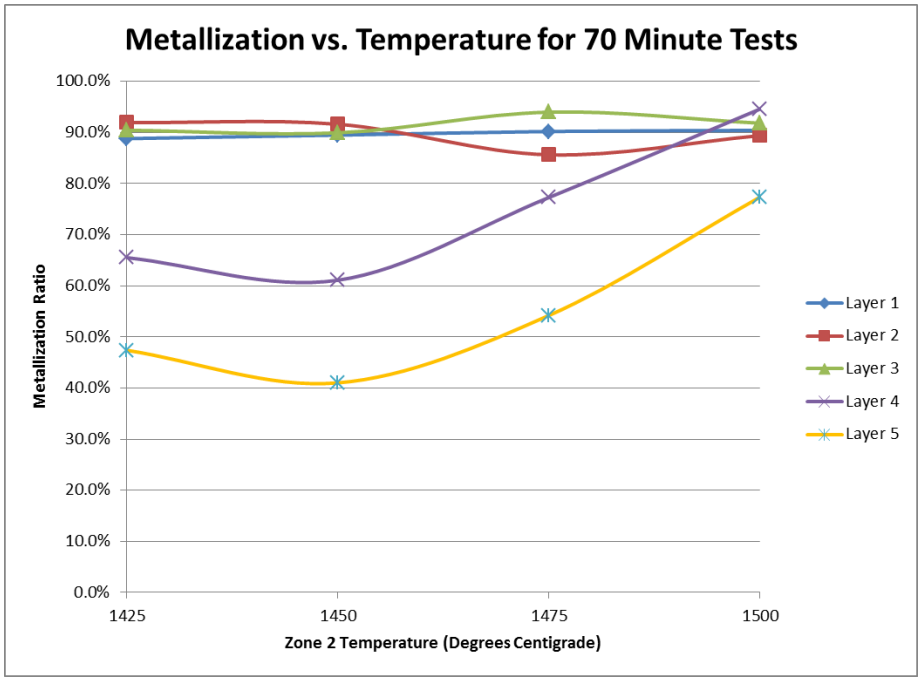


Figure 68: Phase II Metallization vs. Temperature 70 Minute Tests

Layer 5 average pellet shrinkage increased from 1.6% to 4% during the 1425°C to 1450°C temperature range, but then decreased to 2% at 1475°C. From 1475°C to 1500°C, average pellet shrinkage increased again to 7.6%. Figure 69 below displays the average pellet shrinkage versus time for the 70 minute run.

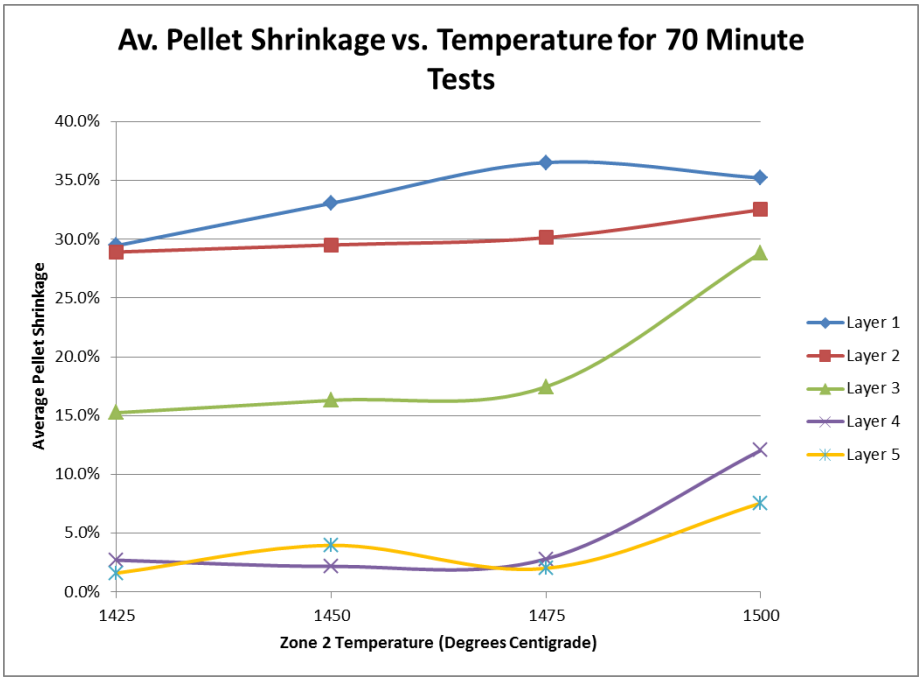


Figure 69: Phase II Average Pellet Shrinkage vs. Temperature 70 Minute Tests

Layer 5 carbon increased from 6.9% to 7.6% during the 1425°C to 1450°C temperature range. Layer 5 carbon content then decreased from 7.6% to 3% from 1450°C to 1500°C. Figure 70 below displays the carbon percentage versus time for the 70 minute run.

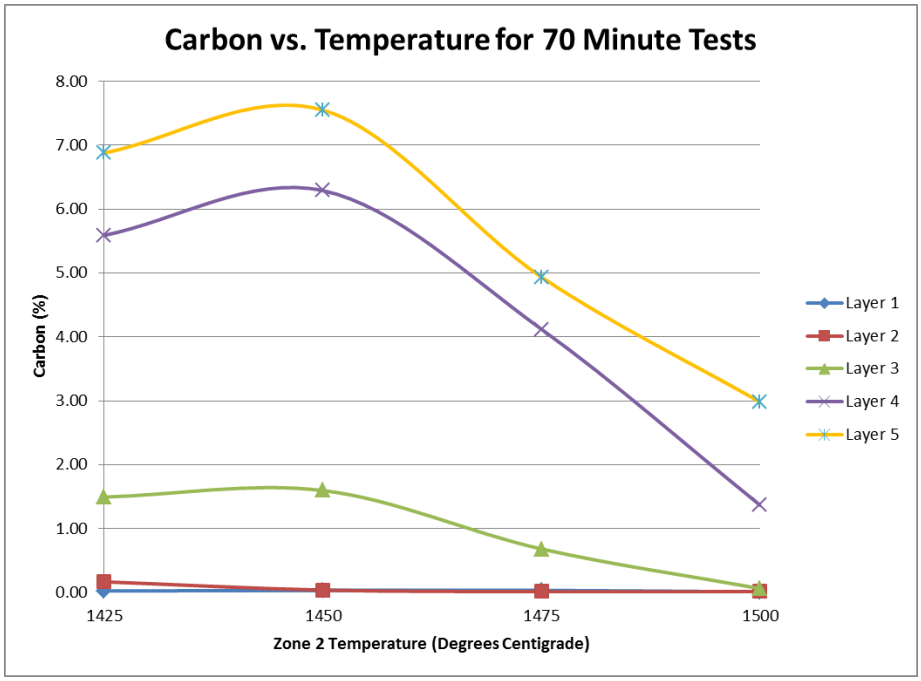


Figure 70: Phase II Carbon vs. Temperature 70 Minute Tests

Layer 5 sulfur remained relatively constant at approximately 0.19% throughout the 1425-1500°C temperature range. Figure 71 below displays the sulfur versus time for the 70 minute run.

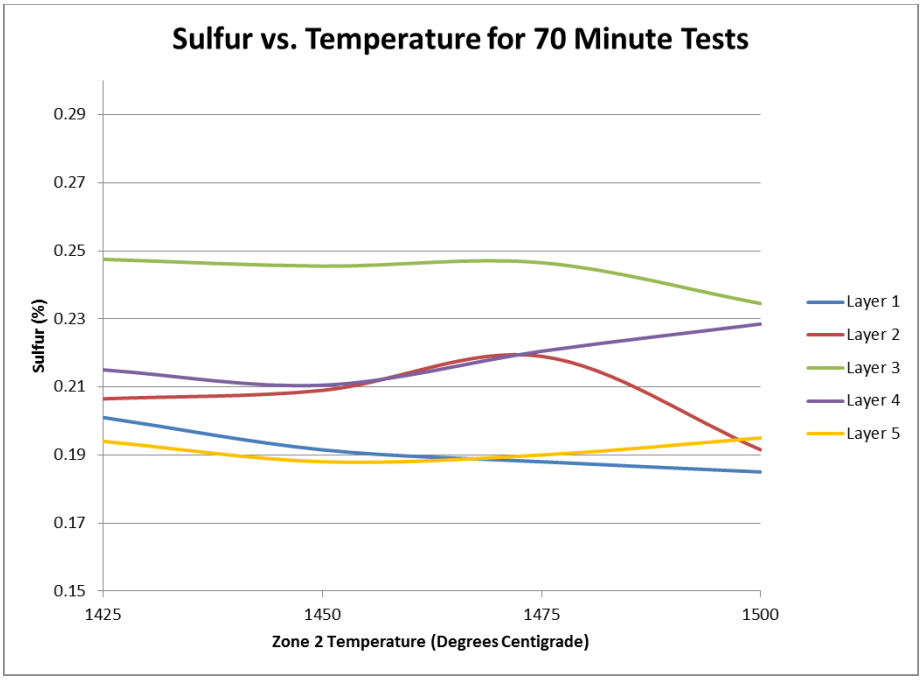


Figure 71: Phase II Sulfur vs. Temperature 70 Minute Tests

Layer 5 ferrous iron remained fairly constant at approximately 32% during the 1425°C to 1450°C temperature range. Layer 5 ferrous iron content then decreased from 32% to 11.5% from 1450°C to 1500°C. Figure 72 below displays the carbon percentage versus time for the 70 minute run.

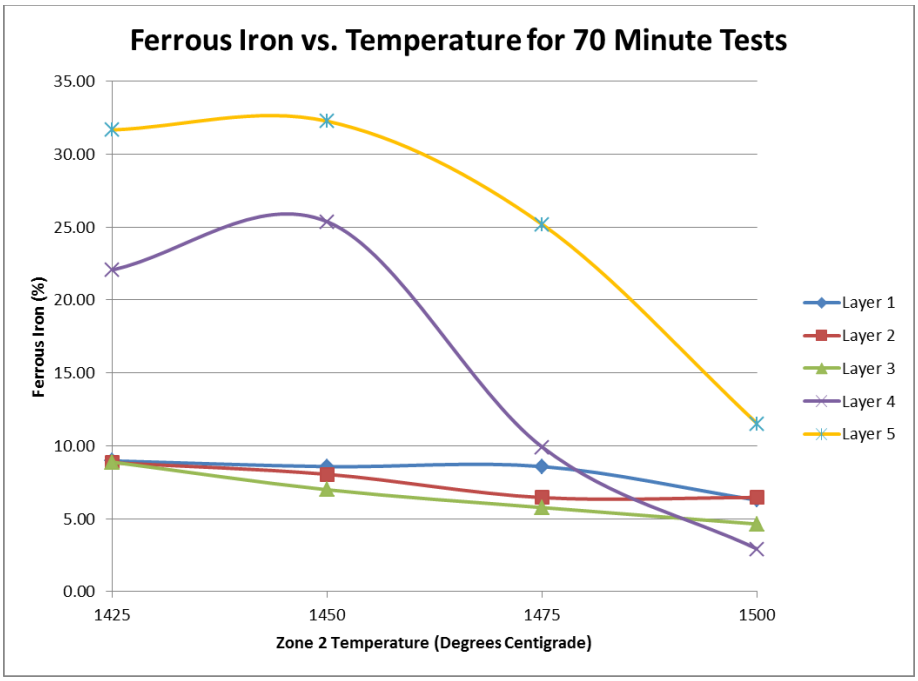


Figure 72: Phase II Ferrous Iron vs. Temperature 70 Minute Tests

Light Firebrick: Vertical Shrinkage vs. Temperature

The vertical shrinkage fluctuated between 32% and 37% between the temperature ranges 1425°C and 1500°C. Figure 73 displays the vertical shrinkage vs. temperature plot for the 70 minute tests.

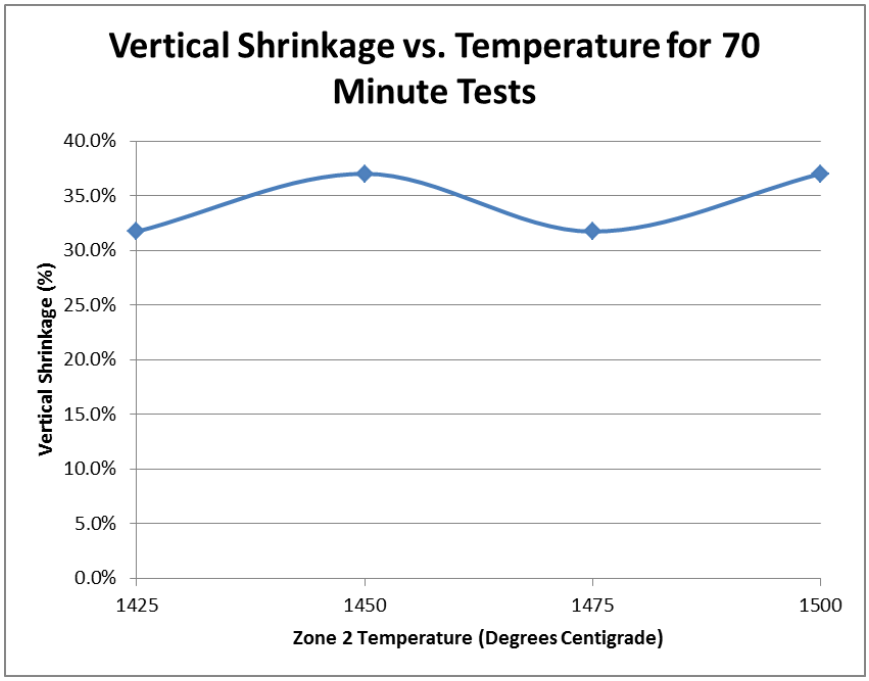


Figure 73: Phase II Vertical Shrinkage vs. Temperature for 70 Minute Tests

Light Firebrick: Weight Loss vs. Temperature

Weight loss over the temperature ranges 1425°C to 1500°C varied slightly, with 1425°C and 1450°C being 35%, 1475°C having a 37% weight loss, and 1500°C having a weight loss of 39%. Figure 74 displays the weight loss vs. temperature plot for the 70 minute tests.

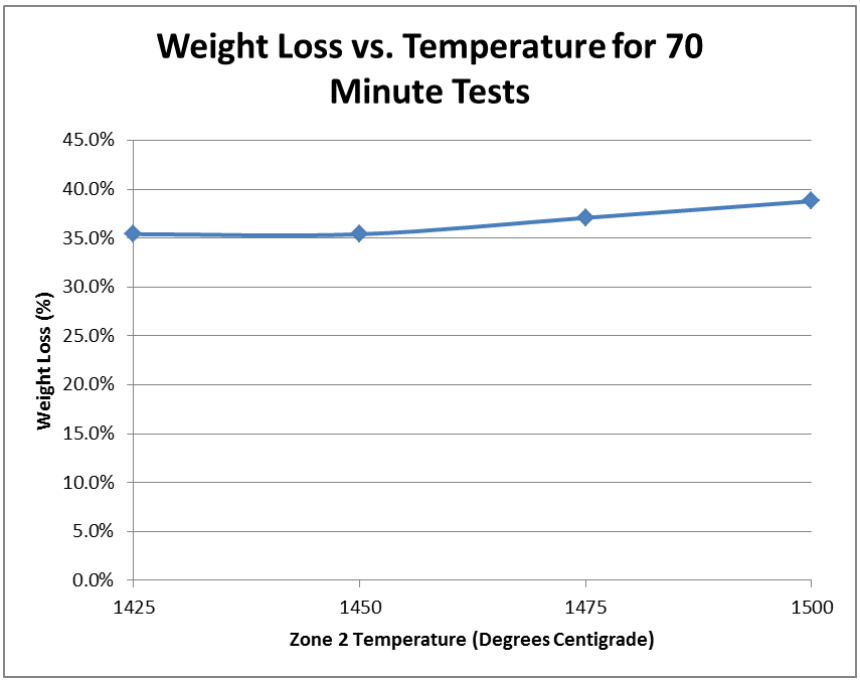


Figure 74: Phase II Weight Loss vs. Temperature for 70 Minute Tests

Dense Refractory Brick: Bed Layer Analyses vs. Temperature

Layer 5 metallization was 60% at 1450°C, nearly 90% at 1475°C, and over 95% at 1500°C. Figure 75 displays the metallization versus time for the 70 minute run.

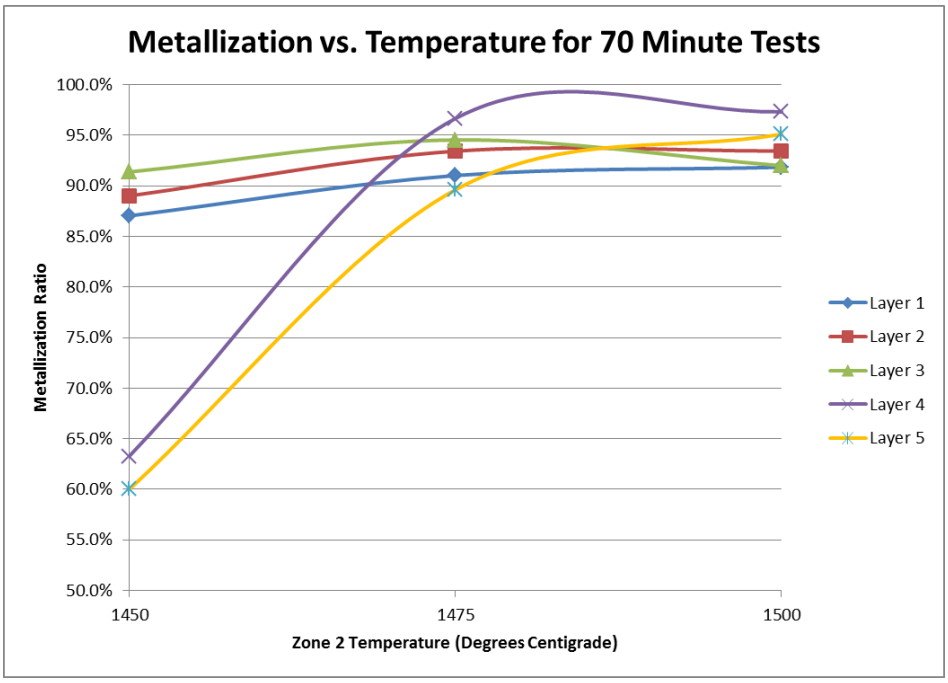


Figure 75: Phase II Metallization vs. Temperature 70 Minute Tests

Average Layer 5 pellets swelled 7% at 1450°C and shrank by 3% and 6% at 1475°C and 1500°C, respectively. Figure 76 below displays the average pellet shrinkage versus time for the 70 minute run.

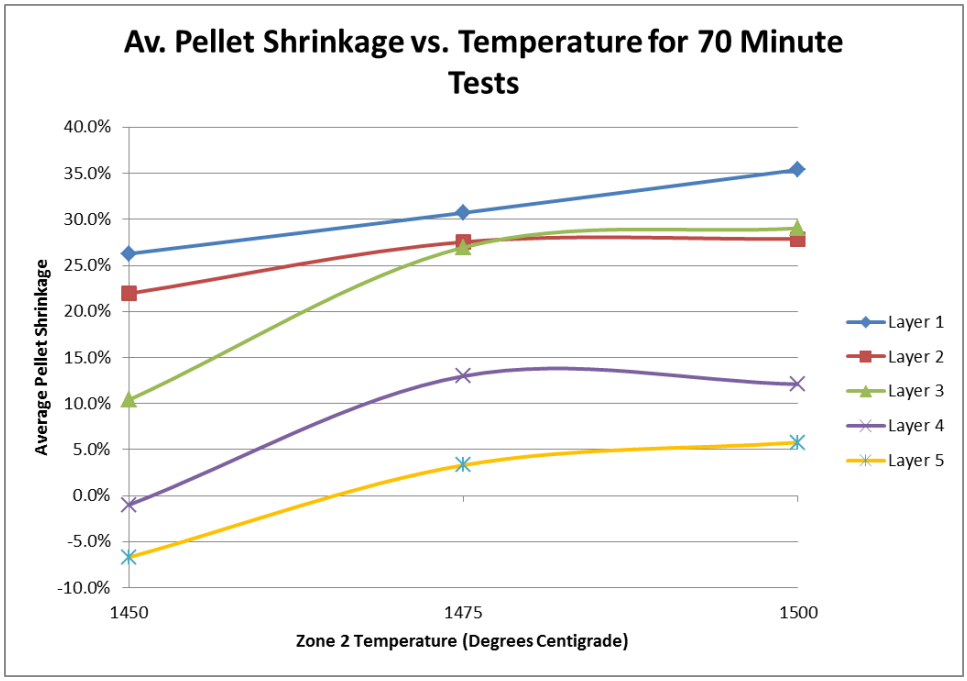


Figure 76: Phase II Average Pellet Shrinkage vs. Temperature 70 Minute Tests

Layer 5 carbon decreased from 5% at 1450°C to 2% and 1% at 1475°C and 1500°C, respectively. Figure 77 below displays the carbon percentage versus time for the 70 minute run.

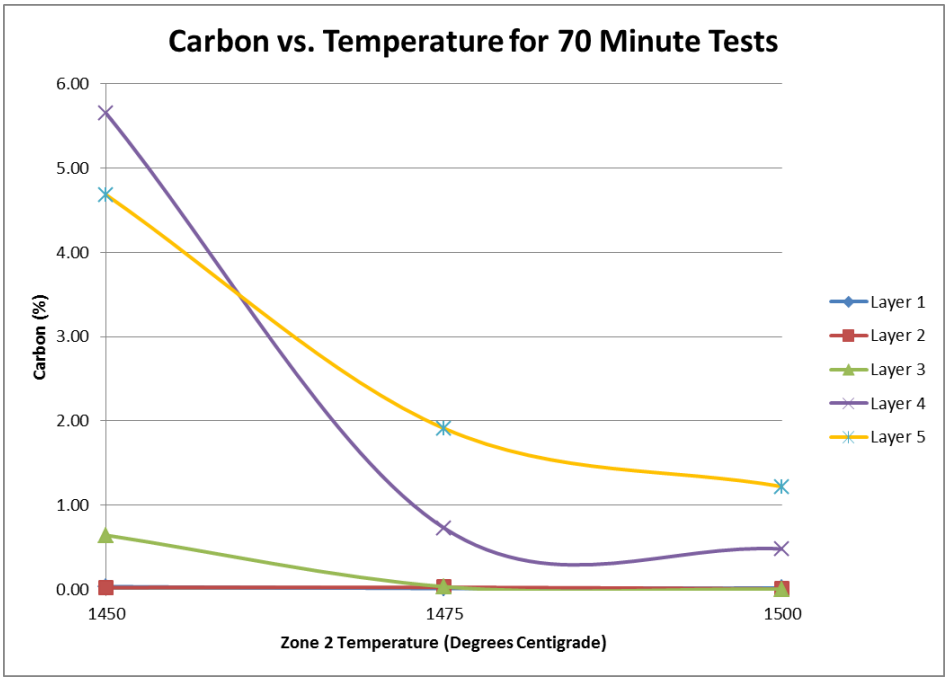


Figure 77: Phase II Carbon vs. Temperature 70 Minute Tests

Layer 5 sulfur varied by +/- 0.01% and averaged 0.22% throughout the 1450-1500°C temperature range. Figure 78 below displays the sulfur versus time for the 70 minute run.

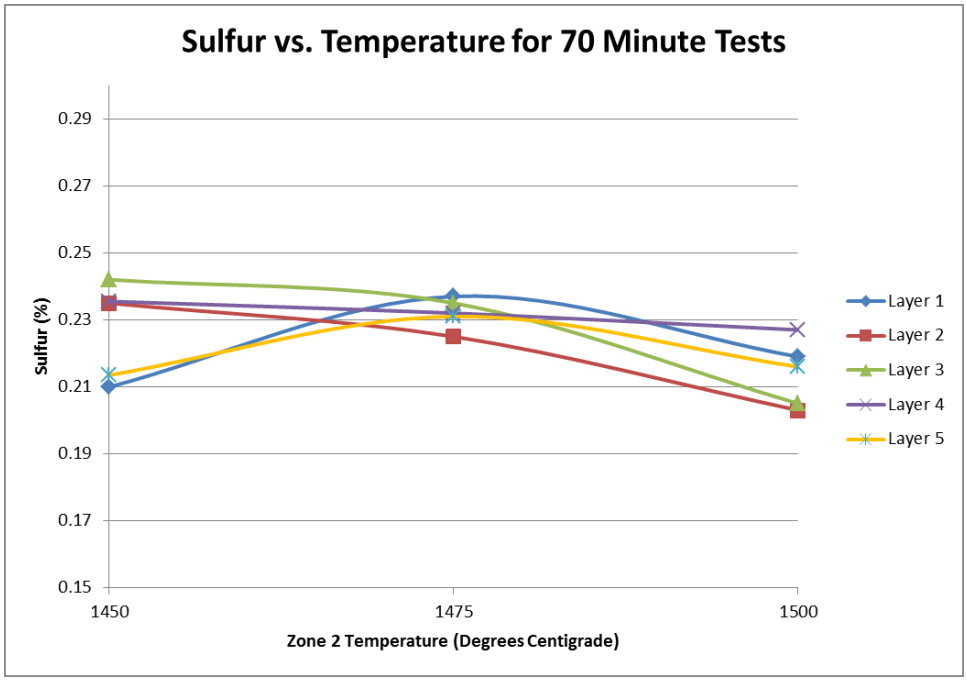


Figure 78: Phase II Sulfur vs. Temperature 70 Minute Tests

Layer 5 ferrous iron was 26% at 1450°C, but dropped to 6.5% and 2.5% at 1475°C and 1500°C, respectively. Figure 79 below displays the ferrous iron percentage versus time for the 70 minute run.

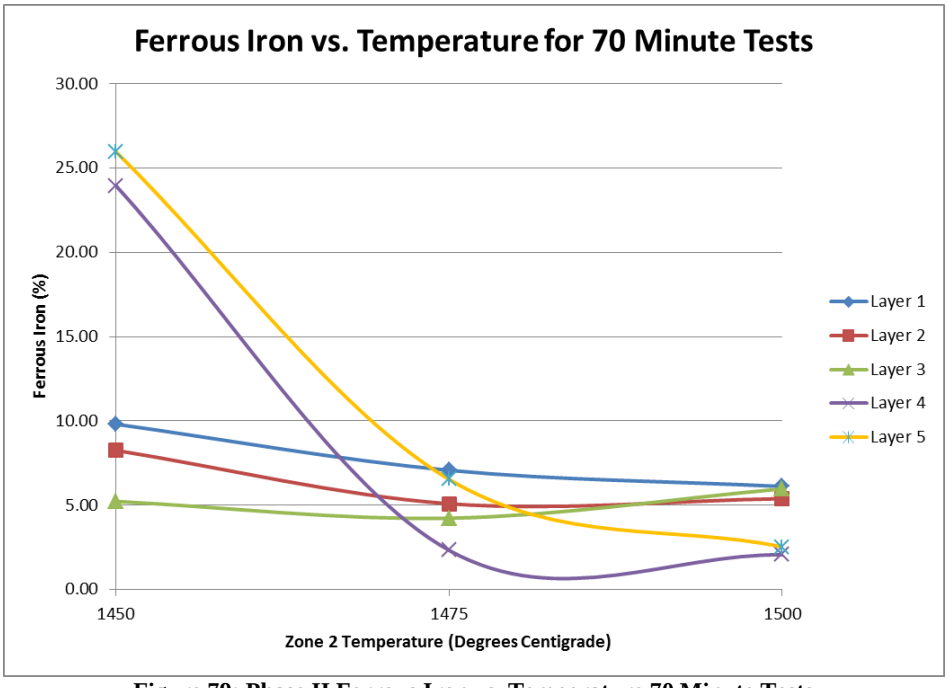


Figure 79: Phase II Ferrous Iron vs. Temperature 70 Minute Tests

Dense Refractory Brick: Vertical Shrinkage vs. Temperature

Vertical shrinkage started at 27% at 1450°C and remained stable at 37% for 1475°C and 1500°C, respectively. Figure 80 displays the vertical shrinkage vs. temperature plot for the 70 minute tests.

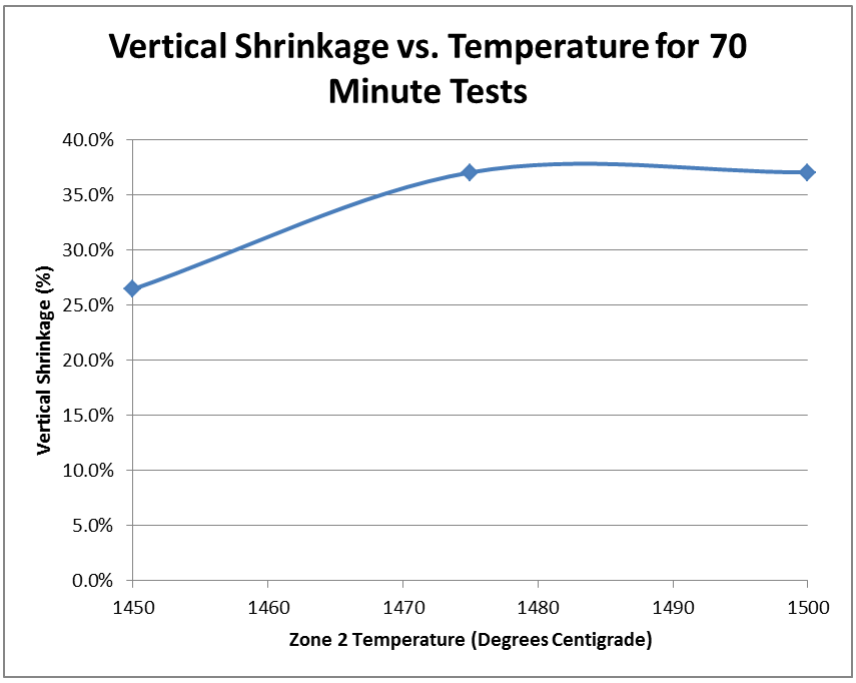


Figure 80: Phase II Vertical Shrinkage vs. Temperature for 70 Minute Tests

Dense Refractory Brick: Weight Loss vs. Temperature

Weight loss increased from 35% at 1450°C to approximately 40% at 1475°C and 1500°C, respectively. Figure 81 displays the weight loss vs. temperature plot for the 70 minute tests.

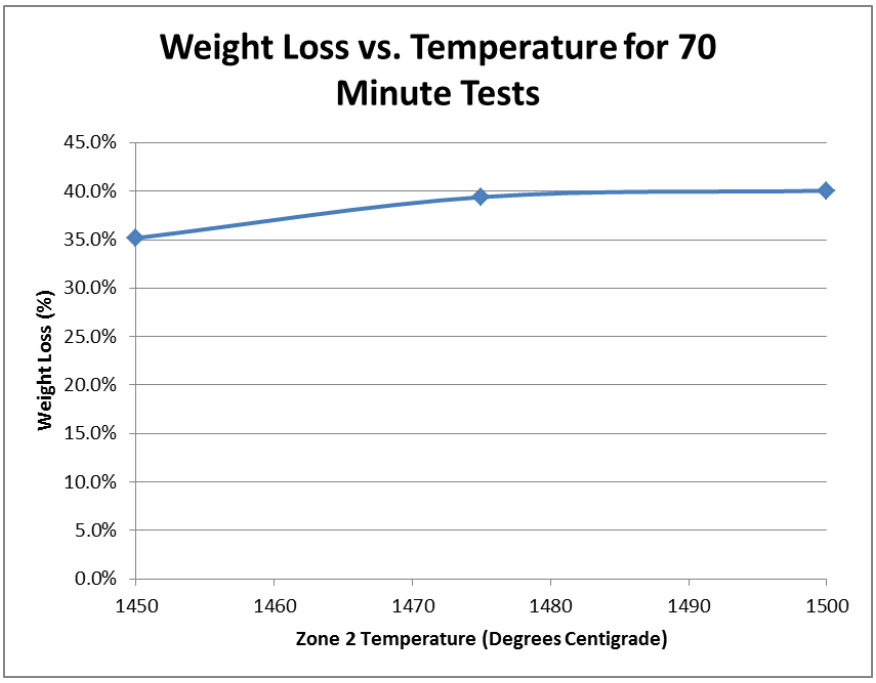


Figure 81: Phase II Weight Loss vs. Temperature for 70 Minute Tests

Hearth Productivity for Light Firebrick and Dense Refractory Brick

The light firebrick hearth productivity can be seen in Table 38 and Figure 82. As shown in Figure 82, the hearth productivity increases with temperature and is very linear. The maximum production tested was at 1500°C and was found to be approximately 1.17 kg/m^2-minute.

Table 38: Phase II Light Firebrick Hearth Productivity

Zone 2 Temp	Zone 2 Time (min)	Total Metallic Iron Produced (g)	Hearth Productivity (g/cm2-min)	Hearth Productivity (kg/m2-min)
1425	65	479.54	0.09	0.91
1450	65	521.50	0.10	0.99
1475	65	561.47	0.11	1.07
1500	65	616.46	0.12	1.17

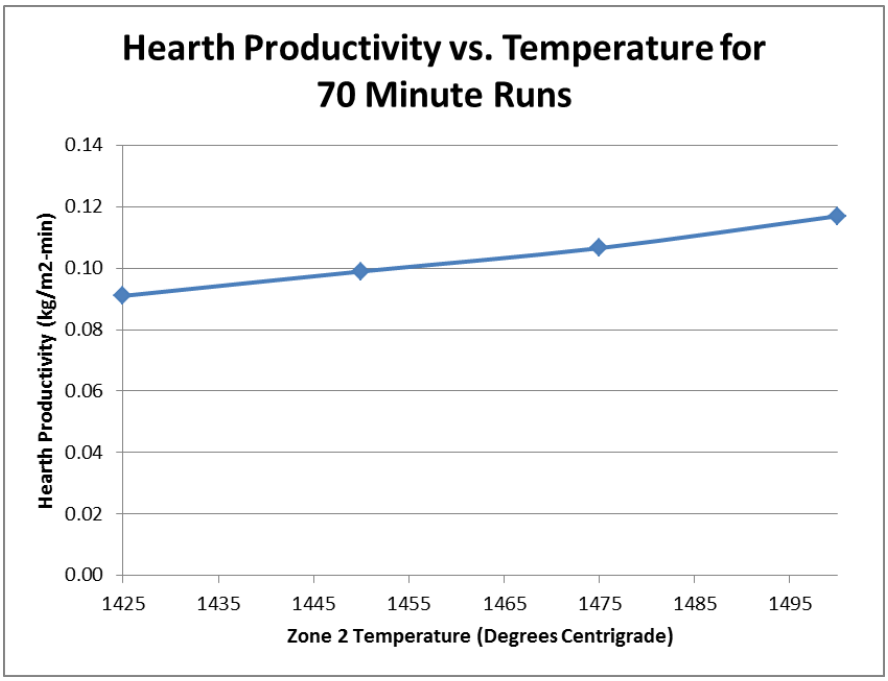


Figure 82: Phase II Light Firebrick Hearth Productivity vs. Temperature

Similar to the light refractory brick the dense refractory brick hearth productivity also increased with temperature, although not as linearly. Table 39 and Figure 83 display the testing data for these tests. Maximum productivity tested was found to be at 1500°C and was 1.20 kg/m^2-minute.

Table 39: Phase II Dense Refractory Brick Hearth Productivity

Zone 2 Temp (deg C)	Zone 2 Time (min)	Total Metallic Iron Produced (g)	Hearth Productivity (g/cm2-min)	Hearth Productivity (kg/m2-min)
1450	65	533	0.10	1.01
1475	65	610	0.12	1.16
1500	65	632	0.12	1.20

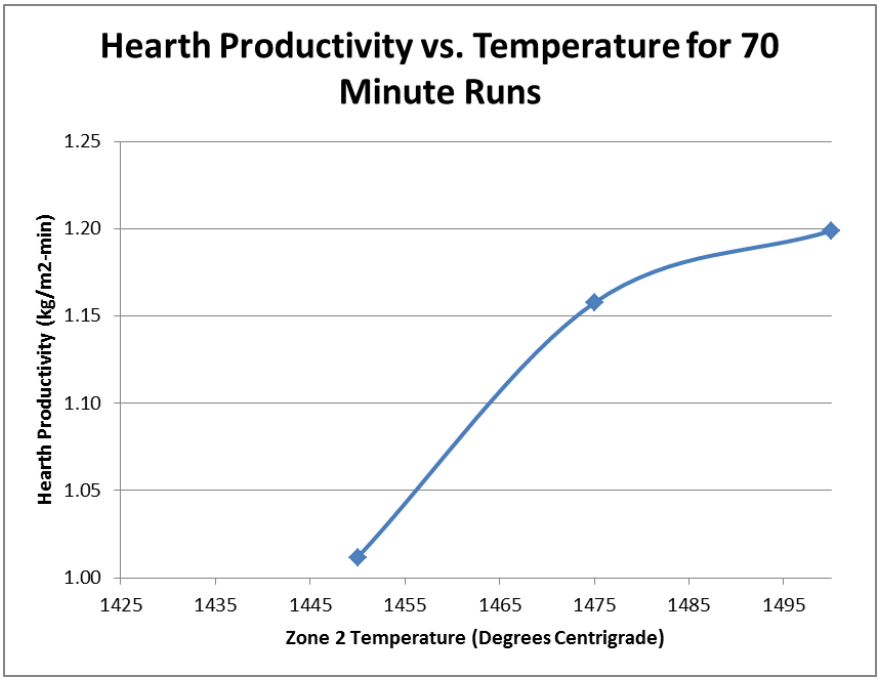


Figure 83: Phase II Dense Refractory Brick Hearth Productivity vs. Temperature

Conclusions and Future Testing Recommendations

The experiments in this study demonstrated that high metallizations of 95% and over one kilogram per square meter per minute production rates are possible from the top of the pellet bed to the bottom depending upon the temperature of the furnace, reaction time, and the degree of preheating of the bottom sliding plate. According to the results from Phase I, 90% metallization throughout the bed required a residence time of greater than 60 minutes at 1500°C. The hearth production under these conditions was found to be approximately 1.1 kg/m^2-minute. According to the results of Phase II, 90% metallization through the top four layers with a light firebrick required greater than 1475°C for 70 minutes and hearth production was approximately 1.1 kg/m^2-minute. To achieve greater than 90% metallization with the dense refractory brick required approximately 1475°C for 70 minutes and hearth productivity was approximately 1.2 kg/m^2-minute.

The experiments provide quantitative information for developing a kinetic model to describe the pellet shrinkage, heat transfer, and gas evolution to aid in scale-up and for development of a CFD (Computational Fluid Dynamics) model of the process. Future testing should include running tests on pilot equipment using natural gas combustion as a heating source to confirm lab scale data and determine scalability of technology. In addition, future test programs should be conducted with waste iron oxides as well.

References

[1] Wei-Kao Lu, "The Final Report on a New Process for Hot Metal Production at Low Fuel Rate," Project Number TRP-9941, Cooperative Agreement Number: DE-FC36-97ID13554, submitted to American Iron and Steel Institute by McMaster University, February 1, 2006.

Appendices

Appendix 1: Sample AISI Project Run Sheet

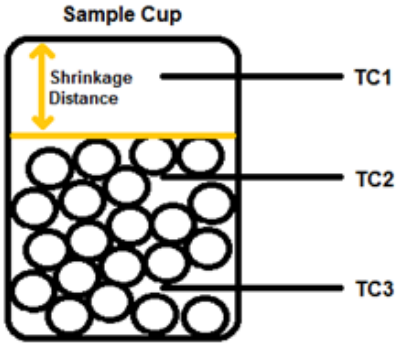
AISI Project Run Sheet

Project: AISI Furnace, 727.437
Engineer: MAM
Technician: SG

Run Number: _____
Date: _____
Hot Zone 1 Temperature Setpoint: _____
Hot Zone 2 Temperature Setpoint: _____
Hot Zone 1 Time: _____
Hot Zone 2 Time: _____
Starting Weight: _____

Time into Zone 1: _____

Ending Weight: _____
Vertical Shrinkage in Cup: _____



Pre-Test Procedure

1. Set temperature setpoints on furnace controllers
2. Prepare +16mm -19mm sample, ~1100 grams (~2.4 lbs)
3. Record starting weight
4. Connect thermocouple three level leads/TC reader (if applicable)
5. Connect and start recording program on Testo 350XL gas analyzer
6. Connect and turn on UEI AGA5000 gas analyzer
7. Turn on exhaust fan and flare
8. Prepare camera and take "Pre-heated" picture of balls in crucible

Test Procedure

9. Run test
    a. 5 minutes in Zone 1
    b. XX minutes in Zone 2
    c. Record thermocouple readings in each level every 30 seconds at beginning
    d. Record UEI AGA5000 gas analyzer numbers every 30 seconds at beginning
10. Cool sample to <100 degF

Post-Test Procedure

11. Recording ending weight and "shrinkage distance" (top of crucible to ball level)
12. Take "Post-heated" picture of balls in crucible
13. Remove sample from sample cup and separate into 5 layers
14. Take photograph of each layer after tagging (e.g., AISI4 Layer 1, AISI10 Layer 3)
15. Bag each layer, prepare half of each layer, then send to chem lab for:
    a. Metallic Iron (Fe_0)
    b. Ferrous (Fe^{++})
    c. Total Iron (Fe_T)
    d. Carbon (C)
    e. Sulfur (S)
16. Give data sheet, camera, and remaining bagged sample to Engineer

Layer 1
Weight: _____
BL #: _____

Layer 2
Weight: _____
BL #: _____

Layer 3
Weight: _____
BL #: _____

Layer 4
Weight: _____
BL #: _____

Layer 5
Weight: _____
BL #: _____

Appendix 2: Phase I Chemistry and Shrinkage Data

The following pages contain the composite chemistry for the testing program. Each test had a five minute preheat at 1200°C in Zone 1, and then was pushed into Zone 2 at 1350°C, 1425°C, or 1500°C.

Run Data			**Chemistry Data, Wt. %**							**Analysis, %**		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1200	0	1	10.24	0.17	61.07	6.59	29.32	25.16	10.8	N/A	-3.5	4.2
		2	14.07	0.18	51.22	1.33	14.89	35.00	2.6		-3.3	
		3	14.36	0.18	52.75	1.27	15.67	35.81	2.4		-0.2	
		4	14.49	0.19	51.42	1.13	13.83	36.46	2.2		-4.2	
		5	13.94	0.19	53.23	1.24	14.98	37.01	2.3		-0.7	
	65	1	0.31	0.26	85.28	70.38	15.38	-0.48	82.5	23.8	11.6	22.2
		2	6.70	0.21	73.99	46.46	23.43	4.10	62.8		2.9	
		3	10.75	0.19	61.43	5.69	45.23	10.51	9.3		0.8	
		4	11.18	0.18	60.68	2.46	44.87	13.35	4.1		0.9	
		5	11.83	0.18	59.12	1.30	37.10	20.72	2.2		1.1	

Run Data			Chemistry Data, Wt. %							Analysis, %		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	L ayer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1350	10	1	7.09	0.23	72.63	40.26	21.34	11.03	55.4	N/A	11.9	9.9
		2	5.89	0.14	66.33	11.63	21.25	33.45	17.5		0.1	
		3	12.77	0.20	53.92	1.37	15.29	37.26	2.5		-0.4	
		4	13.13	0.21	53.24	1.26	14.10	37.88	2.4		1.1	
		5	11.54	0.20	54.84	1.29	15.83	37.72	2.4		0.4	
	20	1	9.20	0.21	69.93	37.64	22.28	10.01	53.8	N/A	9.7	13.3
		2	8.62	0.18	63.30	18.78	23.97	20.55	29.7		7.2	
		3	10.90	0.18	56.40	4.97	16.61	34.82	8.8		1.5	
		4	11.55	0.19	53.28	1.36	14.97	36.95	2.6		-2.8	
		5	10.99	0.19	55.21	1.17	17.27	36.77	2.1		4.7	
	30	1	1.77	0.22	85.26	76.46	7.18	1.62	89.7	23.8	22.3	17.3
		2	7.92	0.22	67.31	30.30	24.35	12.66	45.0		11.6	
		3	10.90	0.19	56.91	1.78	24.53	30.60	3.1		-1.1	
		4	10.63	0.19	57.08	3.45	23.25	30.38	6.0		4.3	
		5	10.82	0.18	56.41	1.36	21.39	33.66	2.4		1.9	
	40	1	0.75	0.19	86.95	78.64	7.43	0.88	90.4	23.8	21.2	22.0
		2	6.81	0.21	74.44	47.59	23.90	2.95	63.9		16.9	
		3	8.69	0.19	64.21	17.16	36.09	10.96	26.7		6.1	
		4	10.18	0.19	58.35	2.51	35.01	20.83	4.3		8.9	
		5	13.08	0.19	57.01	3.50	28.23	25.28	6.1		-0.6	
	50	1	0.23	0.20	87.50	79.03	5.63	2.84	90.3	23.8	25.3	24.1
		2	3.65	0.23	83.68	73.75	9.50	0.43	88.1		12.0	
		3	10.78	0.21	63.79	16.45	30.61	16.73	25.8		-1.7	
		4	11.37	0.21	61.91	10.49	34.64	16.78	16.9		4.9	
		5	12.05	0.21	59.73	5.03	35.62	19.08	8.4		5.0	
	60	1	0.08	0.28	86.08	74.86	9.95	1.27	87.0	34.4	26.2	32.1
		2	0.84	0.24	87.48	83.01	5.81	-1.34	94.9		7.6	
		3	3.47	0.22	82.32	70.57	10.59	1.16	85.7		-9.1	
		4	9.84	0.19	65.83	19.67	38.53	7.63	29.9		1.1	
		5	9.76	0.19	65.44	19.48	36.11	9.85	29.8		1.3	
	65	1	0.12	0.20	86.33	79.10	5.11	2.12	91.6	29.1	30.2	31.8
		2	0.85	0.24	88.14	83.26	5.39	-0.51	94.5		14.0	
		3	6.84	0.23	75.50	50.14	21.35	4.01	66.4		-1.0	
		4	8.96	0.21	66.75	26.33	38.65	1.77	39.4		1.7	
		5	9.14	0.20	65.96	17.65	40.63	7.68	26.8		2.3	

Run Data			Chemistry Data, Wt. %							Analysis, %		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1425	10	1	7.83	0.22	67.61	35.73	17.82	14.06	52.8	29.1	13.8	11.6
		2	10.49	0.21	61.13	15.87	17.78	27.48	26.0		8.5	
		3	12.58	0.20	55.39	7.18	14.19	34.02	13.0		1.2	
		4	13.72	0.21	53.93	1.27	13.82	38.84	2.4		4.6	
		5	13.06	0.20	54.32	1.21	17.08	36.03	2.2		7.8	
	20	1	3.91	0.18	82.09	9.09	70.33	2.67	11.1	26.5	16.3	16.2
		2	11.31	0.19	63.15	26.91	20.64	15.60	42.6		3.7	
		3	13.07	0.20	54.99	19.05	2.06	33.88	34.6		4.1	
		4	13.15	0.21	53.31	19.12	1.26	32.93	35.9		3.1	
		5	12.87	0.20	55.56	20.84	1.29	33.43	37.5		-2.5	
	30	1	1.34	0.22	85.83	77.03	7.58	1.22	89.7	23.8	20.1	20.5
		2	5.37	0.19	77.14	52.50	25.91	-1.27	68.1		7.6	
		3	11.45	0.20	59.10	4.30	38.56	16.24	7.3		2.4	
		4	11.93	0.19	57.88	1.14	23.74	33.00	2.0		2.6	
		5	12.23	0.19	56.54	0.60	25.70	30.24	1.1		4.9	
	40	1	0.20	0.18	87.95	82.21	5.52	0.22	93.5	29.1	28.6	24.6
		2	4.14	0.20	77.62	64.03	20.54	-6.95	82.5		13.0	
		3	9.84	0.20	63.79	16.71	41.57	5.51	26.2		2.7	
		4	11.94	0.19	57.11	1.94	34.87	20.30	3.4		5.3	
		5	12.16	0.20	58.66	4.99	34.29	19.38	8.5		3.3	
	50	1	0.05	0.18	88.27	82.79	5.19	0.29	93.8	31.7	27.4	30.2
		2	2.30	0.24	84.83	76.11	7.48	1.24	89.7		12.7	
		3	8.02	0.24	67.93	33.39	31.38	3.16	49.2		0.5	
		4	11.38	0.20	61.47	9.54	44.22	7.71	15.5		3.4	
		5	11.35	0.21	60.03	7.62	44.82	7.59	12.7		4.5	
	60	1	0.04	0.19	88.06	83.37	4.76	-0.07	94.7	29.1	31.2	35.2
		2	0.14	0.22	88.29	84.98	4.09	-0.78	96.3		23.7	
		3	4.11	0.25	79.13	66.33	12.73	0.07	83.8		2.5	
		4	8.11	0.25	69.98	37.16	27.94	4.88	53.1		-2.5	
		5	10.51	0.22	63.39	16.10	40.78	6.51	25.4		-3.0	
	65	1	0.14	0.23	87.52	78.67	7.16	1.69	89.9	42.3	29.3	37.5
		2	0.04	0.22	88.11	81.73	4.46	1.92	92.8		24.0	
		3	0.43	0.25	88.42	85.42	1.81	1.19	96.6		13.7	
		4	4.12	0.24	81.36	70.17	10.24	0.95	86.2		-6.4	
		5	6.13	0.23	75.25	52.45	20.17	2.63	69.7		-2.4	

Run Data			Chemistry Data, Wt. %							Analysis, %		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1500	10	1	3.89	0.22	80.42	63.75	14.84	1.83	79.3	29.1	16.5	11.1
		2	10.92	0.22	62.46	14.50	36.34	11.62	23.2		-3.7	
		3	13.19	0.21	55.54	1.33	17.49	36.72	2.4		-2.6	
		4	12.57	0.21	54.67	4.89	19.18	30.60	8.9		0.6	
		5	12.54	0.21	56.48	1.32	18.48	36.68	2.3		0.9	
	20	1	0.41	0.18	87.94	84.75	3.15	0.04	96.4	29.1	24.3	17.0
		2	6.77	0.18	69.52	54.90	20.70	-6.08	79.0		10.9	
		3	11.80	0.21	58.33	6.12	24.19	28.02	10.5		0.8	
		4	12.24	0.19	55.72	1.72	19.60	34.40	3.1		1.1	
		5	12.35	0.19	56.15	1.08	21.68	33.39	1.9		-2.4	
	30	1	1.20	0.19	85.99	77.60	6.49	1.90	90.2	23.8	23.8	22.9
		2	7.59	0.19	71.19	35.58	28.28	7.33	50.0		4.1	
		3	11.32	0.19	60.32	4.35	40.03	15.94	7.2		4.2	
		4	12.11	0.19	57.86	1.11	27.89	28.86	1.9		0.7	
		5	12.56	0.18	57.95	1.13	33.57	23.25	1.9		1.1	
	40	1	0.07	0.19	86.44	79.41	5.68	1.35	91.9	29.1	25.9	29.9
		2	3.87	0.23	80.61	63.49	14.42	2.70	78.8		2.3	
		3	8.75	0.21	67.82	24.50	36.16	7.16	36.1		4.6	
		4	9.94	0.19	64.33	14.27	42.04	8.02	22.2		-5.6	
		5	11.08	0.19	61.62	5.74	44.79	11.09	9.3		1.4	
	50	1	0.02	0.21	88.24	82.31	5.47	0.46	93.3	42.3	32.6	33.7
		2	0.25	0.25	88.46	84.60	3.85	0.01	95.6		18.8	
		3	3.91	0.24	80.48	65.21	13.96	1.31	81.0		1.6	
		4	8.50	0.22	69.08	30.67	35.04	3.37	44.4		1.1	
		5	9.56	0.21	65.18	19.89	39.34	5.95	30.5		2.8	
	60	1	0.24	0.20	87.94	81.98	5.99	-0.03	93.2	45.0	38.7	39.7
		2	BDL	0.23	88.06	82.56	5.62	-0.12	93.8		30.5	
		3	0.09	0.26	88.34	85.87	1.40	1.07	97.2		20.6	
		4	2.00	0.26	85.83	81.18	2.26	2.39	94.6		5.4	
		5	4.42	0.24	78.67	65.79	10.60	2.28	83.6		4.5	
	65	1	0.26	0.20	88.59	83.78	4.79	0.02	94.6	47.6	36.5	40.0
		2	0.22	0.21	87.27	80.83	7.73	-1.29	92.6		31.6	
		3	0.06	0.23	88.37	84.48	4.05	-0.16	95.6		29.7	
		4	0.44	0.26	89.00	88.02	0.77	0.21	98.9		23.7	
		5	1.92	0.25	87.51	87.89	0.36	-0.74	100.4		11.9	

Appendix 3: Phase I Photos of the Samples Before and After Testing Procedure

Five Minutes at 1200°C, 0 Minutes at 1200°C

Five Minutes at 1200°C, 65 minutes at 1200°C

Five Minutes at 1200℃, 10 minutes at 1350℃

Five Minutes at 1200°C, 20 minutes at 1350°C

Five Minutes at 1200°C, 30 minutes at 1350°C

Five Minutes at 1200°C, 40 minutes at 1350°C

Five Minutes at 1200°C, 50 minutes at 1350°C

Five Minutes at 1200°C, 60 minutes at 1350°C

Five Minutes at 1200℃, 65 minutes at 1350℃

Five Minutes at 1200℃, 10 minutes at 1425℃

Five Minutes at 1200℃, 20 minutes at 1425℃

Five Minutes at 1200℃, 30 minutes at 1425℃

Five Minutes at 1200℃, 40 minutes at 1425℃

Five Minutes at 1200℃, 50 minutes at 1425℃

Five Minutes at 1200℃, 60 minutes at 1425℃

Five Minutes at 1200℃, 65 minutes at 1425℃

Five Minutes at 1200℃, 10 minutes at 1500℃

Five Minutes at 1200°C, 20 minutes at 1500°C

Five Minutes at 1200°C, 30 minutes at 1500°C

Five Minutes at 1200°C, 40 minutes at 1500°C

Five Minutes at 1200°C, 50 minutes at 1500°C

Five Minutes at 1200°C, 60 minutes at 1500°C

Five Minutes at 1200°C, 65 minutes at 1500°C

Appendix 4: Phase II Chemistry and Shrinkage Data with Light Firebrick Bottom

The following pages contain the composite chemistry for the testing program. Each test had a five minute preheat at 1200°C in Zone 1, and then was pushed into Zone 2 at 1425°C, 1450°C, 1475°C, or 1500°C.

Run Data			**Chemistry Data, Wt. %**							**Analysis, %**		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1425	65	1	0.04	0.20	85.94	75.33	7.32	3.29	87.7	31.7	26.1	36.9
		2	0.05	0.20	86.44	79.46	8.99	-2.01	91.9		28.3	
		3	2.22	0.27	82.49	73.32	10.27	-1.10	88.9		13.8	
		4	4.90	0.22	76.65	54.93	17.22	4.50	71.7		2.4	
		5	6.99	0.20	69.13	30.63	31.33	7.17	44.3		1.9	
	65	1	0.01	0.21	86.56	77.87	10.62	-1.93	90.0	31.7	32.9	34.0
		2	0.28	0.21	86.49	79.52	8.71	-1.74	91.9		29.6	
		3	0.77	0.23	85.93	79.07	7.51	-0.65	92.0		16.7	
		4	6.28	0.21	73.61	43.71	26.90	3.00	59.4		3.0	
		5	6.77	0.19	70.50	35.60	32.00	2.90	50.5		1.3	

Run Data			Chemistry Data, Wt. %							Analysis, %		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1450	65	1	0.05	0.19	86.79	79.50	7.29	0.00	91.6	37.0	33.0	35.7
		2	0.04	0.21	87.06	80.84	6.81	-0.59	92.9		29.5	
		3	0.41	0.24	87.24	82.80	3.81	0.63	94.9		18.0	
		4	6.06	0.23	74.54	48.71	26.91	-1.08	65.3		4.2	
		5	8.35	0.20	68.42	27.24	34.84	6.34	39.8		3.7	
	65	1	0.02	0.19	86.66	75.72	9.87	1.07	87.4	37.0	33.1	35.1
		2	0.04	0.21	86.54	78.23	9.29	-0.98	90.4		29.6	
		3	2.78	0.25	82.09	69.74	10.17	2.18	85.0		14.6	
		4	6.52	0.19	72.36	41.14	23.82	7.40	56.9		0.1	
		5	6.75	0.18	69.93	29.52	29.68	10.73	42.2		4.2	

Run Data			Chemistry Data, Wt. %							Analysis, %		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1475	65	1	0.05	0.18	86.42	78.42	9.68	-1.68	90.7	37.0	35.7	37.4
		2	0.02	0.23	85.60	67.17	8.41	10.02	78.5		31.2	
		3	0.24	0.25	86.51	81.70	7.02	-2.21	94.4		22.9	
		4	2.56	0.23	81.26	67.76	10.75	2.75	83.4		7.8	
		5	2.68	0.20	75.55	42.33	22.82	10.40	56.0		3.2	
	65	1	0.01	0.20	87.43	78.39	7.49	1.55	89.7	26.5	37.3	36.8
		2	0.01	0.21	86.62	80.39	4.50	1.73	92.8		29.1	
		3	1.12	0.24	85.71	80.17	4.52	1.02	93.5		12.0	
		4	5.68	0.21	75.89	54.04	9.06	12.79	71.2		-2.1	
		5	7.19	0.18	71.41	37.42	27.53	6.46	52.4		0.8	

Run Data			Chemistry Data, Wt. %							Analysis, %		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1500	65	1	0.01	0.17	87.61	78.87	6.09	2.65	90.0	N/A	35.4	N/A
		2	0.01	0.19	85.76	75.49	7.26	3.01	88.0		32.6	
		3	0.01	0.22	85.05	74.72	6.85	3.48	87.9		30.6	
		4	N/A	N/A	N/A	N/A	N/A	N/A	N/A		N/A	
		5	N/A	N/A	N/A	N/A	N/A	N/A	N/A		N/A	
	65	1	0.01	0.20	87.18	79.16	6.46	1.56	90.8	37.0	35.1	38.8
		2	0.02	0.19	86.35	78.40	5.67	2.28	90.8		32.4	
		3	0.12	0.25	87.48	83.80	2.43	1.25	95.8		27.1	
		4	1.37	0.23	85.59	80.97	2.92	1.70	94.6		12.1	
		5	2.98	0.20	79.76	61.73	11.51	6.52	77.4		7.6	

Appendix 5: Phase II Chemistry and Shrinkage Data with Dense Refractory Brick Bottom

The following pages contain the composite chemistry for the testing program. Each test had a five minute preheat at 1200°C in Zone 1, and then was pushed into Zone 2 at 1450°C, 1475°C, or 1500°C.

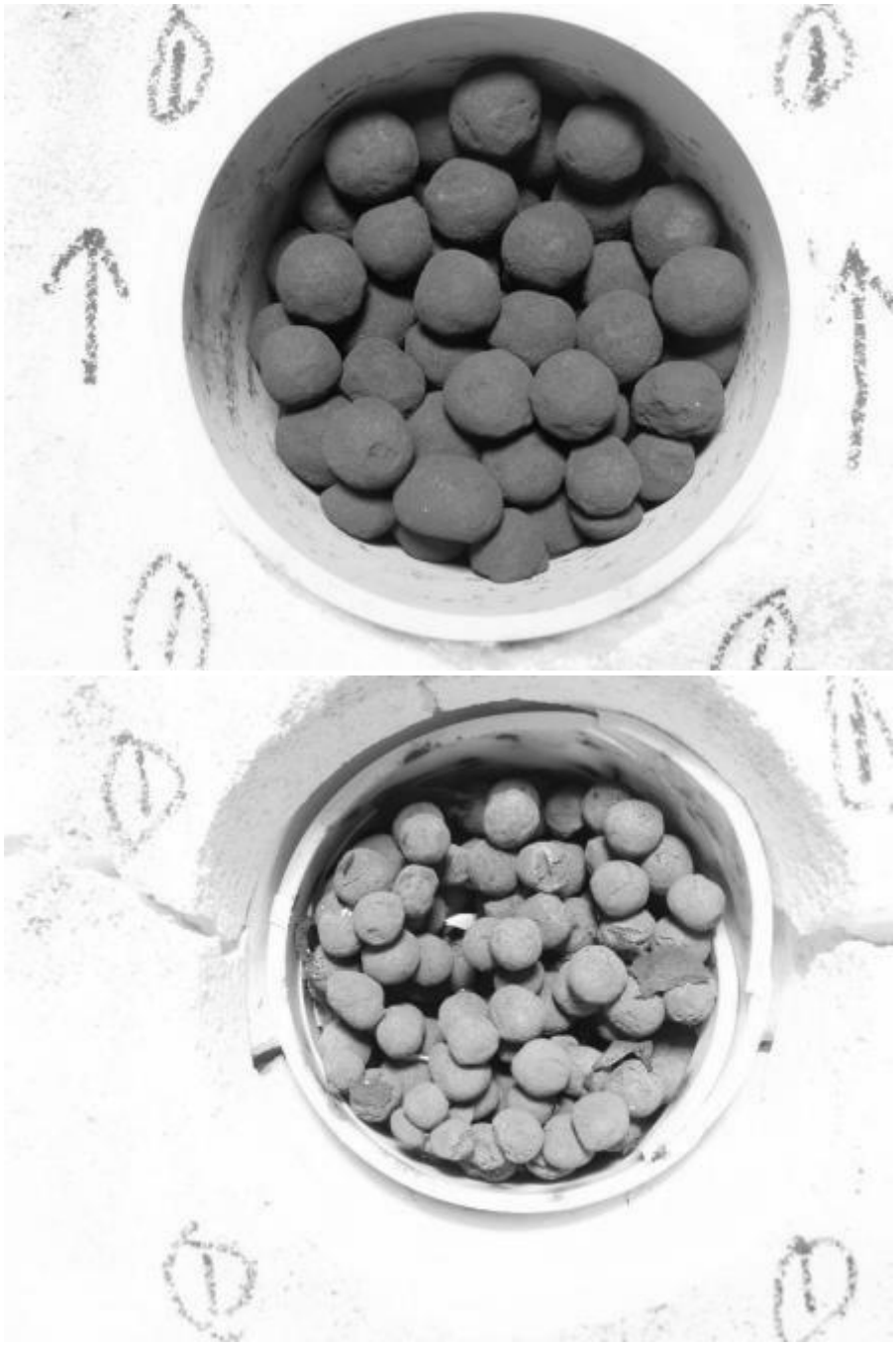
Run Data			**Chemistry Data, Wt. %**							**Analysis, %**		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1450	65	1	0.04	0.22	87.24	71.46	13.36	2.42	81.9	31.7	24.7	34.2
		2	0.02	0.27	84.14	71.39	11.11	1.64	84.8		21.5	
		3	0.24	0.25	86.04	79.91	5.44	0.69	92.9		15.1	
		4	6.05	0.24	68.96	40.60	26.46	1.90	58.9		-1.1	
		5	6.85	0.21	65.02	33.84	30.26	0.92	52.0		-5.5	
	65	1	0.03	0.20	87.04	80.23	6.25	0.56	92.2	21.2	27.9	36.1
		2	0.03	0.20	86.40	80.51	5.40	0.49	93.2		22.4	
		3	1.05	0.24	85.22	76.61	5.01	3.60	89.9		5.7	
		4	5.24	0.23	72.27	48.91	21.45	1.91	67.7		-0.9	
		5	2.51	0.22	77.46	52.63	21.68	3.15	67.9		-7.9	

Run Data			**Chemistry Data, Wt. %**							**Analysis, %**		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage	Average Pellet Shrinkage	Weight Reduction
1475	65	1	0.01	0.24	88.37	80.44	7.07	0.86	91.0	37.0	30.7	39.4
		2	0.03	0.23	86.12	80.47	5.09	0.56	93.4		27.6	
		3	0.03	0.24	86.45	81.73	4.23	0.49	94.5		27.0	
		4	0.73	0.23	86.40	83.52	2.32	0.56	96.7		13.0	
		5	1.91	0.23	82.93	74.32	6.53	2.08	89.6		3.3	

Run Data			Chemistry Data, Wt. %							Analysis, %		
Zone 2 Temperature (deg C)	Zone 2 Time (min)	Layer	C	S	Fe^{Total}	Fe^{0}	Fe^{++}	Fe^{+++} (by difference)	Metallization	Vertical Shrinkage,	Average Pellet Shrinkage,	Weight Reduction
1500	65	1	0.02	0.22	88.36	81.16	6.11	1.09	91.9	37.0	35.4	40.1
		2	0.01	0.20	86.82	81.13	5.39	0.30	93.4		27.9	
		3	0.01	0.21	86.62	79.69	5.97	0.96	92.0		29.1	
		4	0.48	0.23	87.08	84.75	2.06	0.27	97.3		12.1	
		5	1.22	0.22	85.32	81.15	2.53	1.64	95.1		5.8	

Appendix 6: Phase II Photos of the Samples Before and After Testing Procedure with Light Firebrick Bottom

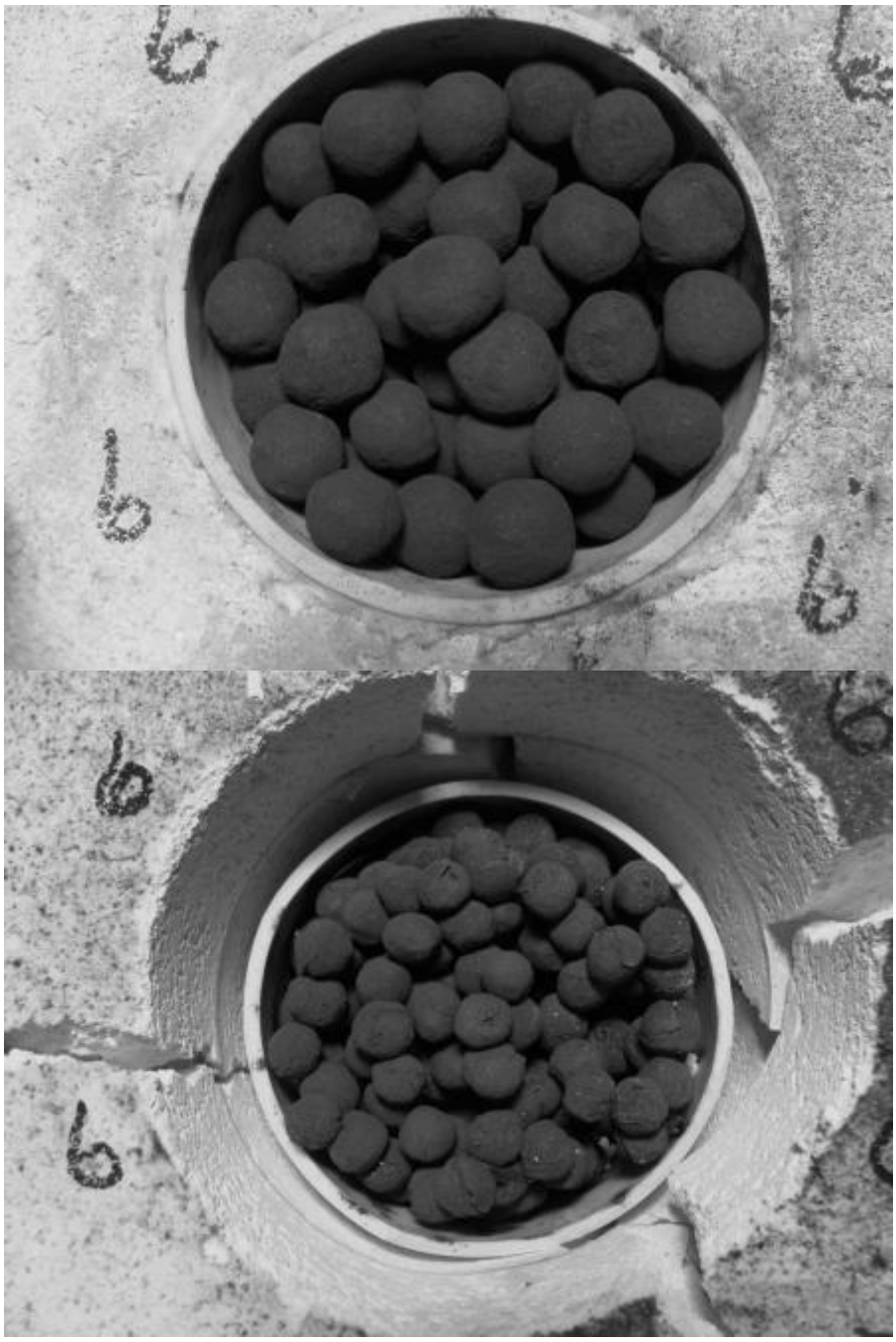
Five Minutes at 1200℃, 65 minutes at 1425℃ Run 1 (Light Firebrick Bottom)



Five Minutes at 1200℃, 65 minutes at 1425℃ Run 2 (Light Firebrick Bottom)

Five Minutes at 1200℃, 65 minutes at 1450℃ Run 1 (Light Firebrick Bottom)

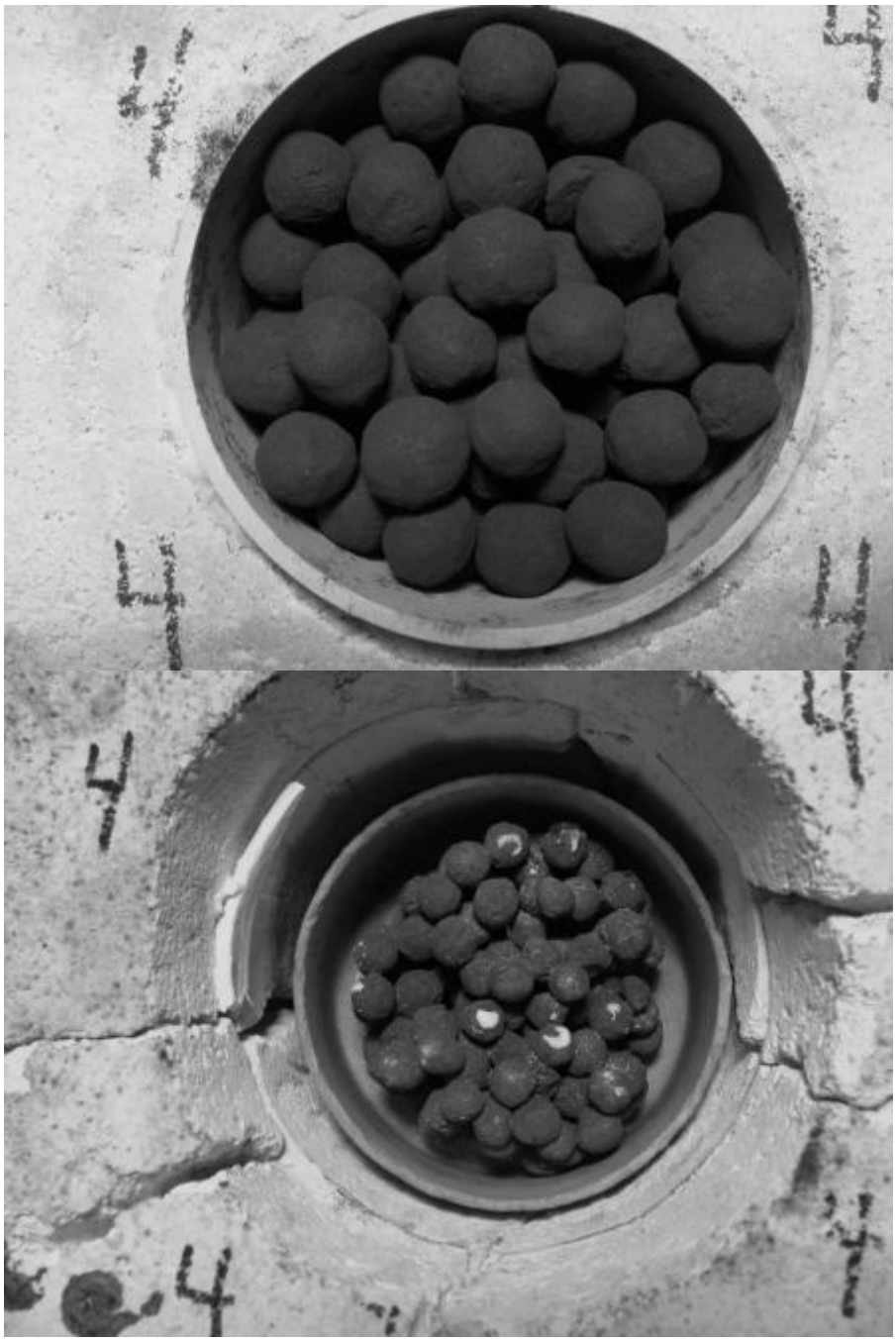
Five Minutes at 1200℃, 65 minutes at 1450℃ Run 2 (Light Firebrick Bottom)



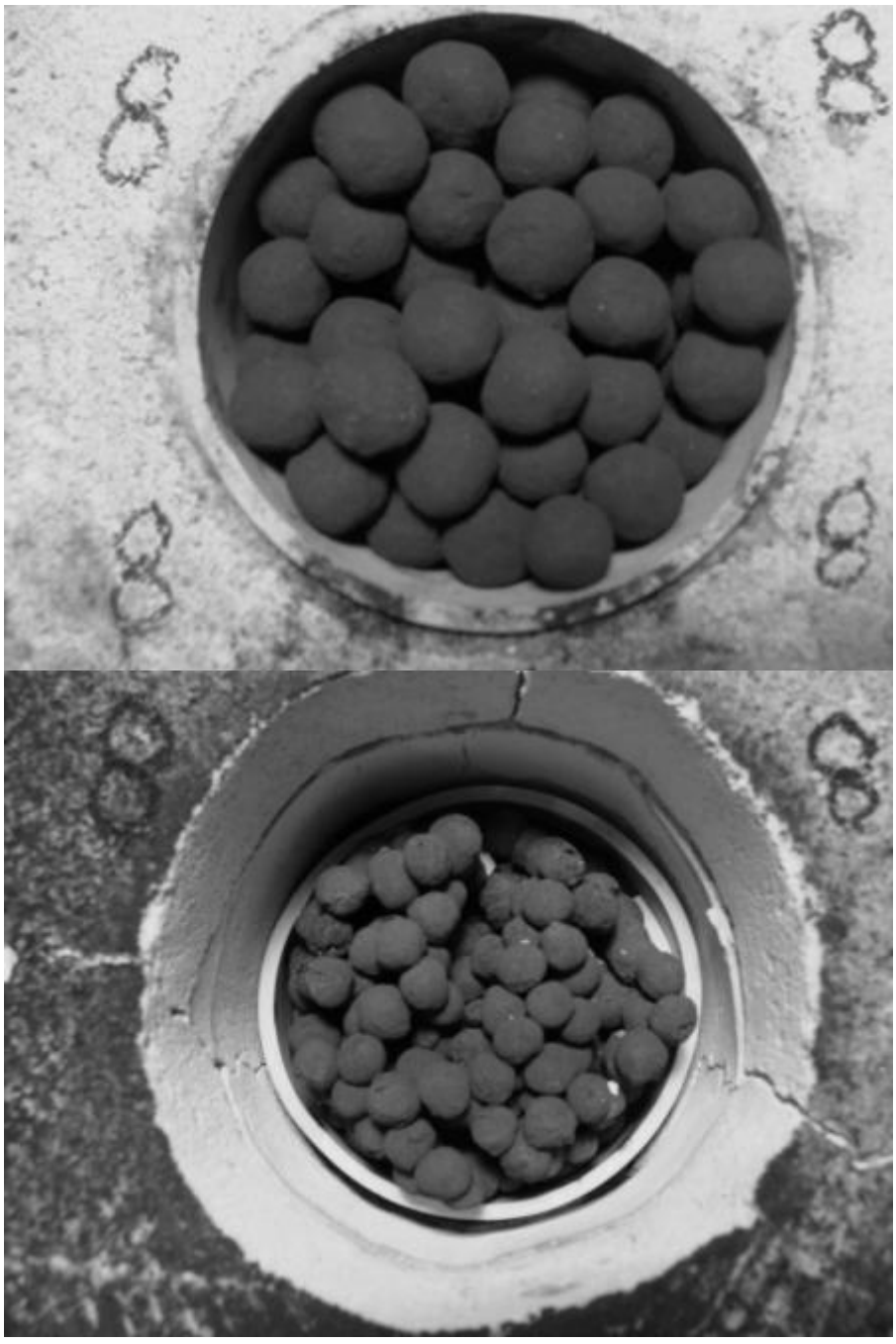
Five Minutes at 1200℃, 65 minutes at 1475℃ Run 1 (Light Firebrick Bottom)

Five Minutes at 1200℃, 65 minutes at 1475℃ Run 2 (Light Firebrick Bottom)

Five Minutes at 1200℃, 65 minutes at 1500℃ Run 1 (Light Firebrick Bottom)



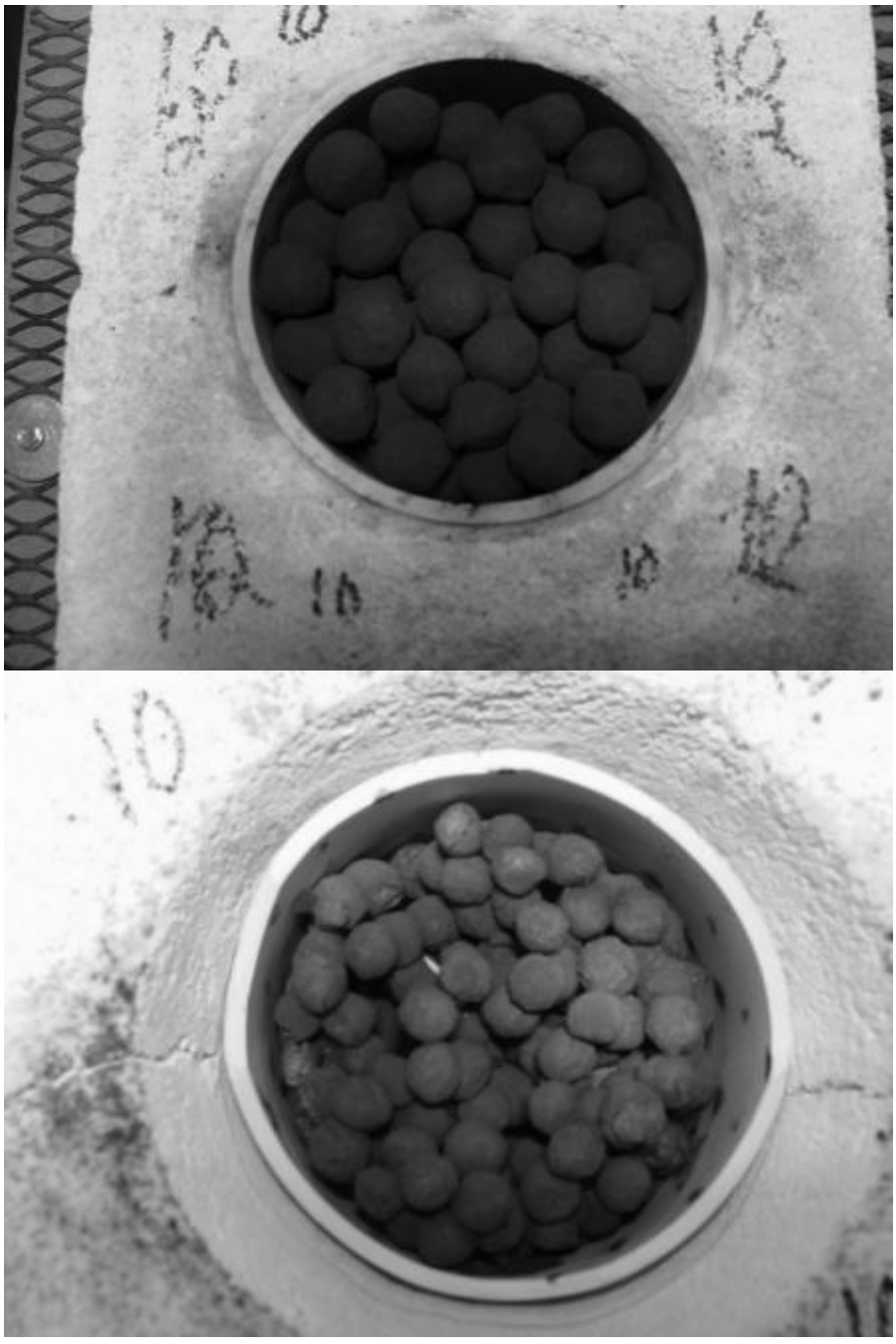
Five Minutes at 1200℃, 65 minutes at 1500℃ Run 2 (Light Firebrick Bottom)



Appendix 7: Phase II Photos of the Samples Before and After Testing Procedure with Dense Refractory Brick Bottom

Five Minutes at 1200℃, 65 minutes at 1450℃ Run 1 (Dense Refractory Brick Bottom)

Five Minutes at 1200℃, 65 minutes at 1450℃ Run 2 (Dense Refractory Brick Bottom)



Five Minutes at 1200℃, 65 minutes at 1475℃ (Dense Refractory Brick Bottom)

Five Minutes at 1200°C, 65 minutes at 1500°C (Dense Refractory Brick Bottom)

Appendix C: PAIRED STRAIGHT HEARTH FURNACE PILOT SCALE STUDIES USING COLERAINE MINERALS RESEARCH LABORATORY LINEAR HEARTH FURNACE (Coleraine Minerals Research Laboratory) May 31, 2014.

UMD Natural Resources Research Institute
University of Minnesota Duluth
Driven to Discover

Paired Straight Hearth Furnace Pilot Scale Studies Using Coleraine Minerals Research Laboratory Linear Hearth Furnace

conducted for the

American Iron and Steel Institute

under

DOE Contract DE-FG36-08GO18133 Paired Straight Hearth Furnace- Transformational Ironmaking Process

COLERAINE MINERALS RESEARCH LABORATORY

May 31, 2014,

By: _____
Basak Anameric – Research Coordinator, NRRI, UMD

By: _____
Harold R. Kokal – Process Portfolio Specialist, ArcelorMittal Global R&D

Approved by: _____
Richard Kiesel – Director Coleraine Minerals Research Laboratory

NRRI/TR-2014/16

Natural Resources Research Institute
University of Minnesota – Duluth
5013 Miller Trunk Highway
Duluth, Minnesota 55811

Coleraine Minerals Research Laboratory
P O Box 188
One Gayley Avenue
Coleraine, Minnesota 55722

This material is based upon work supported by the U.S. Department of Energy under Award Number DE-FG36-08GO18133.

Executive Summary

In 2013, the American Iron and Steel Institute (AISI) engaged the Natural Resources Research Institute (NRRI) to conduct a pilot-scale study to support ongoing efforts towards commercialization of the paired straight hearth furnace (PSHF) process. This study was conducted for AISI to support their activities under the United States Department of Energy (DOE) contract number DE-FG36-08GO18133, Paired Straight Hearth Furnace (PSHF) - Transformational Ironmaking Process issued in September 2008. The PSHF process is a coal-based alternative ironmaking technology developed at McMaster University under a previous DOE grant [1] [2]. Throughout the process, dried greenballs, which contain an iron oxide source, reductant, and binder, are reduced to direct reduced iron (DRI). The process utilizes two parallel pusher furnaces operating in opposite directions with gas transfer between them. The main features of the process are that it couples deep-bed heating with a paired-furnace technology to produce DRI with efficient gas utilization [3] [4].

For this study, pilot-scale simulation of the conditions required for the PSHF process was attempted in the NRRI linear hearth furnace (LHF) [5] . The LHF is a 12.2m (40-ft) long, 0.6 m (2-ft) wide moving-hearth, pilot-scale, high-temperature furnace. LHF is capable of operating at hot- zone temperatures as high as 1500°C. The furnace is composed of three heating zones (Zones 1-3) and one cooling zone. The furnace temperature in each heating zone is controlled separately.

The objectives of this study were to determine some of the operational conditions required for production of high quality DRI, and to evaluate and assess the quality of DRI produced. For this study, dried greenballs, which contain either magnetite concentrate or revert material (basic oxygen furnace (BOF) dust) as an iron oxide source, coal (high-volatile bituminous coal) as a reductant, and bentonite as a binder, were used as feed material. The study was conducted in five phases. These phases included:

Phase I – Modifications of the LHF to simulate the operational conditions required for the PSHF process

During the initial phase of the study, the LHF was modified to simulate conditions required for the PSHF process as closely as possible, without making changes to the existing cart handling system. These modifications included: (i) installation of furnace refractories to accommodate the high operating temperatures (1500°C (2732°F)) required, (ii) relocation of the exhaust duct to Zone 3 to allow for co-current flow, (iii) increasing the height of the ceramic fiber refractory on the furnace cart system to accommodate deep beds of dried greenballs (initial bed heights up to 12.7 cm (5 inches)), and (iv) lining the base of the sample carts with a single layer of dense, high-alumina brick to simulate a castable or solid brick refractory hearth for heat retention. Moreover, in order to be able to contain gasses evolved from the hot carts during loading of the dried greenballs, an exhaust hood was fabricated and installed.

Phase II – Identification of the necessary LHF operational conditions

The second phase of the study included identification of LHF operational conditions. During this phase, experiments were conducted to determine operational conditions such as damper positions, fan speeds, cooling rates, cart speeds in Zones 1, 2, and 3 and the cooling zone to achieve required residence times, and burner oxygen-to-gas ratios to simulate PSHF process conditions. The maximum hearth preheat temperature attained was 800°C.

Experiments were conducted to determine effect of residence time required in the LHF cooling zone. When DRI cooled with a short residence time (15 min), and was removed, the bottom layer was still hot. This indicated that temperature at the bottom of the bed was high enough for remaining carbon to burn, but not high enough for reduction reactions. For DRI cooled with a longer residence time (45 min), percent metallization at the bottom of the bed was slightly higher. This could have been due to re-oxidation of the DRI cooled with a short residence time. Thus, DRI which had a longer residence time in the cooler had better quality. Additional experiments were conducted to investigate whether the cooling of the DRI could be further improved. For these experiments, the DRI was discharged from the LHF cooler at a long residence time, shoveled from the carts, put in trays, and placed under an external cooling hood. The cooling hood was purged with nitrogen. Minimal re-oxidation of the DRI was observed for these samples.

Experiments were also conducted with two different types of carts to determine the effect of heat retention on the sides of the carts on the DRI quality. Two different types of carts were used for the experiments. The first cart was a “pyro-log” cart with ceramic fiber sidewalls and alumina brick installed at the bottom. The second cart was a cart with alumina brick installed both at the sides inside of the ceramic fiber cart and at the bottom of the cart. Both of the carts had the same size opening. DRI produced using the carts with alumina bricks installed on the sides exhibited more horizontal shrinkage, and the percent metallization of DRI produced was slightly higher. A further study to investigate the effects on heat transfer and reduction kinetics with brick-sided carts is recommended.

Phase III – Reduction of dried greenballs which contain magnetite concentrate

In this phase, an investigation was conducted on the effects of (i) furnace temperature, (ii) furnace residence time, (iii) dried greenball molar carbon-to-oxygen ratio, and (iv) initial bed height, on the reduction of dried greenballs which contain magnetite concentrate. Throughout the experiments, the highest percent metallization was achieved at a furnace temperature of 1500°C, residence time of 80 min, dried greenball molar carbon-to-oxygen ratio of 1.1, and at an initial bed height of 7.6 cm. The percent metallization at the top, middle and bottom of the bed was 89.22%, 87.32%, and 83.22%, respectively. For DRI produced using dried greenballs which contain magnetite concentrate, furnace temperature had a greater impact on the percent metallization when compared with furnace residence time. When operating at furnace temperatures below 1450°C, the percent metallization achieved was considerably lower. In

addition, percent metallization of the DRI increased considerably when the dried greenball molar carbon-to-oxygen ratio was increased from 1.0 to 1.1. However, a further increase in the dried greenball molar carbon-to-oxygen ratio to 1.2 did not seem to significantly affect the DRI quality. Moreover, as the initial bed height increased, the percent metallization achieved at the bottom of the bed decreased. This could have been due to heat and gas transfer limitations at higher initial bed heights, or to lower than anticipated initial cart hearth temperatures that were limited to 800°C. Thus, future studies should be conducted to investigate the effects of higher cart bottom temperatures on the percent metallization with varying initial bed heights.

Phase IV – Simulation of Continuous Operation

In this phase, a simulation of continuous operation of the PSHF process using the LHF was performed. For this experiment, twelve carts loaded with dried greenballs which contain magnetite concentrate were loaded in the furnace. The cart speed was kept constant. Volatile evolution and combustion in Zone 1 increased as each successive cart entered the furnace. When the tenth cart entered Zone 1, excessive temperatures were encountered, which activated the high temperature safety feature. Thus, this experiment was not successfully completed. Further studies should be conducted to simulate a continuous operation. These studies should include furnace modification to properly exhaust all volatiles evolved.

Phase V – Reduction of Dried greenballs which contain revert material

In this phase, an investigation was conducted on the effects of (i) furnace temperature, (ii) furnace residence time, (iii) dried greenball molar carbon-to-oxygen ratio, and (iv) initial bed height on the reduction of dried greenballs which contain revert material. Throughout the experiments, the highest percent metallization was achieved at a furnace temperature of 1500°C, residence time of 80 min, a dried greenball molar carbon-to-oxygen ratio of 1.1, and an initial bed height of 7.6 cm. Percent metallization at the top, middle and bottom of the bed was 86.14%, 82.20%, and 83.62%, respectively. For DRI produced using dried greenballs which contain revert material, the percent metallization at the top, middle and bottom of the bed increased as the furnace temperature and residence time increased. In addition, percent metallization of the DRI at the bottom of the bed increased considerably when the dried greenball molar carbon-to-oxygen ratio was increased from 1.0 to 1.1. In order to verify this finding, further studies should be conducted with dried greenballs made with various molar carbon-to-oxygen ratios to optimize the DRI quality. For DRI produced at several initial bed heights, the percent metallization achieved at the bottom of the bed decreased as the initial bed height increased.

Only a limited number of assays were conducted to determine DRI zinc content (wt % Zn). The DRI with the lowest zinc content throughout the bed was produced at a furnace temperature of 1400°C and residence time of 100 min, using dried greenballs which had a molar carbon-to-oxygen ratio of 1.1 at an initial bed height of 7.6 cm. Zinc content at the top, middle and bottom of the bed was 0.029%, 0.020%, and 0.029%, respectively. As the initial bed height increased, the percent zinc content of the DRI increased. Further studies should be

conducted to identify zinc (and lead) removal kinetics, and limiting factors. The effects of initial bed height and dried greenball molar carbon-to-oxygen ratio on lead and zinc removal should be quantified.

Grate factors were estimated for dried greenballs which contain magnetite concentrate and for dried greenballs which contain revert material. In both cases, optimum bed depth where metallization was the highest in these experiments was identified as 7.6 cm (3 inches), and the optimum furnace hot-zone residence time was 80 minutes. The optimum molar carbon-to-oxygen ratio for the coal used was 1.1. The optimum furnace hot-zone temperature for production of DRI using dried greenballs which contain magnetite concentrate was 1500°C. But the optimum furnace hot-zone temperature for production of DRI using dried greenballs which contain revert material was lower at 1450°C. The cart loading was 95.8 kg/m^2 for the dried greenballs which contain magnetite concentrate, so the grate factor would be 71.9 kg/m^2/h at 80 min furnace hot-zone residence time. For the dried greenballs which contain revert material, the loading was 105.45 kg/m^2, so the grate factor would be 79.1 kg/m^2/h at 80 min furnace hot-zone residence time. For both cases, the hearth preheat temperature was 800°C, and the residence times in Zone 1 and cooling zone were not included.

Future studies are recommended to further understand the operational conditions required for production of high quality DRI using the PSHF.

- For this study, the initial cart hearth temperature was 800°C. It was shown in a previous study conducted at NRRI that the temperature at the bottom of the carts prior to loading of the dried greenballs had a great impact on the percent reduction achieved at the bottom of the bed [6]. Because the highest achievable temperature at the bottom of the carts in this study was 800°C, additional laboratory-scale experiments should be conducted to identify the effects of both temperature and heat retention in the refractory at the bottom of the cart on the percent metallization at the bottom layers.

- During this study, only one type of coal with volatile matter of 35-37 percent was used as a reductant. Additional studies should be conducted to determine the optimum type of coal needed for producing high-quality DRI from the raw materials on hand.

- High quality DRI production using the PSHF process is highly dependent on the heat and gas transfer within the bed. For DRI produced using dried greenballs which contain revert material, a considerable amount of fines generation was observed. Presence of these fine materials in the bed limits the heat and gas transfer within the bed. Thus, further studies are recommended to improve revert material balling and to eliminate fines generation during heating and reduction.

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1.0 Introduction

In 2013, the American Iron and Steel Institute (AISI) engaged the Natural Resources Research Institute (NRRI) to conduct a pilot-scale study to support ongoing efforts towards commercialization of the paired straight hearth furnace (PSHF) process. This study was conducted for AISI under the United States Department of Energy (DOE) contract number DE-FG36-08GO18133, Paired Straight Hearth Furnace (PSHF) -Transformational Ironmaking Process initiated in September 2008. The PSHF process is a coal-based alternative ironmaking technology developed at McMaster University under a previous DOE grant [1] [2]. Throughout the process, dried greenballs which contain an iron oxide source, a reductant, and a binder are heated and reduced to direct-reduced iron (DRI). The process utilizes two parallel pusher furnaces operating in opposite directions with gas transfer between them. The main advantages of the paired furnace technology are that it accomplishes deep bed heating of dried greenballs and reduction to metal with efficient gas utilization [3] [4] .

For this study, pilot-scale simulation of the conditions required for the PSHF process was achieved in the NRRI linear hearth furnace (LHF) [5]. The LHF is a 12.2m (40-ft) long, 0.6 m (2-ft) wide (inside the refractories), moving-hearth, pilot-scale, high-temperature furnace. The furnace is composed of three heating zones (Zones 1-3) of equal lengths, and one cooling zone. The furnace temperature in each heating zone is controlled separately. Zones 2 and 3 are capable of operating at 1500°C (2732°F). For this study, the combination of Zones 2 and 3 is referred to as the hot-zone. The cooling zone can be purged with nitrogen gas. The moving hearth is composed of a series of carts, 50.8 cm by 50.8 cm (20 inch by 20 inch) with an active hearth area opening of 40.6 cm by 40.6 cm (16 inch by 16 inch). Each cart can accommodate a bed of dried greenballs up to 12.7 cm (5 inches) deep.

The objectives of this study were to determine the operational conditions required for production of high-quality DRI and to evaluate and assess the quality of DRI produced. For this study, dried greenballs which contained either magnetite concentrate or revert material (basic oxygen furnace (BOF) dust) as the iron oxide source, coal (high volatile bituminous coal) as a reductant, and bentonite (clay) as a binder, were used as the feed material to the LHF. The study was conducted in five phases. These phases were as follows:

Phase I – Modifications to LHF to simulate the operational conditions required for the PSHF process

During the initial phase of the studies, the LHF was modified to simulate conditions required for the PSHF process as closely as possible, without making changes to the existing cart handling system. These modifications included, (i) installation of furnace refractories to accommodate the high operating temperatures (1500°C (2732°F)) required, (ii) relocation of the exhaust duct to Zone 3 to allow for co-current flow, (iii) increasing the height of the ceramic fiber refractory on the furnace cart system to accommodate a deep bed of dried greenballs

(initial bed heights up to 12.7 cm (5 inches)), and (iv) lining the base of the sample carts with a single layer of dense, high-alumina brick to simulate a castable or solid brick refractory hearth for heat retention. Moreover, in order to be able to contain gasses evolved from the hot carts during loading of the dried greenballs, an exhaust hood was fabricated and installed.

Phase II – Identification of the necessary LHF operational conditions

During this phase, experiments were conducted with dried greenballs which contain magnetite to determine the operational conditions required to simulate the PSHF process, including damper positions, fan speeds, cooling rate, cart speeds (to achieve the required residence times), and burner oxygen-to-gas ratios.

Phase III – Reduction of dried greenballs which contain magnetite concentrate

In this phase, an investigation was conducted on the effects of (i) furnace temperature, (ii) furnace residence time, (iii) dried greenball molar carbon-to-oxygen ratio, and (iv) initial bed height on the reduction of dried greenballs which contain magnetite concentrate.

Phase IV – Simulation of continuous operation

In this phase an experiment was conducted to simulate continuous operation. Twelve carts containing dried greenballs which contain magnetite concentrate were loaded in the furnace.

Phase V - Reduction of dried greenballs which contain revert material

In this phase, an investigation was conducted on the effects of (i) furnace temperature, (ii) furnace residence time, (iii) dried greenball molar carbon-to-oxygen ratio, and (iv) initial bed height on the reduction of dried greenballs which contain revert material.

2.0 Natural Resources Research Institute Linear Hearth Furnace

The NRRI Linear Hearth Furnace (LHF) is a pusher-type, moving-hearth furnace capable of performing reduction of iron oxides to metallic iron. The furnace, consisting of three individual heating zones (Zones 1-3) and a final cooling section, is 12.2 m (40 ft.) long, and 0.6 m (2 ft.) wide inside the insulating refractories. A picture of the LHF is shown in Figure 1.

The LHF has undergone several stages of development, transitioning from a walking beam, natural gas-air fired furnace to one with a continuous moving cart system and three distinct combustion systems that can be used individually or in combination. The primary purpose of the furnace was to develop sufficient understanding of the controlling variables associated with taconite iron ore reduction and smelting using carbon-based reductant materials. It has routinely been used to test a variety of the variables shown to be important

from box furnace and tube furnace tests. The laboratory furnaces allow very precise manipulation of key variables under very controlled experimental conditions. The LHF facility allows these basic studies to be expanded to a significantly larger scale and to create bulk samples of product for further testing. The conditions studied in the course of development have shown that metallic iron can be produced with various operating conditions by manipulating the correct variables.

Figure 1 . NRRI Linear Hearth Furnace.

2.1 Zone Control

The LHF consists of three heating zones (Zones 1-3) and a cooling section. The zones are controlled individually according to temperature, pressure, and feed rate, making this furnace capable of simulating several reduced-iron processes and operating conditions. A picture of the LHF heating zone configuration is shown in Figure 2.

- Zone 1 is described as an initial heating, de-volatization, and partial reduction zone. Its purpose is to bring samples to sufficient temperature for drying, removing hydrocarbons and initiating the reduction stages. The burners are operated sub-stoichiometrically to minimize oxygen levels.
- Zones 2 and 3 are described as the reduction zones. The function of these zones is to complete the reduction of iron oxides to wustite (FeO) and metallic iron. For the PSHF

studies, the furnace temperature in Zones 2 and 3 was kept the same throughout the studies.

- It should be noted that the LHF was previously used to make Nodular Reduced Iron (NRI). When the LHF was being used for making NRI, Zone 3 was used for melting of the metallic iron. Thus, in Zone 3, complete reduction of wustite to metallic iron, and fusing of the iron into metallic iron nodules took place.

- The final zone, or Cooling Zone, is a water-jacketed section of the furnace 1.83 m (6 ft) long. The purpose of this zone is to cool the samples. This zone is purged with nitrogen.

Each of the three heated zones has individual temperature and pressure control settings with heating capability of up to 1500^{o}C (2732^{o}F). Each zone has an individual exhaust duct and control damper to manipulate the flow of process gasses. A picture of the furnace exhaust system is shown in Figure 3.

Materials to be processed are loaded into carts, which are passed through the furnace. Residence time of the carts in each of the zones is controlled automatically to simulate any length furnace. The furnace is typically operated in a batch mode because it does not have the capability for continuous feed or product removal; however, on several occasions continuous operation has been simulated by manually inserting each tray or cart in a sequence into the furnace and removing the carts sequentially on the exit end.

2.2 Control System

The control system consists of an ALLEN BRADLEY PLC micro logic controller with RSView HMI (Human Machine Interface). The control system, which has been developed over several years, is user friendly and capable of process simulation. Figures 4 and 5 illustrate the operator interface, which shows screen options for setting furnace temperatures and zone controls.

The control system has been designed with a safety emphasis by adding skin-temperature monitoring, duct-temperature monitoring, gas and combustion-air monitoring, and exhaust-temperature monitoring. As a secondary safety precaution, a barometric leg into a level-controlled water tank has been installed between the common header and exhaust fan to absorb any sudden pressure changes. If any of these features are tripped, the furnace will take the necessary steps to ensure safety including an aggressive shut-down procedure that is automatically engaged.

Figure 2. NRRI LHF heated-zone configuration.

Figure 3. NRRI LHF exhaust duct work.

2.3 Refractory

The LHF is lined with Pyro-Bloc ZR grade ceramic fiber modules designed for a 1500^{o}C (2732^{o}F) maximum operating temperature. The ceramic fiber facilitates the aggressive heating and cooling schedule required on a pilot-scale furnace. The hearth is a Criterion 80XL castable refractory designed for an operating temperature of up to 1538^{o}C (2800^{o}F) with a maximum temperature rating of 1760^{o}C (3200^{o}F). To create thermal storage and minimize temperature

drop, a firebrick refractory has been installed on the inner lining of Zones 2 and 3. Compressed ceramic fiber has been installed around each of the duct transitions from each of the zones in the furnace. The ductwork is designed with a castable spool piece at the furnace discharge, transitioning into a high-alloy stainless steel duct that is quenched with a mist of cooling water. This allows carbon steel to be used in the remaining ducts.

2.4 Gas Analysis

The LHF is equipped with a Laser Gas Analysis (LGA) system. The LGA is a unique gas sampling and analysis system that measures concentrations of eight gasses simultaneously. It includes a completely integrated computer controller and sampling system that rapidly monitors industrial gas process operations. The analyzer has multi-zone sequencing that measures O_2, CO, CO_2, N_2, H_2, NH_3 and C_xH_y. Water vapor is estimated by a calculation using the dew-point temperature. The Laser Gas Analyzer uses Raman Spectroscopy that exploits the phenomenon that gas molecules struck by laser light absorb it and re-emit light at frequencies different from the laser. The differences are so discrete and precise that the intensity of light observed at various shifted frequencies is directly proportional to the concentrations of constituent molecules in the atmosphere. For this analysis, and since the dew-point temperature at 1412^{o}C (2575^{o}F) is impractical to measure, the dew point was estimated at 63^{o}C (145^{o}F) and kept constant for relative comparison. The analyzer and screen display are shown in Figure 6.

Sample plumbing and a valve manifold system connect the detector to the center of furnace Zones 1, 2 and 3 (identified as ports 1, 2, and 4) with an intermediate sampling point between Zones 2 and 3 (port 3). The valve manifold assures that the gas samples drawn from each location are presented uncontaminated to the sampling chamber.

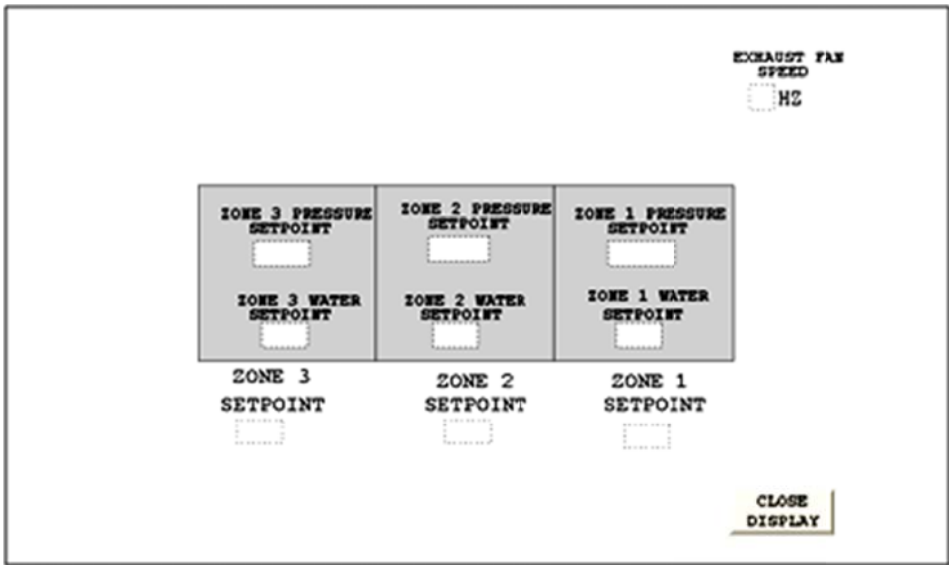

Figure 4. LHF set point control screen.

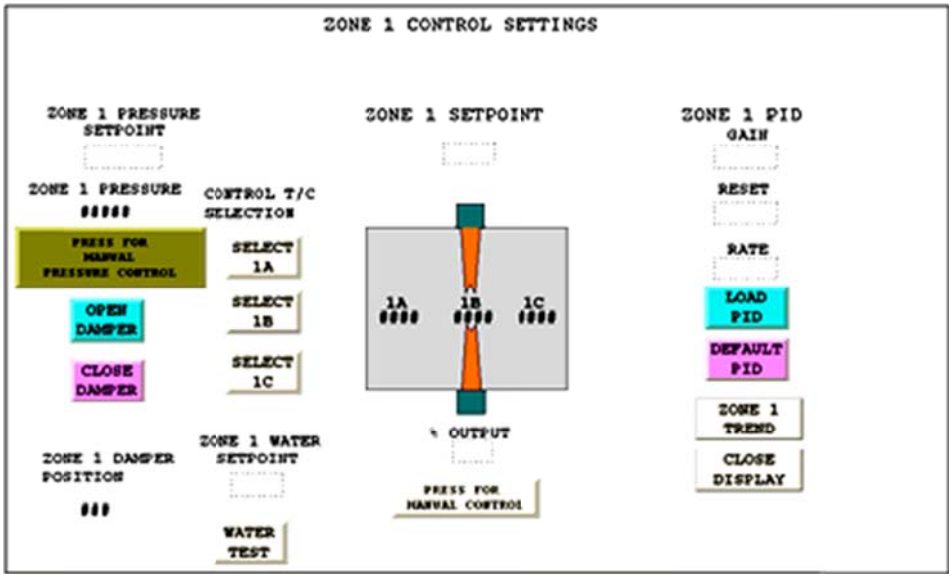

Figure 5. LHF zone control screen.

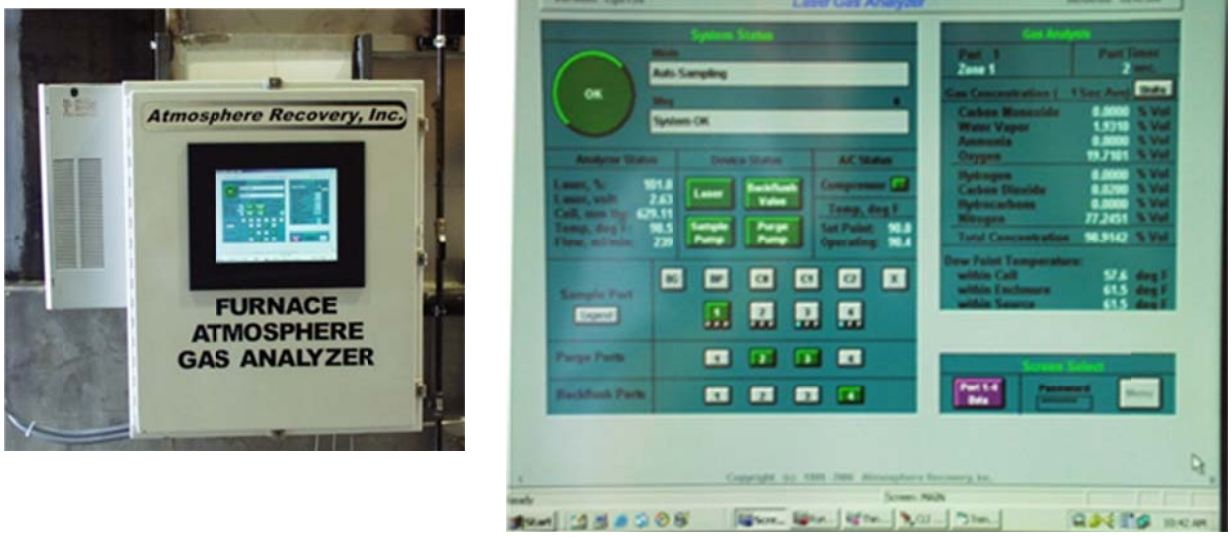

Figure 6. LHF gas analyzer and screen display.

2.5 The Linear Hearth Furnace - Modified Design

Oxygen-fuel burners offer many advantages over air-fuel burners. They are inherently more stable throughout a wide range of operating conditions and excess oxygen ratios. They provide good turndown performance, and can be designed and operated to produce either compact, high-velocity, low-luminosity flames, or, long, highly luminous, low-velocity flames. Oxygen-fuel burners can produce a wide range of oxidizing or reducing products-of-combustion streams. For flexibility, the LHF has been equipped with three distinct combustion systems that can be operated separately or in combination:

- Eclipse natural gas – combustion-air blower system
- Eclipse natural gas – oxygen (oxy-fuel) combustion system
- Maxon pulverized dilute-phase coal – oxygen (oxy-coal) combustion system

2.5.1 Natural Gas – Air Combustion System

The LHF natural gas-air combustion system consists of two Eclipse Thermjet TJ0400, 474,383 kJ/hr (450,000 BTU/hr) natural gas fired burners in each of Zones 1 and 2. Zone 1 is rated for a continuous operating temperature of up to 1316^{o}C (2400^{o}F), while Zone 2 can be continuously operated up to 1500^{o}C (2732^{o}F). Zone 3 is fired by a pair of 1.05 E^{6} kJ/hr (1,000,000 BTU/hr), Eclipse Thermjet TJ1000 burners required to achieve the operating temperatures of 1500^{o}C (2732^{o}F) in a reasonable time to complete testing. A photograph of the Eclipse Thermjet TJ0400 burner is shown in Figure 7.

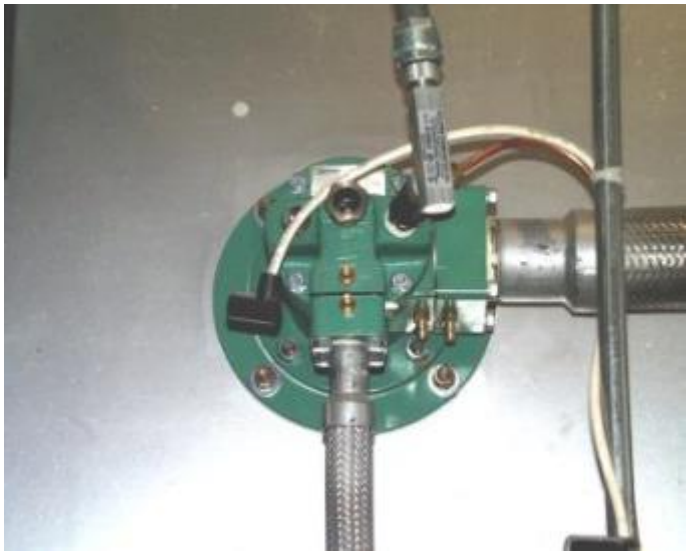

Figure 7. Natural Gas – Air combustion burner.

2.5.2 Oxygen - Natural Gas Combustion System

Based on results from early studies using the LHF, the appropriate design modifications were made for installation of oxy-fuel combustion. Several burner designs were considered. The burner selected was demonstrated at the Eclipse, Inc., development facility in Rockford, IL, in Feb. 2008, and the design was approved for construction. The burner design chosen was an Eclipse Primefire 300 flat-flame burner, located in close proximity to the top of the bed of sample material in the furnace, to take advantage of the highly luminescent flame and the radiant energy associated with the oxygen-fuel combustion. The burner was designed to provide a lazy flame profile that can achieve necessary temperatures without providing oxidants or scrubbing away the atmospheric "boundary layer" established above the samples. Pictures of the burner-flame shape, composed of an inner gas flow with an annular oxygen flow, are shown in Figure 8.

The burners, control system, and oxygen/gas train were sized for application to the LHF. Eight (8) 263,546 kJ/hr (250,000 Btu/hr) oxy-fuel burners were recommended to achieve the desired temperatures. The burners were located as follows: two (2) in each of Zones 1 and 2, and a total of four (4) in Zone 3. Offsetting them from the existing air-fuel burners allowed retention of both combustion systems for comparison studies as shown in Figure 9. The PLC control system was modified to control both systems.

Figure 8. LHF flat flame burner design.

Figure 9. Dual – Combustion system burner arrangement.

The oxygen supply system is composed of a 24 m^3 (6400 gallon) oxygen tank installed on a cement pad just outside the location of the furnace, to comply with NFPA and University code. Figures 10 and 11 show pictures taken during installation of the oxygen tank, and also the completed installation of the oxygen valve train equipped with mass-flow controllers for accurate metering and measurement of both oxygen and natural gas flows.

Figure 10. Bulk oxygen tank installation.

Figure 11. Oxygen – Fuel combustion system valve train.

2.5.3 Dilute Phase Pulverized Coal – Oxygen Combustion System

The LHF is equipped with a dilute-phase, coal-oxygen burner. A 590,343 kJ/hr (560,000 Btu/hr) oxy-coal burner was positioned to fire horizontally from the end of the furnace, down the length of the LHF. The coal is fed from a hopper with a variable-speed screw feeder. The pulverized coal, approximately 80% passing 0.149 mm (100 mesh), is conveyed by an air blower through an eductor system (dilute-phase coal injection) to provide sufficient velocity through the burner. The airflow rate is regulated by a manual gate valve and controlled/measured with an orifice plate installed inline prior to the eductor. A time-weight calibration on the coal

feeder is used to determine the flow rate of pulverized coal, and is controlled by the PLC. Oxygen is also monitored through the PLC control system to match coal addition and to adjust stoichiometry. The feed rate of the coal is regulated to provide a baseline energy load in the LHF, while temperature control is provided through the natural gas-oxygen combustion system. The oxy-coal combustion arrangement is shown in Figures 12 and 13, respectively.

Figure 12. Oxy-coal burner, orifice plate and Eductor system.

Figure 13. Blower for conveying coal.

2.6 Continuous Moving Cart System

The cart system is designed with a hydraulic pusher cylinder cycled from one end to push carts one against the other to move them through the furnace. An indexer on the feed end of the furnace was developed to control the length and number of cycles required by each cylinder to control the cart speed. The carts are recycled underneath the furnace back to the feed end. Carts are either raised or lowered into position using hydraulically driven elevators. The carts are made with carbon-steel frames and are lined with refractory brick on the bottoms and ceramic fiber on the sides to accommodate the aggressive heating and cooling cycles. A sand seal along the length of the furnace and a radiation seal formed by the cart design are used to prevent furnace atmosphere and high temperature from contacting the undercart rails and cart wheels which have graphite bearings. An auxiliary exhaust duct/damper with a pressure sensor was also installed in the undercart region to control the pressure at slightly negative, relative to the furnace proper, to prevent ingress leakage. Pictures of the moving cart system at the furnace entrance and exit are shown in Figures 14 and 15, respectively.

The continuous moving cart design allows the furnace flexibility to simulate several processes. Carts exiting the furnace can be recycled to mimic hot-hearth systems or new carts can be inserted at the entrance to simulate cold-hearth processes.

Figure 14. LHF moving cart system, feed end.

Figure 15. LHF moving cart system, discharge end.

3.0 Experimental

3.1 Raw Materials

Throughout this study, dried greenballs which contain either magnetite concentrate or revert material as an iron oxide source, coal as a reductant, and bentonite as a binder were heated in the LHF to make DRI. The magnetite concentrate was supplied by a taconite operation located in Northern Minnesota. It contained 68.20% iron ($Fe_{(total)}$), and 4.30% silica (SiO_2). Two different revert materials were supplied by a steel company. Both revert materials were basic oxygen furnace (BOF) electrostatic precipitator dust. They were labeled as Revert A, and Revert B. The compositions of these revert materials are shown in Table I. Due to the unforeseen issues with the agglomeration of the Revert A, leading to production of very weak dried greenballs, experiments with the Revert A were suspended until further research could be conducted to optimize its agglomeration. Thus, all the experiments summarized in this report were conducted using Revert B, which had the higher zinc content.

The coal used as a reductant was a pulverized, high-volatile bituminous coal supplied by a steel company. This coal is normally used for coal injection at a blast furnace. Analysis of the coal is shown in Table II.

Table I. Composition of the revert materials received (dry basis).

	Revert A (Wt. %)	**Revert B (Wt. %)**
$Fe_{(total)}$	59.00	61.65
Fe^{++}	18.02	13.70
ZnO	0.26	3.76
SiO_2	1.23	1.15
Al_2O_3	0.06	0.13
MnO	0.73	0.67
CaO	11.33	3.44
MgO	4.29	1.44
Na_2O	0.160	0.566
K_2O	0.156	0.232
S	0.071	0.073
C	0.34	0.370

Table II. Analysis of the high-volatile bituminous coal used as a reductant .

	As Received (Wt. %)	**Dry Basis (Wt.%)**
Moisture	0.73	
Volatiles	36.87	37.14
Fixed Carbon	55.59	56.00
Ash	6.81	6.86
Sulfur	0.80	0.81
Carbon	77.34	77.91

3.2 Dried Greenball Recipes

3.2.1 Dried Greenballs Which Contain Magnetite Concentrate

Throughout these experiments, four different recipes of dried greenballs which contain magnetite concentrate as an iron oxide source, coal as a reducing agent and bentonite as a binder were tested. A summary of these recipes is shown in Table III. These recipes were calculated to produce dried greenballs with four different molar carbon-to-oxygen ratios between 0.9 and 1.2. It should be noted that the molar carbon-to-oxygen ratio was calculated with the consideration of total carbon present in the coal.

Table III. A summary of recipes used for production of dried greenballs which contain magnetite concentrate is shown. These recipes were calculated to produce dried greenballs with four different molar carbon-to-oxygen ratios.

Component	Dried greenballs which contain magnetite concentrate			
	13- 1	**13-2**	**13-3**	**14-6**
Dry wt % Magnetite Concentrate Addition	79.30 %	76.20 %	80.90 %	77.60 %
Dry wt % Coal Addition	20.04 %	23.14 %	18.44 %	21.74 %
Dry wt % Bentonite Addition	0.66 %	0.66 %	0.66 %	0.66 %
Molar C/O Ratio	1.0	1.2	0.9	1.1
Bulk Density (g/cm^3)	1.26	1.25	1.27	1.26

3.2.2 Dried Greenballs Which Contain Revert Material

Throughout these experiments, two different recipes which contain revert material as an iron oxide source, coal as a reducing agent and bentonite as a binder were tested. A summary of the recipes is shown in Table IV. These recipes using revert B were calculated to produce dried greenballs with two different molar carbon-to-oxygen ratios of 1.0 and 1.1. It should be noted that the molar carbon-to-oxygen ratio was calculated with the consideration of total carbon present in the coal.

Table IV. A summary of recipes used for production of dried greenballs which contain revert material is shown. These recipes were calculated to produce dried greenballs with molar carbon-to-oxygen ratios of 1.0 and 1.1.

	Dried greenballs which contain revert	
	Dried Greenballs 14- 8	**Dried Greenballs 14 -5**
Dry wt % Revert Material B Addition	80.14 %	79.00 %
Dry wt % Coal Addition	19.20 %	20.34 %
Dry wt % Bentonite Addition	0.66 %	0.66 %
Molar C/O Ratio	1.0	1.1
Bulk Density (g/cm^3)	1.38	1.37

3.3 Agglomeration

A standardized procedure was used for production of greenballs. An iron oxide source, coal, and bentonite were mixed in a Simpson Muller mixer, and the balls were made using the pilot-scale balling disk. Pictures of the Simpson Muller mixer and the pilot-scale balling disk are shown in Figures 16 and 17, respectively. The greenballs produced were dried in an oven at 100°C. The dried greenballs were sized between 16 mm and 19 mm (5/8 inch to 3/4 inch). The greenballs and dried greenballs were tested to determine physical quality. It can be seen from Table V that the balls had both good green strength and good dry strength.

Figure 16. Pilot-scale Simpson Muller mixer.

Figure 17. Pilot-scale balling disk 0.91 m (3 ft) diameter.

Table V. Green strength and dry strength properties of the greenballs produced. The dried greenball recipes 13-1 and 14-6 were made with magnetite concentrate; greenball recipes 14-5 and 14-8 were made with revert B material as the iron oxide source.

	Dried greenballs which contain magnetite concentrate		**Dried greenballs which contain revert material**	
	Dried Greenball Recipe 13-1	**Dried Greenball Recipe 14-6**	**Dried Greenball Recipe 14-5**	**Dried Greenball Recipe 14-8**
Greenball moisture (%)	10.9	11.8	11.4	11.4
45.7 cm (18 inch) drop strength (Number of Drops)	7.4	5.4	+10	+10
Greenball compression strength (lbs)	5.7	5.8	8.1	10.1
Dried greenball, compression strength (lbs)	20.2	16.3	43.3	42.9

3.4 Loading of the Dried Greenballs in the Carts

The LHF carts are 50.8 cm by 50.8 cm (20 inch by 20 inch) and the active hearth area opening is 40.6 cm by 40.6 cm (16 inch by 16 inch). The active hearth area per cart is 1648 cm^2 (256 in^2). Each cart can accommodate a bed of dried greenballs up to 12.7 cm (5 inches) deep. The dried greenballs were loaded in carts at initial bed heights of either 7.6 cm, 10.2 cm, or 12.7 cm. During one experiment, while using dried greenballs which contain revert material as feed, an initial bed depth of 5.1 cm was also used. The required amount of dried greenballs per cm of bed height was 2.08 kg/cm for dried greenballs which contain magnetite concentrate, and 2.29 kg/cm for dried greenballs which contain revert material.

The weight of material used at each height and the calculated loadings were:

a. For an initial bed height of 7.6 cm (3 inches), either 15.8 kg (95.76 kg/m^2) of dried greenballs which contain magnetite concentrate, or 17.4 kg (105.45 kg/m^2) of dried greenballs which contain revert material was loaded in the carts.

b. For an initial bed height of 10.2 cm (4 inches), either 21.2 kg (128.48 kg/m^2) of dried greenballs which contain magnetite concentrate, or 23.3 kg (141.21 kg/m^2) of dried greenballs which contain revert material was loaded in the carts.

c. For an initial bed height of 12.7 cm (5 inches), either 26.4 kg (160.00 kg/m^2) of dried greenballs which contain magnetite concentrate, or 29.1 kg (176.36 kg/m^2) of dried greenballs which contain revert material was loaded in the carts.

Dried greenballs were loaded onto hot carts using at least two plastic buckets. Prior to loading, dried balls were screened to remove any fines that might have been present. The pre-heated cart was positioned on the elevator at the furnace entrance beneath the exhaust hood. The required amount of dried balls was poured carefully into the cart from the plastic buckets by two technicians to minimize the loading time. The dried balls were leveled by hand to ensure a uniform bed height across the carts prior to moving the carts into the furnace.

3.5. Linear Hearth Furnace Operation

Throughout this study the burners located at Zone 1 were not operated. Heating of Zone 1 was accomplished by the excess heat escaping from Zones 2 and 3. It was observed that when the burners were operated in Zone 1, the zone would overheat. Then the furnace safety feature would activate, shut down the burners, and purge the furnace.

Furnace temperatures at Zones 2 and 3 were set to be run at a certain set point temperature, and the combination of Zones 2 and 3 was called the “hot-zone.” The cart speeds through these zones were adjusted separately. Carts were pushed through Zone 1 in 5-10 minutes as required by the PSHF process. The speed of the carts throughout the hot-zone was adjusted according to the required residence times of 40 to 120 minutes. A separate series of experiments was conducted solely to determine the required cart speeds in the cooling zone.

For all experiments, carts lined with high-density alumina bricks on the bottoms were used. Prior to each experiment, the carts were pre-heated by cycling through the furnace three times to ensure that the dense alumina brick at the bottom of the carts was soaked with heat. After each cart passed through the furnace, it was covered with a loose ceramic fiber blanket to retain heat as the cart moved from the exit end of the furnace to the entrance end. The measured temperature on the refractory bricks at the bottom of the recycled carts was slightly higher than 800°C (about 1500°F) just before the fiber blankets were removed and before the carts were loaded with dried greenballs.

The burners located at Zones 2 and 3 were operated under sub-stoichiometric conditions. Carts containing anthracite coal were passed through the furnace before and after the sequence of test carts to be able to simulate a steady state furnace atmosphere. Furnace atmosphere conditions throughout the experiments were monitored. Oxygen content measured throughout the experiments was zero. In the cooling zone, nitrogen was introduced to replace any oxygen that might have been present. The furnace was operated at a slightly positive pressure. No leakage of process gasses was observed in the furnace building.

3.6. Sampling of the DRI Produced

DRI produced throughout the experiments was sampled from the top, middle and bottom of the bed. Samples were analyzed for total iron (% $Fe_{(total)}$), divalent iron (% Fe^{++}), metallic iron (% Fe^{0}), sulfur (% S), and carbon (% C). In addition, percent metallization at the top, middle and bottom of the bed was calculated. For DRI produced using dried greenballs which contained revert material, the DRI was also analyzed for zinc (% Zn) and lead (% Pb) content.

4.0 Results and Discussion

4.1 Phase I - Modifications to the LHF

During the first phase of the study, modifications were made to the LHF to simulate conditions required for the PSHF process. The existing configuration with three equal zone lengths separated by refractory baffle walls was maintained to avoid structural issues.

Modifications to the furnace included, (i) installation of new furnace refractories to accommodate high operating furnace temperatures (1500°C (2732°F)) required by the PSHF process, (ii) the exhaust duct was relocated to Zone 3 to allow for co-current flow, (iii) the ceramic fiber refractory on the furnace cart system was modified to accommodate a deeper initial bed of dried greenballs, (iv) a single layer of dense high alumina brick was placed at the bottom of the carts to imitate a castable or solid brick refractory hearth for heat retention, and (v) an exhaust hood was fabricated and installed to contain emissive gasses from the hot carts during loading of the dried greenballs.

4.2 Phase II – Identification of Operational Conditions

The second phase of the study included identification of LHF operational conditions. During this phase, experiments were conducted to determine operational conditions such as: damper positions, fan speeds, cooling rate, cart speeds at Zones 1, 2, and 3, and cooling to achieve required residence time, as well as burner oxygen-to-gas ratios required to simulate the PSHF process. In this phase of the study, experiments were conducted to determine the residence times required at the LHF cooling zone. In addition, experiments were also conducted

with two different types of carts, to determine the effects of heat retention on the sides of the carts on the DRI quality.

4.2.1 DRI Cooling

A series of experiments was conducted to determine the effects of cooling on DRI quality, and appropriate methods for cooling. Initial experiments included varying the residence time in the cooler. For these experiments, dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0) were heated at a furnace temperature of 1500°C, residence time of 80 min, and initial bed height of 12.7cm. After heating, residence time in the cooler zone was varied to either 15 min (fast cooling) or 45 min (slow cooling). The LHF cooler was purged with nitrogen, to replace any oxygen that would be available for re-oxidizing the DRI. A summary of the experimental findings is given in Table VI. Pictures of DRI produced are shown in Figures 18 A and B. The DRI which had a short residence time (fast cooling) in the cooler is shown in Figure 18 A, and the DRI which had a longer residence time (slow cooling) in the cooler is shown in Figure 18 B. The DRI which had a short residence time in the cooler had a bright orange glow at the bottom of the bed. On the other hand, the DRI which had a longer residence time in the cooler had colder temperatures at the bottom. It can be seen from Table VI that DRI carbon content at the bottom of the bed increased with longer residence time in the cooler. This is because, at a shorter cooler residence time, DRI temperature at discharge was sufficient for carbon combustion. In addition, slightly higher levels of percent metallization were observed for DRI which had longer cooler residence time. This might be due to re-oxidation of the DRI. Thus, it was concluded that DRI quality increased with longer residence times in the cooler.

Additional tests were conducted to further optimize cooling of the DRI. For these experiments, a hood was constructed and positioned external to the furnace. The DRI samples discharged from the LHF cooler were shoveled out from the carts, put in trays and placed under the hood. The hood was purged with nitrogen. For these experiments, dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O = 1.1) at an initial bed height of 7.6 cm were heated at a furnace temperature of 1500°C and a residence time of 80 min. Pictures of DRI produced, and the procedure for shoveling the DRI out of the carts and placing it under the hood with nitrogen purge are shown in Figure 19. Minimal re-oxidation was observed for this sample. Thus, for future studies, a greater amount of focus should be given to methods for cooling the samples rapidly while eliminating re-oxidation. In this report, the cooling method for the specific samples will be indicated in the text and figure captions.

Table VI. A summary of the experimental findings, for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0), at an initial bed height of 12.7 cm, and furnace temperature of 1500°C, and residence time of 80 min. The DRI was cooled in the LHF cooler. For these samples, the residence time in the cooler was varied.

For the DRI sampled from the top of the bed,

Residence Time in the LHF Cooler	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
Short – 15 min	88.64	78.53	88.59	8.13	0.023	0.148
Long – 45 min	89.64	80.85	90.19	8.60	0.026	0.171

For the DRI sampled from the middle of the bed,

Residence Time in the LHF Cooler	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
Short – 15 min	83.63	67.33	80.51	7.24	0.022	0.158
Long – 45 min	84.41	69.38	82.19	5.99	0.049	0.173

For the DRI sampled from the bottom of the bed,

Residence Time in the LHF Cooler	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
Short – 15 min	64.77	2.7	4.17	9.08	1.96	0.108
Long – 45 min	62.18	7.77	12.50	15.41	5.80	0.145

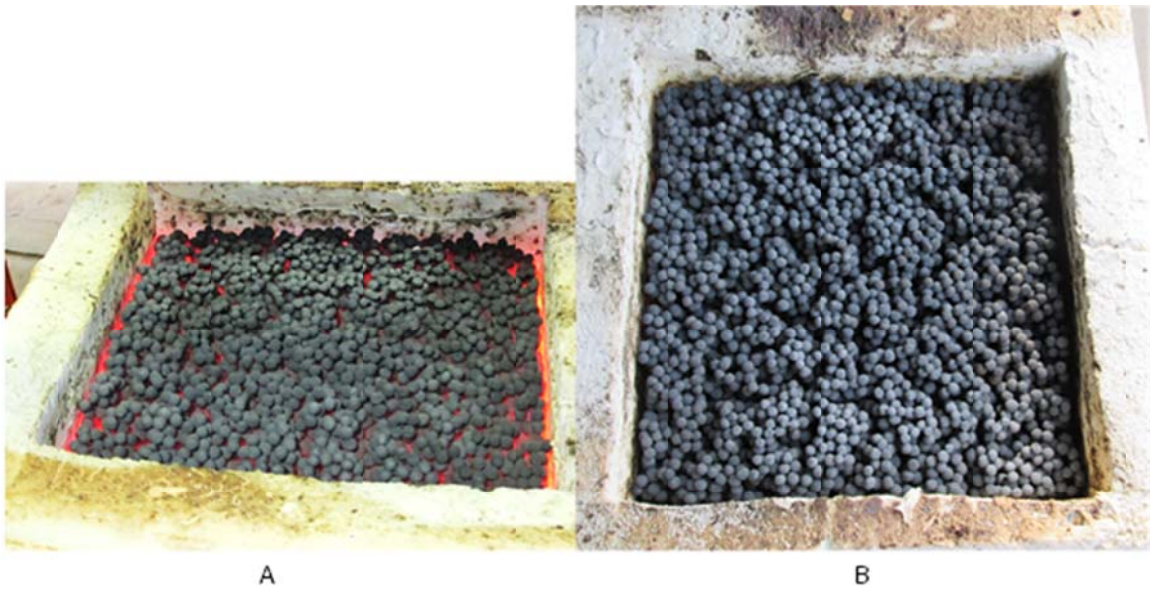

Figure 18. DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0) at an initial bed height of 12.7 cm, furnace temperature of 1500°C, and residence time of 80 min. The DRI shown in A was cooled in the LHF cooler at short residence time. The DRI shown in B was cooled in the LHF at long residence time.

Figure 19. DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm, and furnace temperature of 1500°C, and residence time of 80 min. The DRI was cooled in the LHF cooler (long residence time) then shoveled out of the cart into a pan. The pan was placed under the cooling hood, and purged with nitrogen for complete cooling of the DRI.

4.2.2 Sample Carts

A series of experiments was conducted to determine whether sample carts that have high-density alumina bricks installed at the sides would be beneficial for production of high-quality DRI. A schematic drawing of the sample carts is shown in Figure 20. For both types of sample carts, the opening in the center where the dried greenballs were loaded had the same dimensions (40.6 cm x 40.6 cm).

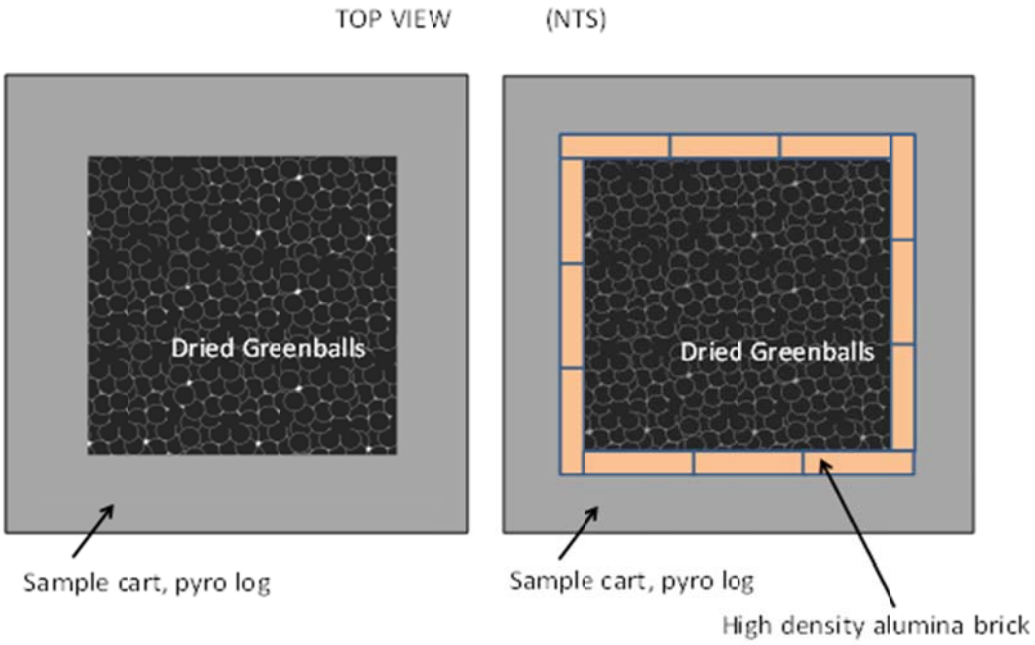

Figure 20. A schematic drawing of the two different types of carts used for the experiments.

Throughout these experiments, dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0) were heated at an initial bed height of 12.7 cm, furnace temperature of 1500°C, and residence time of 80 min. A summary of the experimental findings is given in Table VII. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time. Pictures of DRI produced are shown in Figures 21 and 22. It was observed that DRI produced in the cart with alumina bricks on the sides had more horizontal shrinkage, was more compact, and generated less fines. In addition, DRI located at the top and middle of the bed had a higher percent metallization. Further studies should be conducted to investigate the effects of side heating on the reduction kinetics.

Table VII. A summary of the experimental findings, for DRI produced using either normal pyro-log carts or carts with alumina brick on the sides. Dried greenballs which contain magnetite concentrate were used as feed material. They were heated at an initial bed height of 12.7 cm, a furnace temperature of 1500°C, and a residence time of 80 min.
DRI produced was cooled in the LHF cooler.

For the DRI sampled from the top of the bed,

Sample Cart Type	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
Normal	89.64	80.85	90.19	8.60	0.026	0.171
Brick Sides	90.38	83.31	92.18	7.16	0.036	0.139

For the DRI sampled from the middle of the bed,

Sample Cart Type	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
Normal	84.41	69.38	82.19	5.99	0.049	0.173
Brick Sides	86.77	77.67	89.51	4.68	0.047	0.144

For the DRI sampled from the bottom of the bed,

Sample Cart Type	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
Normal	62.18	7.77	12.50	15.41	5.80	0.145
Brick Sides	62.90	7.87	12.51	11.84	4.48	0.128

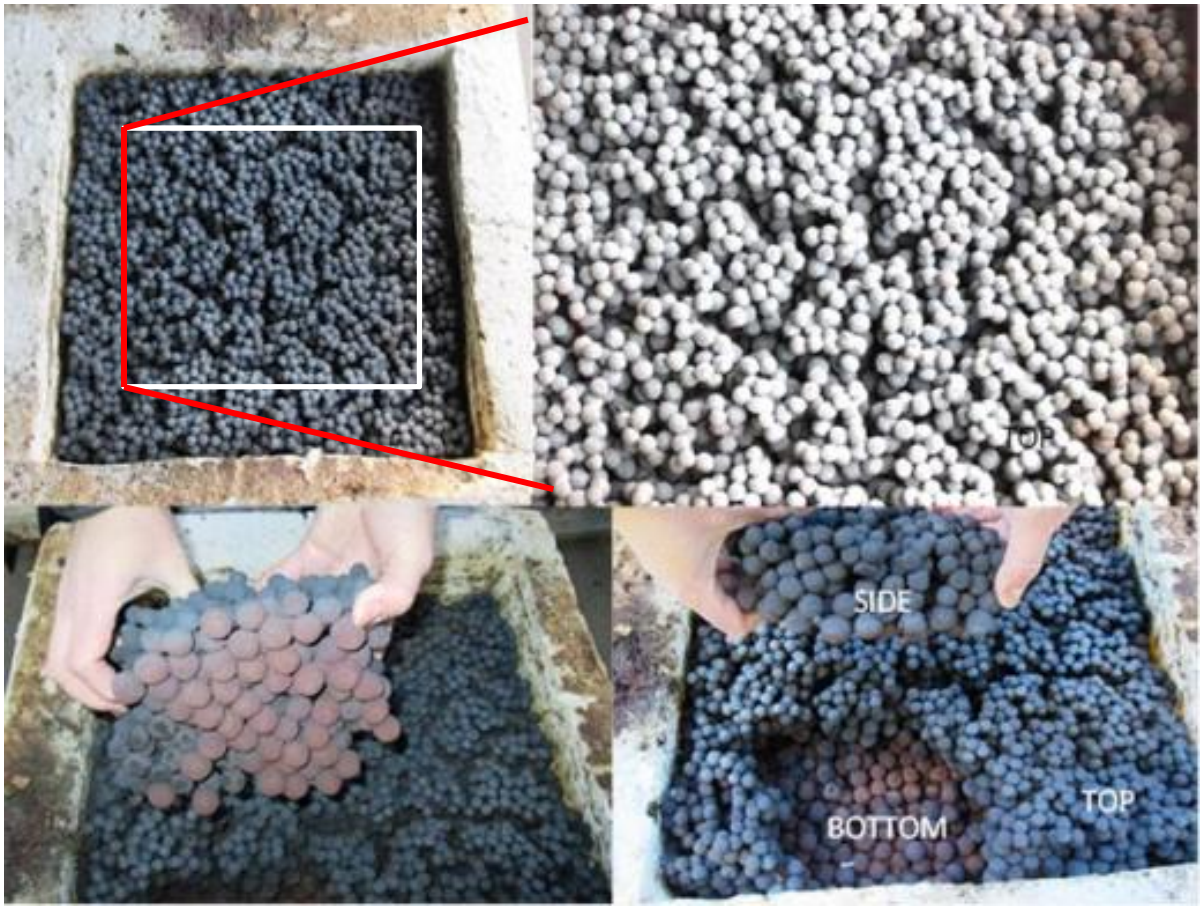

Figure 21. DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0) at an initial bed height of 12.7 cm, a furnace temperature of 1500°C, and a residence time of 80 min. The DRI was cooled in the LHF cooler (long residence time). A normal, pyro -log cart was used for placing the dried greenballs in the LHF.

Figure 22. DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0) at an initial bed height of 12.7 cm, a furnace temperature of 1500°C, and a residence time of 80 min. The DRI was cooled in the LHF cooler (long residence time). A cart with sides of alumina brick was used for placing the dried greenballs in the LHF.

4.3 Phase III—Experiments with Dried Greenballs which contain Magnetite Concentrate

4.3.1 Effect of Residence Time at Three Temperatures on the DRI Quality (7.6 cm Bed Height)

A series of experiments was conducted using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm, furnace temperatures of 1400°C, 1450°C, and 1500°C, and various residence times, to investigate the effects of furnace hot-zone residence time on the quality of DRI produced. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time, and then shoveled out of the carts and further cooled under the hood. A summary of the experimental findings is given in Table VIII. A picture of DRI produced at a furnace temperature of 1500°C and residence time of 80 min is shown in Figure 23. This DRI had the highest percent metallization when compared with the other DRI produced in this series of experiments.

It can be seen from Figure 23 that some of the individual DRI balls had holes in them. These DRI balls were located at the bottom of the bed; it appeared that these DRI balls had metallized shells, and fines at the center. Further studies should be conducted to investigate the formation mechanism of these holes, and their relationship with fines generation at the bottom of the bed.

The relationship between percent metallization of the DRI and furnace hot-zone residence time at a furnace hot-zone temperature of 1400°C is plotted in Figure 24. It can be seen from Figure 24 that as the furnace residence time increases, percent metallization of the DRI at both the middle and the bottom of the bed increases considerably. On the other hand, although an increase in the percent metallization of the DRI at the top of the bed is observed, the increase was not as significant as the increase observed for either the middle or bottom of the bed. The relationship between percent metallization of the DRI and furnace hot-zone residence time at a furnace hot-zone temperature of 1450°C is plotted in Figure 25. It can be seen from Figure 25 that as the residence time increases, a slight increase in the percent metallization of the DRI is observed.

Table VIII. A summary of the experimental findings for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm and various furnace temperatures and residence times.

For the DRI sampled from the top of the bed,

Furnace Temp (°C)/Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1400°C / 50 min	78.10	59.92	76.72	17.91	2.080	0.124
1400°C / 80 min	84.33	66.47	78.85	15.83	0.020	0.126
1400°C / 100min	85.17	67.74	79.54	17.09	0.052	0.045
1450°C / 50 min	79.77	67.23	84.28	7.85	1.150	0.263
1450°C / 80 min	86.06	75.97	88.28	6.20	0.237	0.181
1450°C / 100min	87.59	76.33	87.14	3.88	0.250	0.172
1500°C / 80 min	88.80	79.23	89.22	9.35	0.021	0.084

Table VIII cont. A summary of the experimental findings for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm and various furnace temperatures and residence times.

For the DRI sampled from the middle of the bed,

Furnace Temp (°C)/Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1400°C / 50 min	67.37	19.16	28.44	12.33	5.730	0.137
1400°C / 80 min	80.95	36.89	45.57	6.84	0.504	0.140
1400°C / 100min	83.42	47.98	57.52	15.11	0.012	0.140
1450°C / 50 min	80.47	67.22	83.53	10.86	0.027	0.273
1450°C / 80 min	82.35	70.58	85.71	9.81	0.039	0.194
1450°C / 100min	85.43	74.07	86.70	8.61	0.019	0.182
1500°C / 80 min	84.20	73.52	87.32	7.73	0.034	0.178

For the DRI sampled from the bottom of the bed,

Furnace Temp (°C)/Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1400°C / 50 min	55.73	1.27	2.28	9.74	11.70	0.139
1400°C / 80 min	63.06	7.39	11.72	11.31	7.55	0.174
1400°C / 100min	80.13	38.08	47.52	12.40	0.011	0.175
1450°C / 50 min	83.06	65.57	78.94	12.91	0.022	0.207
1450°C / 80 min	87.85	69.24	78.82	15.44	0.044	0.083
1450°C / 100min	87.27	67.53	77.38	15.14	0.031	0.081
1500°C / 80 min	80.10	69.08	83.22	6.82	1.75	0.164

Figure 23. DRI produced at a furnace temperature of 1500°C and residence time of 80 min using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1). DRI was cooled in the LHF cooler at a long residence time, and then it was shoveled into a tray and further cooled in nitrogen under the external hood. The bed height was 7.6 cm.

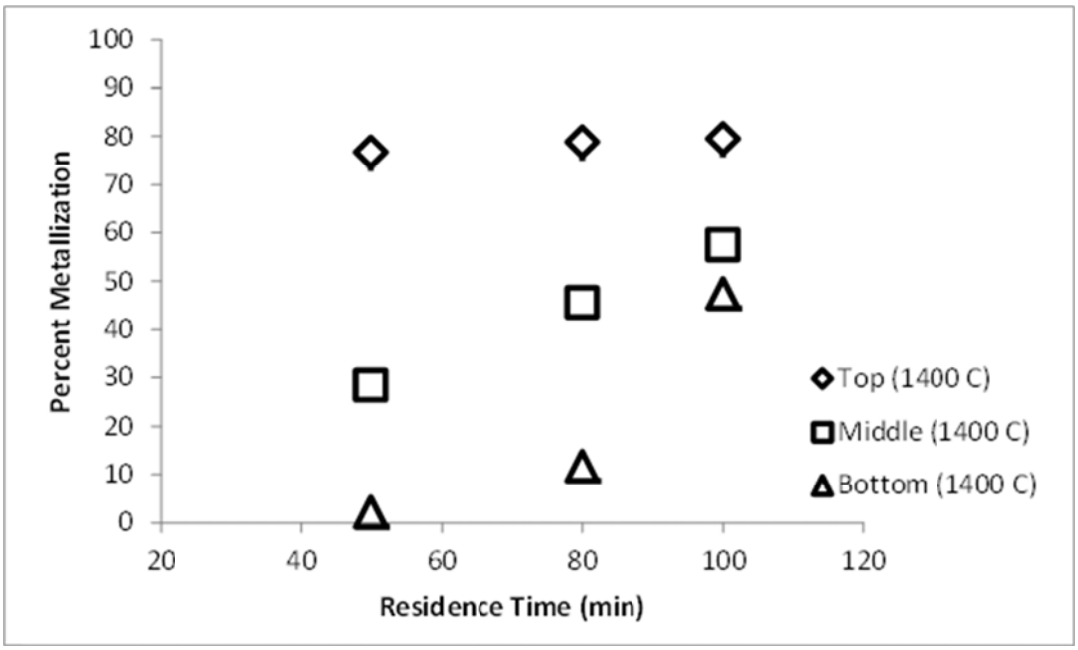

Figure 24. Relationships between percent metallization and furnace hot-zone residence time for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at a furnace hot-zone temperature of 1400°C (2552°F). The bed height was 7.6 cm.

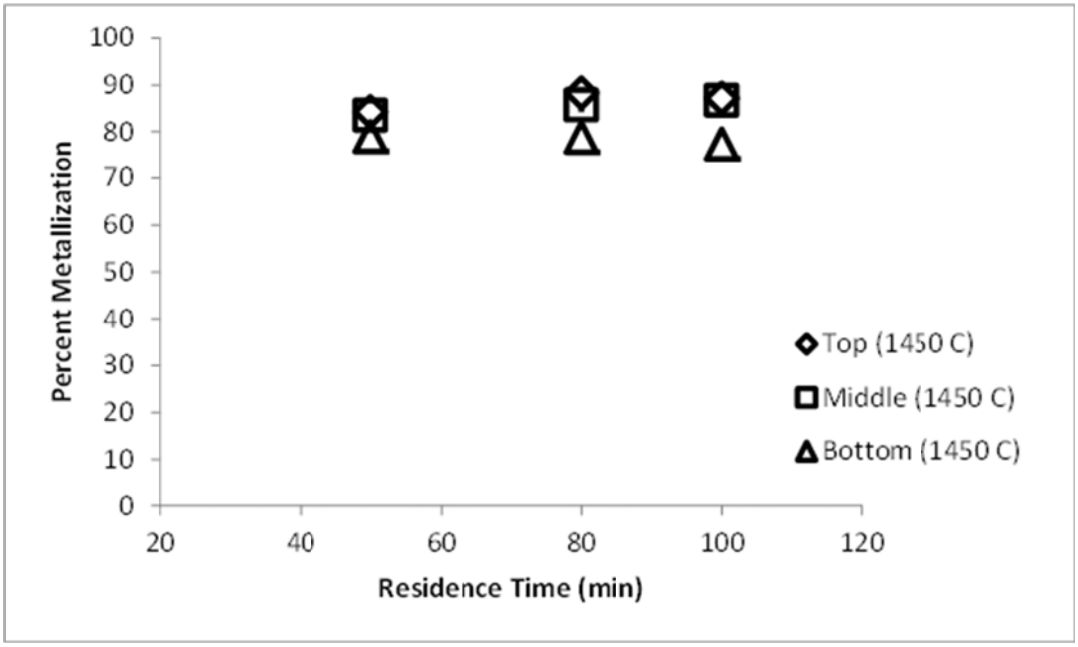

Figure 25. Relationships between percent metallization and furnace hot-zone residence time for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at a furnace hot-zone temperature of 1450°C (2642°F). The bed height was 7.6 cm.

4.3.2 Residence Time Required for High Quality DRI Production

A series of experiments was conducted using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at furnace temperatures of 1400°C, 1450°C, and 1500°C, and various residence times, to determine the optimum residence time required for high-quality DRI production with a 7.6 cm bed height. Relationships between percent metallization of DRI located at the top, middle and bottom of the bed at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C, and furnace hot-zone residence times of 50 min, 80 min, and 100 min are plotted in Figures 26, 27, and 28, respectively.

For DRI produced at furnace hot-zone temperatures of 1450°C and 1500°C, the percent metallization at the top, middle and bottom of the bed does not change considerably with increased furnace residence time. On the other hand, for DRI produced at a furnace hot-zone temperature of 1400°C, as the furnace residence time increased, a considerable increase in the percent metallization of DRI located at top, middle and bottom of the bed was observed. Thus, it can be concluded that the reduction of the dried greenballs which contain magnetite concentrate is influenced more by the furnace hot-zone temperature rather than the furnace residence time. Furnace temperatures higher than 1450°C are more favorable for high-quality DRI production.

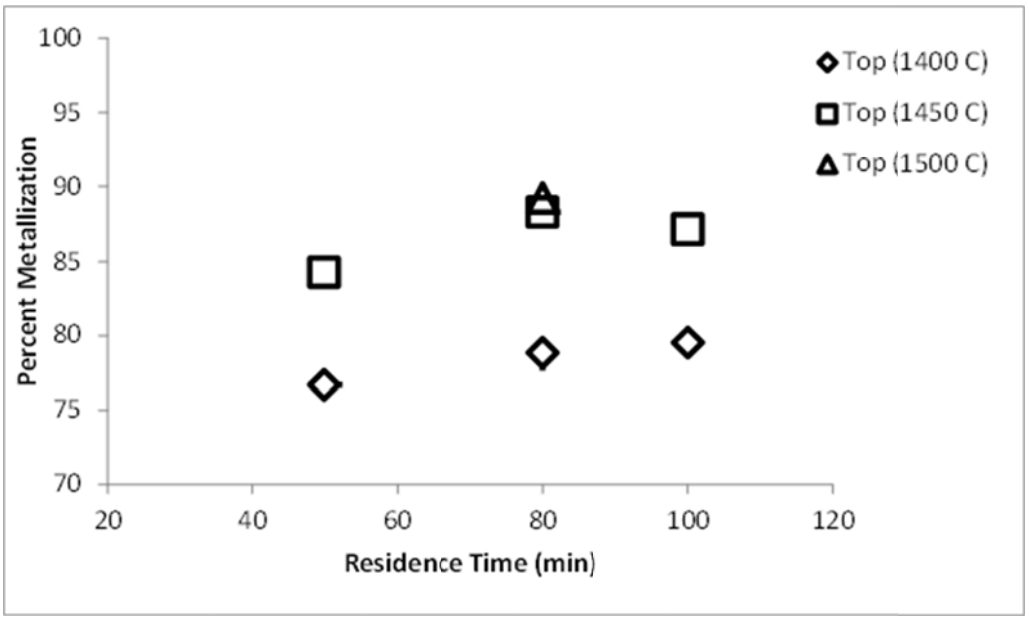

Figure 26. Relationships between percent metallization of DRI located at the top of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C. The bed height was 7.6 cm.

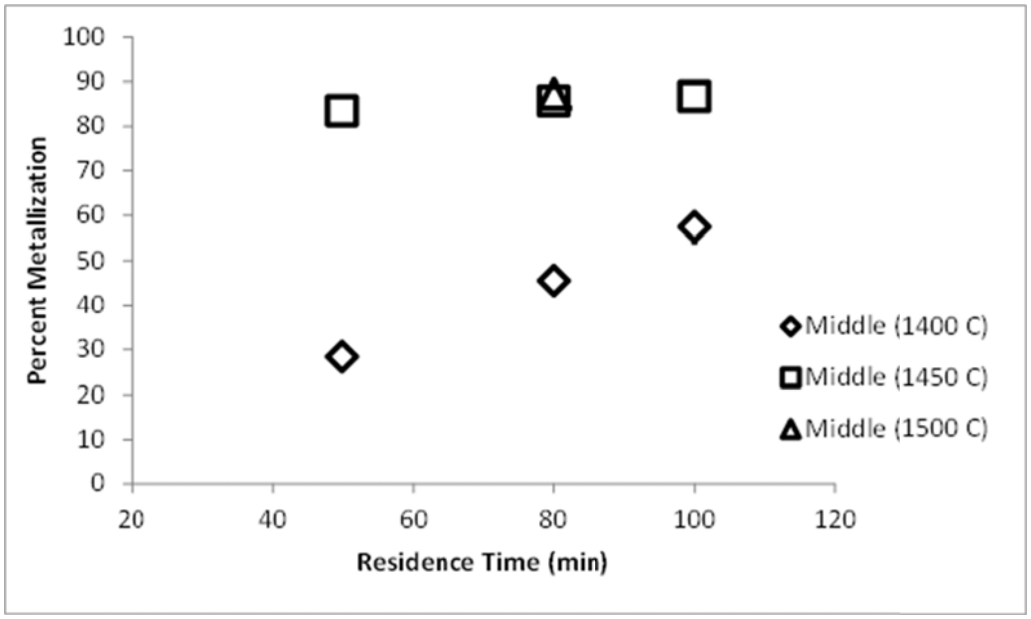

Figure 27. Relationships between percent metallization of DRI located at the middle of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C. The bed height was 7.6 cm.

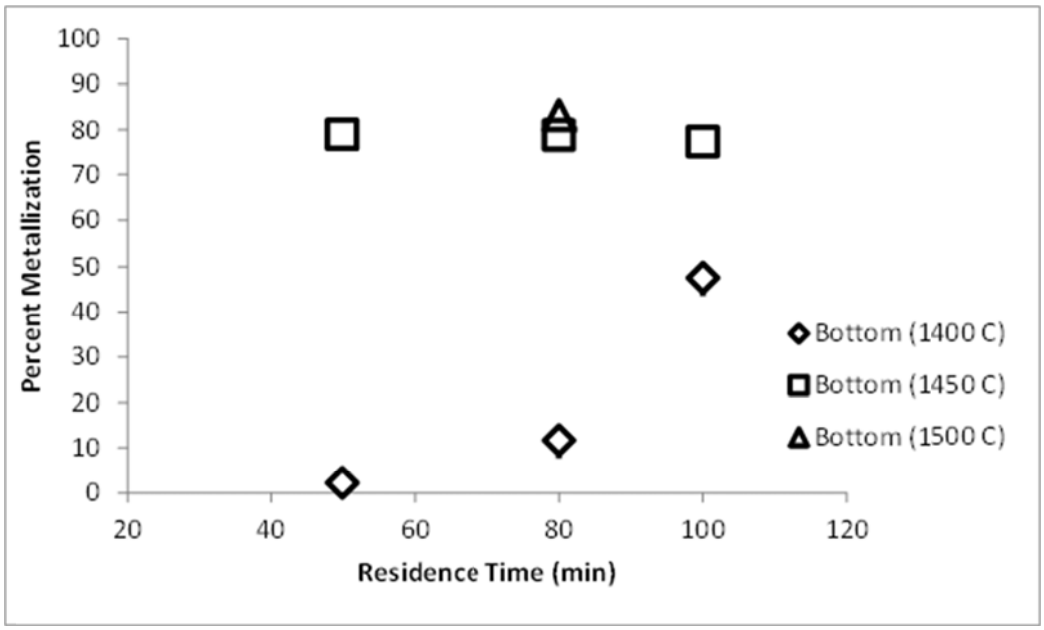

Figure 28. Relationships between percent metallization of DRI located at the bottom of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C. The bed height was 7.6 cm.

4.3.3 Effect of Furnace Temperature on the DRI Quality

A series of experiments was conducted using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm, furnace residence times of 50 min, 80 min, and 100 min, and various furnace hot-zone temperatures, to investigate the effects of furnace hot-zone temperature on the quality of DRI produced. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time, shoveled into trays, and further cooled in nitrogen under the external hood.

The relationships between percent metallization of the DRI and furnace hot-zone temperature at furnace hot-zone residence times of 50 min, 80 min, and 100 min are plotted in Figures 29, 30, and 31, respectively. It can be seen from these figures that as the furnace hot-zone temperature increases to 1450°C, the percent metallization at the middle and bottom of the bed increases considerably, and the percent metallization at the top of the bed increases slightly.

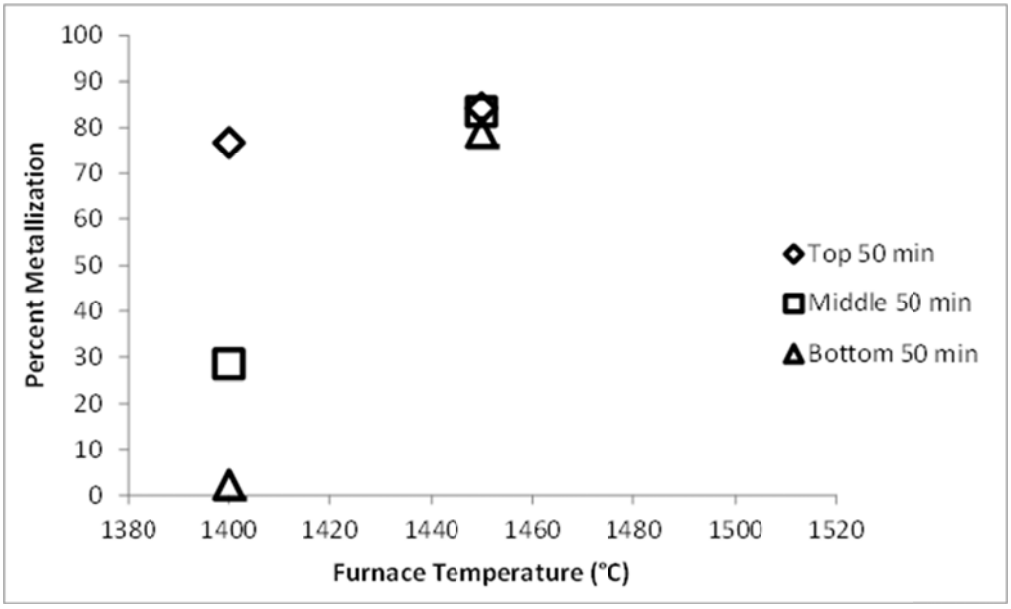

Figure 29. Relationships between percent metallization and furnace hot-zone temperature for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at a constant furnace hot-zone residence time of 50 min. Bed height was 7.6 cm.

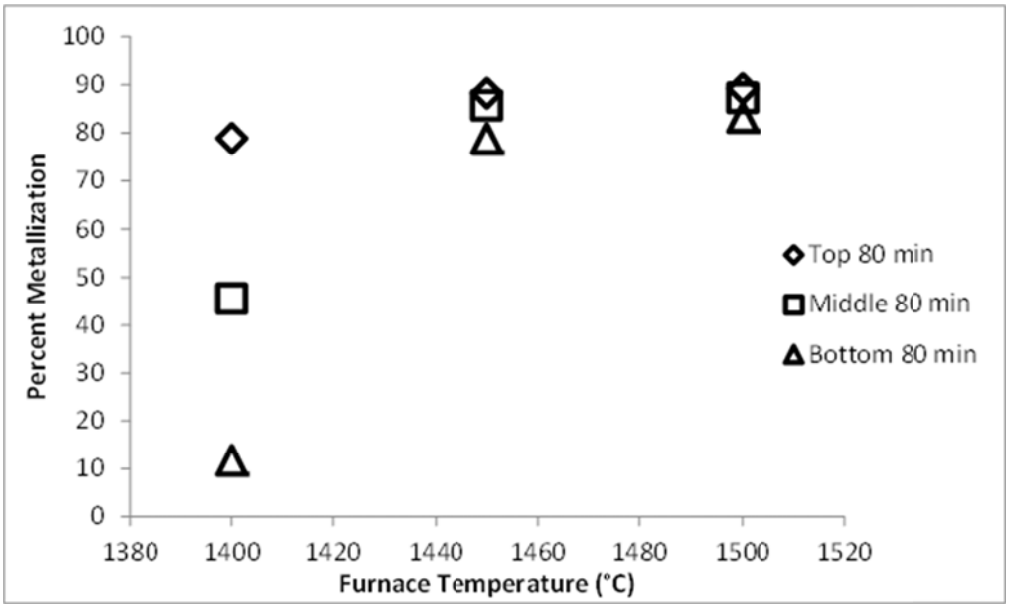

Figure 30. Relationships between percent metallization and furnace hot-zone temperature for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at a constant furnace hot-zone residence time of 80 min. Bed height was 7.6 cm.

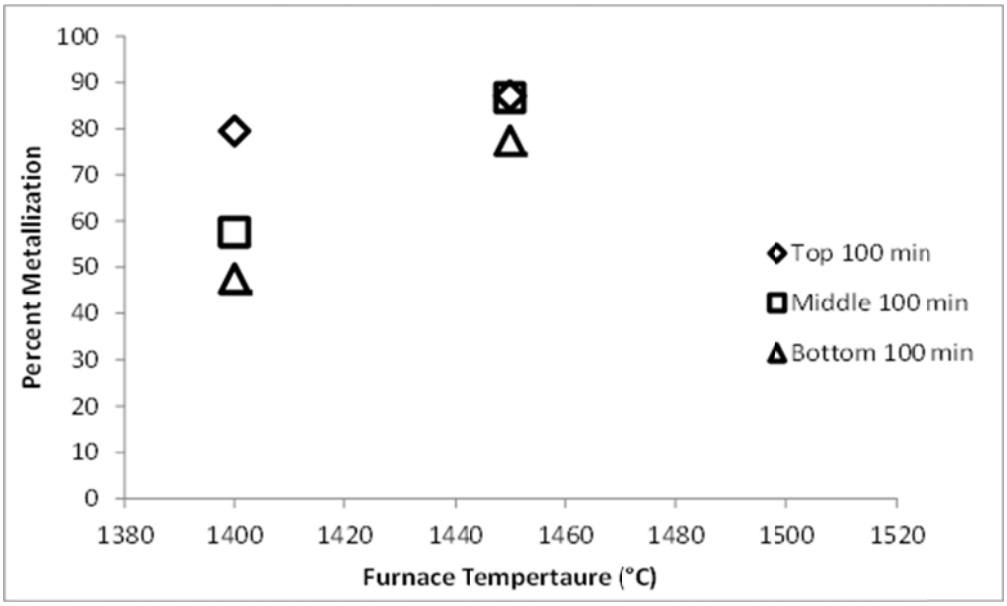

Figure 31. Relationships between percent metallization and furnace hot-zone temperature for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at a constant furnace hot-zone residence time of 100 min. Bed height was 7.6 cm.

4.3.4 Furnace Temperature Required For High-Quality DRI Production

A series of experiments was conducted using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio =1.1) at furnace residence times of 50 min, 80 min, and 100 min, and various hot-zone temperatures, to determine the optimum furnace hot-zone temperature required for high-quality DRI production with a bed height of 7.6 cm. Relationships between percent metallization of DRI located at the top, middle and bottom of the bed, at furnace hot-zone residence times of 50 min, 80 min, and 100 min, and several furnace temperatures, are plotted in Figures 32, 33, and 34, respectively. It can be seen from these figures that considerable increases in the percent metallization of DRI located at the middle and bottom of the bed, and a slight increase in percent metallization of DRI located at the top of the bed, were observed when the furnace hot-zone temperature was increased from 1400°C to 1450°C. The one experiment conducted at a furnace temperature of 1500°C and 80 min residence time indicated that the additional change in percent metallization was not very significant. Thus, it can be concluded that a 1450°C hot-zone temperature might be sufficient for production of high quality DRI when the initial bed height is 7.6 cm.

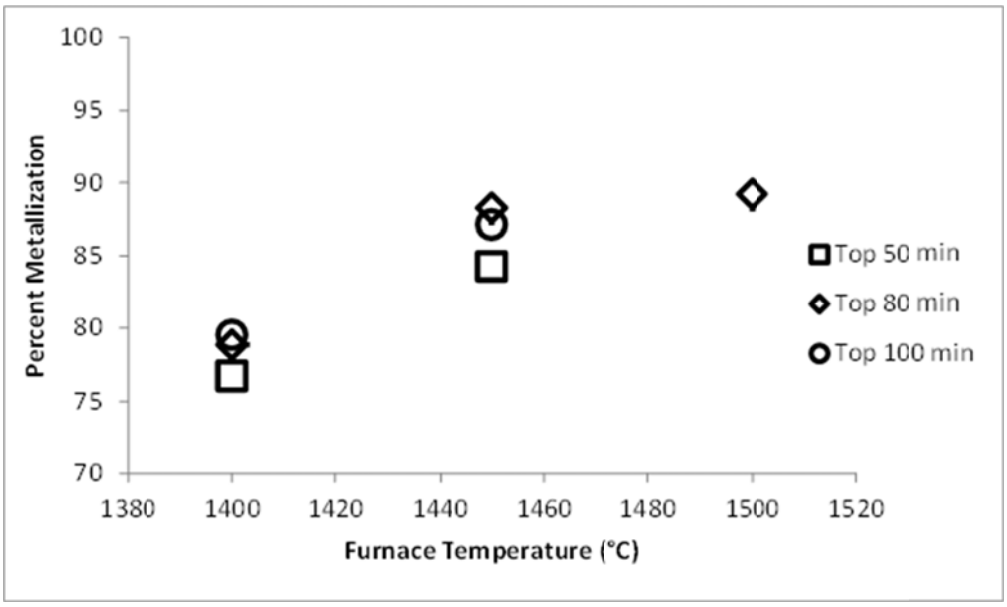

Figure 32. Relationships between percent metallization of DRI located at the top of the bed and furnace hot-zone temperature for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at furnace hot-zone residence times of 50 min, 80 min, and 100 min. Bed height was 7.6 cm.

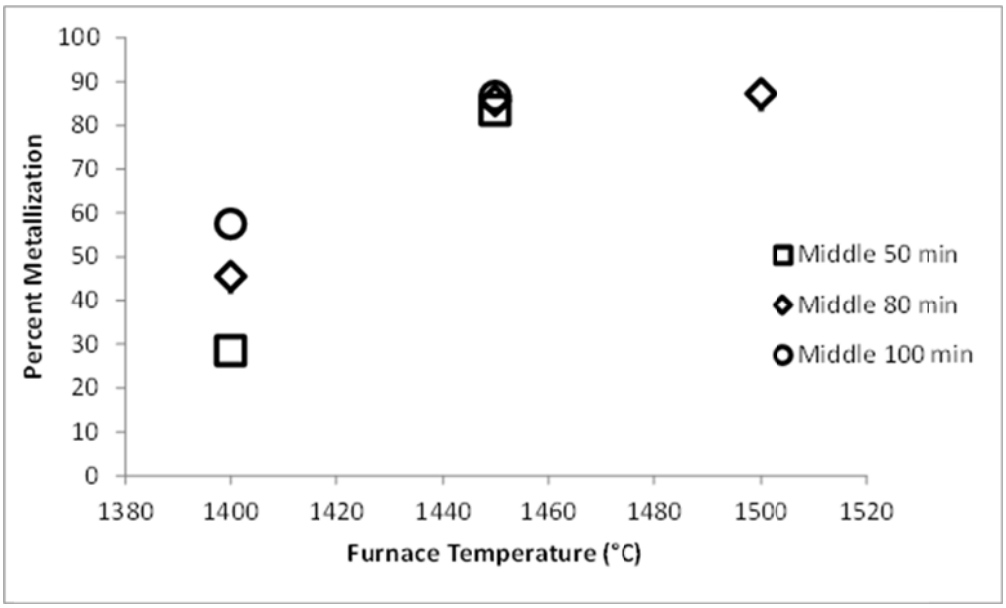

Figure 33. Relationships between percent metallization of DRI located at the middle of the bed and furnace hot-zone temperature for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at furnace hot-zone residence times of 50 min, 80 min, and 100 min. Bed height was 7.6 cm.

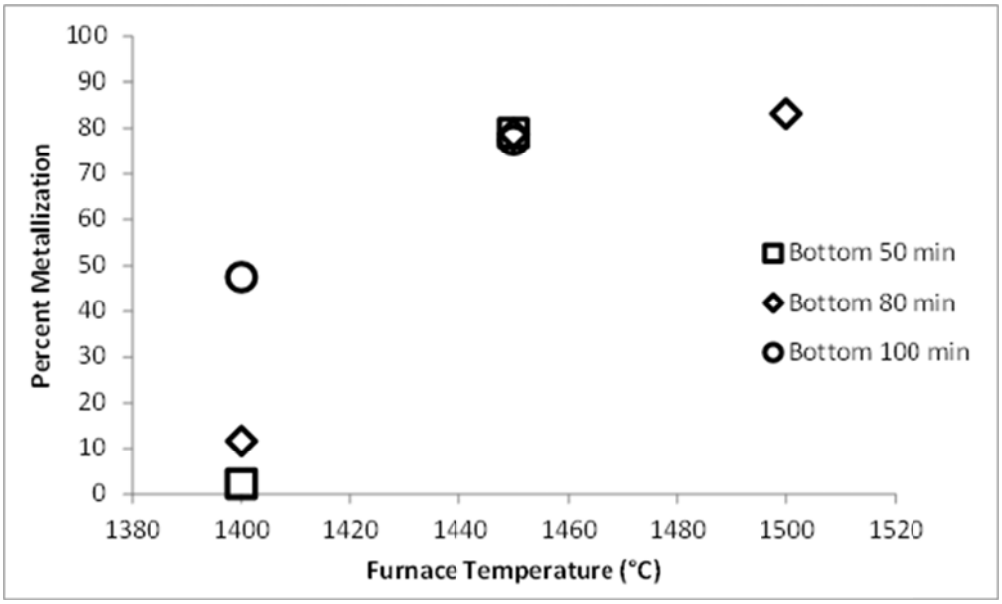

Figure 34. Relationships between percent metallization of DRI located at the bottom of the bed and furnace hot-zone temperature for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio = 1.1) at furnace hot-zone residence times of 50 min, 80 min, and 100 min. Bed height was 7.6 cm.

4.3.5 Effect of Dried Greenball Molar Carbon-to-Oxygen Ratio on DRI Quality

A series of experiments was conducted to determine the effects of molar carbon-to-oxygen ratio of dried greenballs made with magnetite on the quality of DRI produced. The dried greenballs which contain magnetite concentrate used for these experiments had molar carbon-to-oxygen ratios of 0.9, 1.0, 1.1, or 1.2. The dried greenballs were heated at a furnace hot-zone temperature of 1500°C, with a residence time of 80 min and an initial bed height of 7.6 cm. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time. A summary of the experimental findings is given in Table IX.

The relationship between percent metallization of DRI located at the top, middle and bottom of the bed and greenball molar carbon-to-oxygen ratio is shown in Figure 35. It can be seen from Figure 35 that as the molar carbon-to-oxygen ratio of the greenballs increases from 1.0 to 1.1, percent metallization increases considerably. On the other hand, the increase in percent metallization with an increase in molar carbon-to-oxygen ratio from either 0.9 to 1.0 or 1.1 to 1.2 is not as great. Thus, it can be concluded that the dried greenballs with a molar carbon-to-oxygen ratio of 1.1 are well suited for DRI production at an initial bed height of 7.6 cm. Further studies should be conducted to determine the optimum molar carbon-to-oxygen ratio for dried greenballs with other initial bed heights.

Table IX. A summary of the experimental findings for DRI produced using dried greenballs which contain magnetite concentrate at various molar carbon-to-oxygen ratios, a furnace temperature of 1500°C, and a residence time of 80 min.

For the DRI sampled from the top of the bed,

Molar C/O Ratio	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
0.9	89.60	67.53	75.37	20.70	0.027	0.057
1.0	88.41	71.49	80.86	13.16	0.021	0.073
1.1	88.80	79.23	89.22	9.35	0.021	0.084
1.2	89.72	79.96	89.12	9.17	0.014	0.127

For the DRI sampled from the middle of the bed,

Molar C/O Ratio	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
0.9	87.83	68.71	78.23	15.64	0.017	0.109
1.0	83.46	65.87	78.92	15.61	0.012	0.165
1.1	84.20	73.52	87.32	7.73	0.034	0.178
1.2	86.43	77.04	89.14	3.29	0.316	0.154

For the DRI sampled from the bottom of the bed,

Molar C/O Ratio	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
0.9	83.11	65.12	78.35	16.34	0.016	0.146
1.0	82.70	64.44	77.92	14.95	0.015	0.184
1.1	83.01	69.08	83.22	6.82	1.75	0.164
1.2	89.72	77.46	86.34	10.67	0.014	0.127

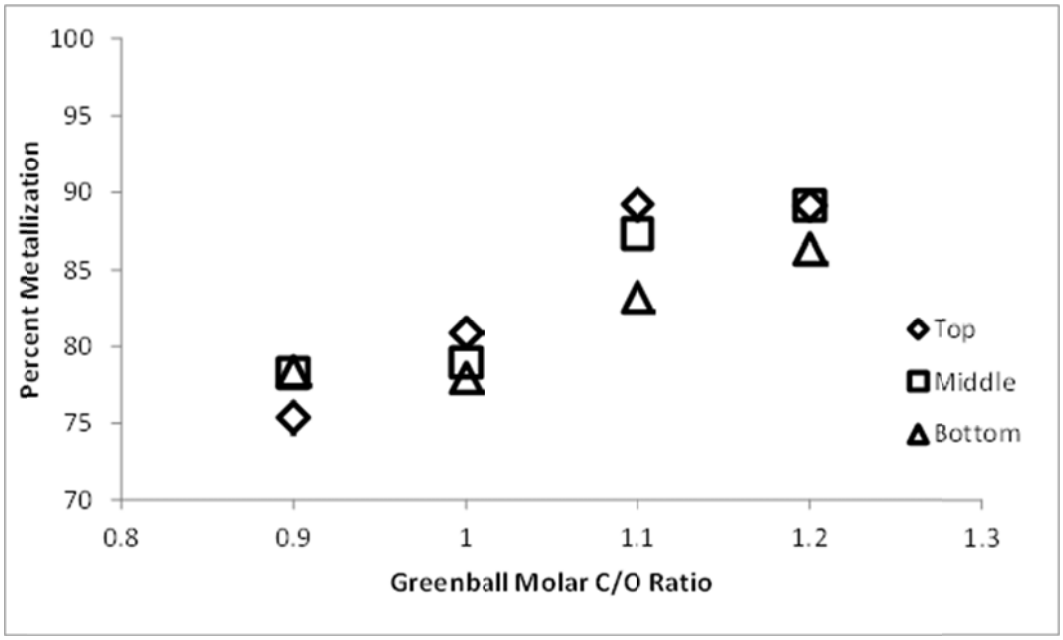

Figure 35. Relationships between percent metallization of DRI located at top, middle and bottom of the bed and greenball molar carbon-to-oxygen ratio for DRI produced at a furnace temperature of 1500°C, a residence time of 80 min, and an initial bed height of 7.6 cm.

4.3.6 Effect of Initial Bed Height on the DRI Quality

A series of experiments was conducted using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio =1.0) at furnace temperatures of 1450°C, 1475°C, and 1500°C, and a residence time of 80 min, at various initial bed heights of 7.6 cm, 10.2 cm, and 12.7 cm. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time. For these experiments, only the DRI sampled from the bottom of the bed was analyzed. A summary of the experimental findings is given in Table X. Pictures of DRI produced at a furnace temperature of 1475°C and a residence time of 80 min at initial bed heights of 7.6 cm, 10.2 cm, and 12.7 cm are shown in Figures 36, 37, and 38, respectively.

The relationship between percent metallization of DRI located at the bottom of the bed and furnace hot-zone temperature for DRI produced at various initial bed heights is plotted in Figure 39. It can be seen from Figure 39 that as the furnace temperature increases, percent metallization at the bottom of the bed increases. In addition, as the initial bed height decreased, the percent metallization at the bottom of the bed increased. It should be noted that as the initial bed height increased to 12.7 cm, the percent metallization at the bottom of the bed decreased.

Table X. A summary of the experimental findings, for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio =1.0) at furnace temperatures of 1450°C, 1475°C, and 1500°C and a residence time of 80 min. Three different initial bed heights of 7.6 cm, 10.2 cm, and 12.7 cm were used when loading the dried greenballs in the furnace.

For the DRI sampled from the bottom of the bed at an initial bed height of 7.6 cm

Furnace Temperature (°C)/ Initial Bed Height (cm)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1500°C/ 7.6 cm	82.70	64.44	77.92	14.95	0.015	0.184
1475°C/ 7.6 cm	80.90	59.63	73.71	11.06	0.188	0.184
1450°C/ 7.6 cm	84.05	69.51	82.70	5.49	0.284	0.192

For the DRI sampled from the bottom of the bed at an initial bed height of 10.2 cm

Furnace Temperature (°C)/ Initial Bed Height (cm)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1500°C/ 10.2 cm	73.43	49.94	68.01	17.34	2.43	0.225
1475°C/ 10.2 cm	76.93	48.78	63.41	8.14	1.78	0.208
1450°C/ 10.2 cm	65.64	9.85	15.01	9.80	1.54	0.114

For the DRI sampled from the bottom of the bed at an initial bed height of 12.7 cm

Furnace Temperature (°C)/ Initial Bed Height (cm)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1500°C/ 12.7 cm	64.76	8.14	12.57	18.61	4.75	0.160
1475°C/ 12.7 cm	64	2.66	4.16	16.58	4.05	0.125
1450°C/ 12.7 cm	65.28	1.16	1.78	6.63	0.839	0.080

Figure 36. DRI produced at a furnace temperature of 1475°C, and residence time of 80 min using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0) at an initial bed height of 7.6 cm. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time.

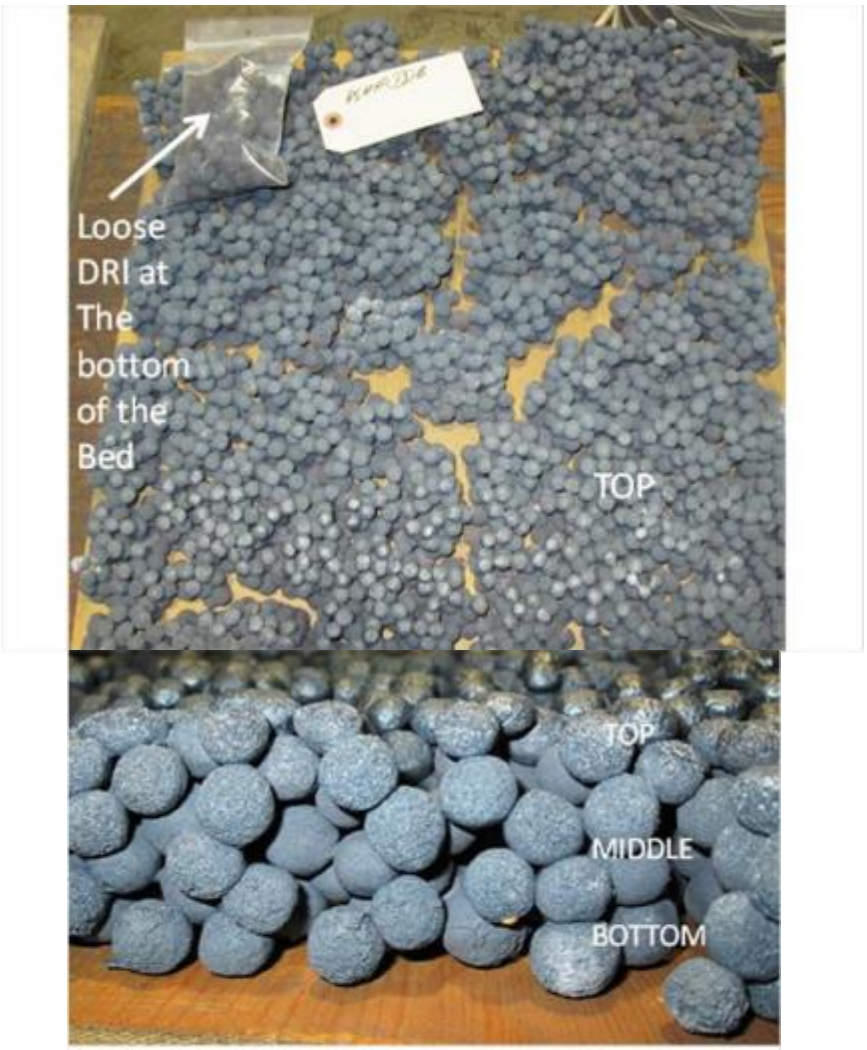

Figure 37. DRI produced at a furnace temperature of 1475°C and residence time of 80 min using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0) at an initial bed height of 10.2 cm. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time.

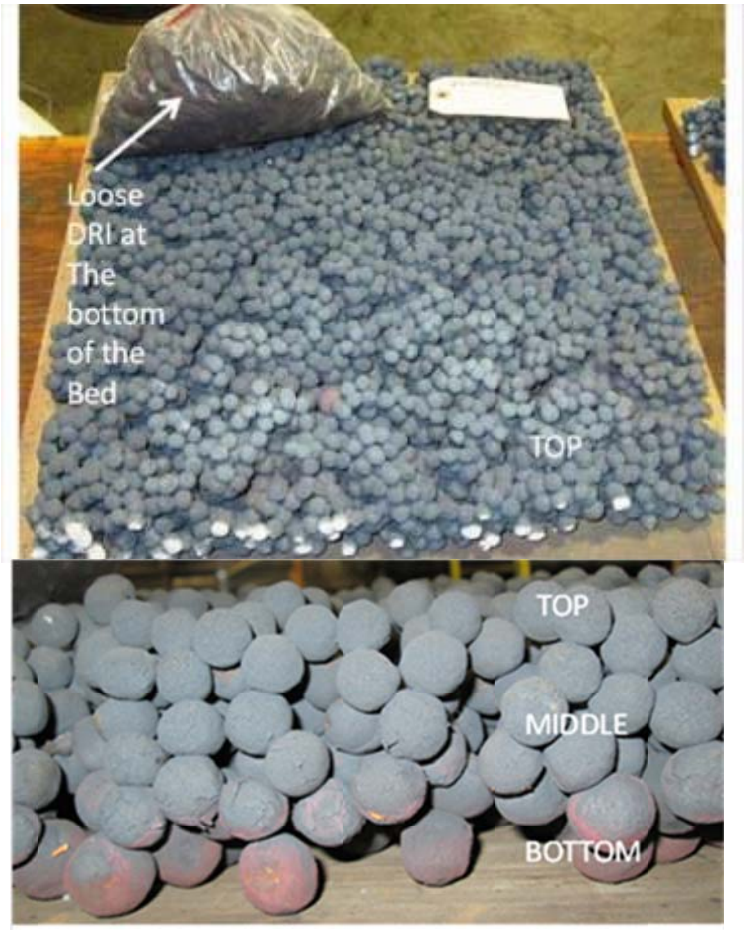

Figure 38. DRI produced at a furnace temperature of 1475°C and residence time of 80 min using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio = 1.0) at an initial bed height of 12.7 cm. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time.

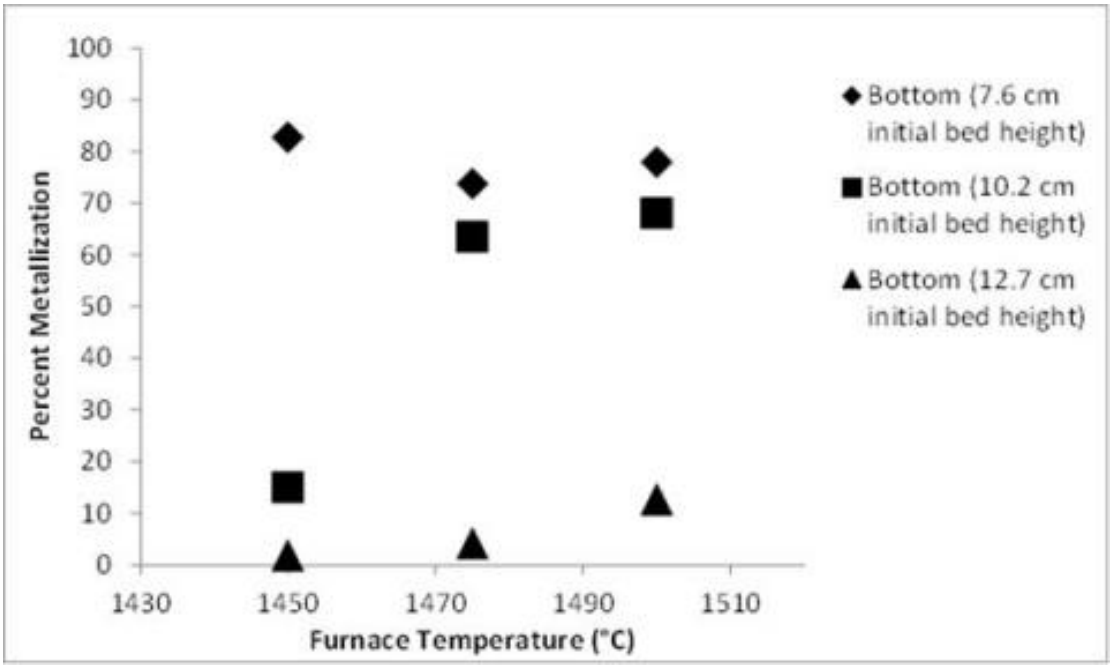

Figure 39. Relationships between percent metallization of DRI located at the bottom of the bed and furnace hot-zone temperature, for DRI produced at various initial bed heights of 7.6 cm, 10.2 cm, and 12.7 cm.

4.4 Phase IV—Simulation of Continuous Operation Using the LHF

An experiment was conducted to simulate the operation of one-half of a PSH furnace through continuous operation of the LHF. For this experiment, twelve (12) carts were loaded with dried greenballs which contain magnetite concentrate. The cart loading pattern is summarized in Table XI. The initial four (4) carts were loaded with dried greenballs which contain magnetite concentrate at a molar carbon-to-oxygen ratio of 1.2 and an initial bed height of 7.6 cm. The next four (4) carts were loaded with dried greenballs which contain magnetite concentrate at a molar carbon-to-oxygen ratio of 1.2 and an initial bed height of 10.2 cm. The following two (2) carts were loaded with dried greenballs which contain magnetite concentrate at a molar carbon-to-oxygen ratio of 0.9 and initial bed heights of 7.6 cm and 10.2 cm. And the final two (2) carts were loaded with dried greenballs which contain magnetite concentrate at a molar carbon-to-oxygen ratio of 1.0 and initial bed heights of 7.6 cm and 10.2 cm, respectively.

The cart speed throughout the LHF was kept constant. The residence time per cart in Zone 1 was approximately 30 min, and the residence time per cart in the hot-zone (Zones 2-3) was approximately 60 min. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time. The furnace hot-zone temperature was 1500°C. After the tenth cart was pushed into the furnace, the safety feature of the furnace was automatically activated due to combustion of the large amount of volatiles evolved and the resultant increase in temperature in LHF zone 1. This feature shuts down the burners and purges the furnace. Thus,

this experiment was not successfully completed. Further studies should be conducted to simulate a continuous operation. These studies should include modifications to the furnace to properly exhaust the large amount of volatiles evolved.

Although the furnace safety feature was activated and some of the carts were not heated in the desired way, the first six (6) carts were heated at the required conditions. A summary of the experimental findings is shown in Table XII. Pictures of DRI produced in the first four (4) to six (6) carts are shown in Figures 40 through 43.

Table XI. Cart loading pattern.

Cart Number	Dried Greenball Recipe Number	Dried Greenball Molar C/O Ratio	Initial Bed Height
1	13-2	1.2	7.6 cm
2	13-2	1.2	7.6 cm
3	13-2	1.2	7.6 cm
4	13-2	1.2	7.6 cm
5	13-2	1.2	10.2 cm
6	13-2	1.2	10.2 cm
7	13-2	1.2	10.2 cm
8	13-2	1.2	10.2 cm
9	13-3	0.9	7.6 cm
10	13-3	0.9	10.2 cm
11	13-1	1.0	7.6 cm
12	13-1	1.0	10.2 cm

Table XII. A summary of the experimental findings, for DRI produced using dried greenballs which contain magnetite concentrate (greenball recipe 13-2) (molar C/O ratio = 1.2), at a furnace hot-zone temperature of 1500°C, and residence time of 60 min. This experiment was conducted to simulate continuous operation of the furnace.

For DRI located at the top of the bed,

Cart Number	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}
1	86.52	73.75	85.24	10.41
2	86.99	72.70	83.57	11.56
3	85.25	71.55	83.93	13.55
4	89.11	78.07	87.61	9.30
5	88.47	80.80	91.33	5.09
6	89.22	80.94	90.72	4.84

For DRI located at the bottom of the bed,

Cart Number	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}
1	63.18	21.15	33.48	12.98
2	70.14	30.11	42.93	6.65
3	68.94	23.96	34.75	10.72
4	65.40	21.98	33.61	9.73
5	65.64	1.25	1.95	7.68
6	65.67	1.36	2.07	7.60

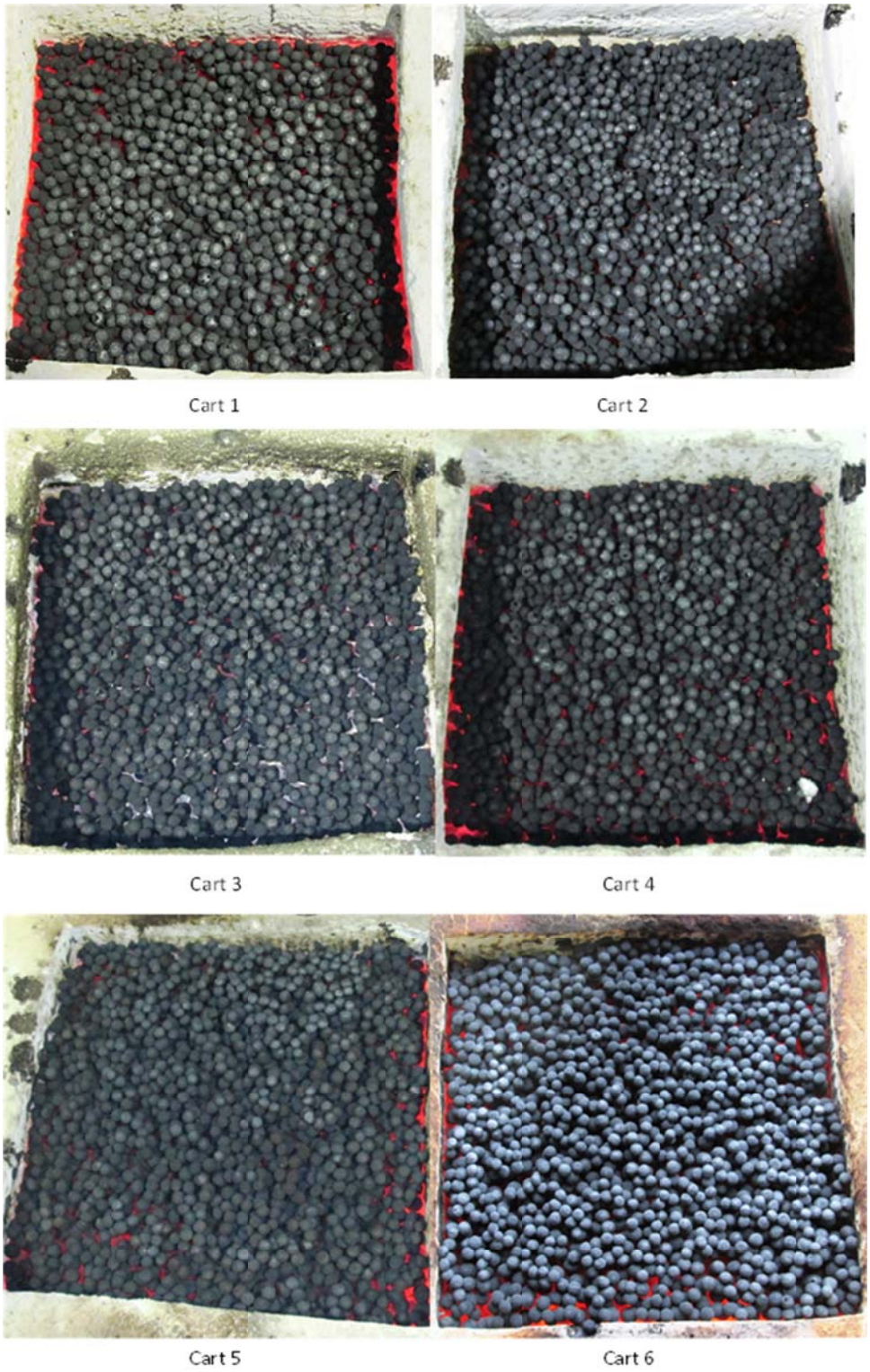

Figure 40. DRI produced in carts 1 through 6 for the experiment conducted to simulate continuous operation. DRI produced throughout this experiment was cooled in the LHF cooler at a long residence time. The initial bed height was 7.6 cm in carts 1-4 and 10.2 cm in carts 5-6.

Figure 41. DRI produced in carts 1 through 4. Dried greenballs which contain magnetite concentrate (greenball recipe 13-2) (molar C/O ratio = 1.2) were used as a feed material. The initial bed height was 7.6 cm. DRI produced was cooled in the LHF cooler at a long residence time.

Figure 42. DRI produced in carts 1 through 7. Dried greenballs which contain magnetite concentrate (greenball recipe 13-2) (molar C/O ratio = 1.2) were used as a feed material. For carts 1 through 4, the initial bed height was 7.6 cm, and for carts 5, 6, and 7 the initial bed height was 10.2 cm. DRI produced was cooled in the LHF cooler at a long residence time.

Figure 43. DRI located at the top layer in cart 6 from the experiment conducted to simulate continuous operation. Dried greenballs which contain magnetite concentrate (greenball recipe 13-2) (molar C/O ratio = 1.2) were used as a feed material. The initial bed height was 10.2 cm. The DRI was cooled in the LHF cooler at a long residence time.

4.5 Phase V—DRI Produced Using Dried Greenballs Which Contain Revert Material

4.5.1 Effect of Furnace Residence Time on DRI Quality

A series of experiments was conducted using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm, furnace temperatures of 1400°C, 1450°C, and 1500°C, and several residence times, to investigate the effects of furnace hot-zone residence time on the quality of DRI produced. A summary of the experimental findings is given in Table XIII. Pictures of DRI produced at a furnace hot-zone temperature of 1400°C and three residence times (50 min, 80 min, and 100 min) are shown in Figures 44,45, and 46, respectively. Pictures of DRI produced at a furnace hot-zone temperature of 1450°C and three residence times (50 min, 80 min, and 100 min) are shown in Figures 47, 48, and 49, respectively. Pictures of DRI produced at a furnace hot-zone temperature of 1500°C and two residence times (50 min and 80 min) are shown in Figures 50 and 51, respectively. For these experiments, DRI produced was cooled in the LHF cooler at a long residence time, and then shoveled into trays and further cooled in nitrogen under the external hood. It can be seen from these pictures that as the residence time increases, the amount of metallized DRI observed increases.

Table XIII. DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at a bed height of 7.6 cm, three furnace temperatures, and several residence times.

For the DRI sampled from the top of the bed,

Furnace Temp (°C)/Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1400°C / 50 min	75.83	45.00	59.34	7.33	0.183	0.186
1400°C / 80 min	85.02	74.79	87.97	9.18	0.032	0.205
1400°C / 100min	83.20	73.79	88.69	5.53	0.354	0.25
1450°C / 50 min	84.55	68.49	81.01	13.36	0.044	0.169
1450°C / 80 min	83.98	72.13	85.89	10.83	0.035	0.220
1450°C / 100min	91.26	79.72	87.35	10.45	0.029	0.113
1500°C / 50 min	82.92	66.22	79.86	12.73	0.027	0.242
1500°C / 80 min	86.12	74.18	86.14	11.00	0.030	0.141

For the DRI sampled from the middle of the bed,

Furnace Temp (°C)/Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1400°C / 50 min	61.30	10.34	16.87	19.4	6.210	0.246
1400°C / 80 min	83.29	66.58	79.94	14.84	0.026	0.250
1400°C / 100min	84.12	71.39	84.87	9.56	0.024	0.239
1450°C / 50 min	80.49	71.40	88.71	5.85	0.049	0.285
1450°C / 80 min	79.62	67.84	85.20	8.05	0.133	0.318
1450°C / 100min	84.59	67.88	80.25	15.36	0.015	0.192
1500°C / 50 min	81.05	66.85	82.48	10.06	0.246	0.261
1500°C / 80 min	79.17	65.08	82.20	9.16	0.075	0.306

Table XIII cont. DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at a bed height of 7.6 cm, three furnace temperatures and several residence times.

For the DRI sampled from the bottom of the bed,

Furnace Temp (°C)/Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1400°C / 50 min	51.73	2.26	4.37	17.33	13.80	0.260
1400°C / 80 min	83.31	65.98	79.20	15.01	0.420	0.286
1400°C / 100min	84.53	70.18	83.02	7.18	0.285	0.244
1450°C / 50 min	78.17	58.93	75.39	15.81	0.498	0.299
1450°C / 80 min	79.07	60.72	76.79	14.84	1.09	0.283
1450°C /100min	79.19	61.61	77.80	11.96	0.231	0.295
1500°C / 50 min	56.84	13.51	23.76	33.83	13.1	0.260
1500°C / 80 min	79.19	66.22	83.62	9.11	0.123	0.330

For the DRI fines sampled from the bottom of the bed,

Furnace Temp (°C)/Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1400°C / 50 min	50.58	4.25	8.40	16.17	15.10	0.255
1400°C / 80 min	85.15	52.92	62.15	2.74	0.306	0.228
1400°C / 100min	81.27	72.10	88.72	4.73	2.78	0.306
1450°C / 50 min	62.51	28.02	44.82	18.96	6.98	0.264
1450°C / 80 min	72.33	61.55	85.10	6.46	5.76	0.346
1450°C / 100min	77.92	44.96	57.70	3.94	4.59	0.312
1500°C / 50 min	NT*	NT*	NT*	NT*	NT*	NT*
1500°C / 80 min	78.14	60.80	77.81	0	2.51	0.322

NT*, not tested

Figure 44. DRI produced at a furnace hot-zone temperature of 1400°C and residence time of 50 min. Dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) were used as a feed material. The initial bed height of the dried greenballs was 7.6 cm. The DRI was cooled in the LHF cooler at a long residence time, and then was shoveled out to a tray and further cooled in nitrogen under the external hood.

Figure 45. DRI produced at a furnace hot-zone temperature of 1400°C and residence time of 80 min. Dried greenballs which contain revert material (14-5) (molar C/O ratio = 1.1) were used as a feed material. The initial bed height of the dried greenballs was 7.6 cm. The DRI was cooled in the LHF cooler at a long residence time, and then was shoveled out to a tray and further cooled in nitrogen under the external hood.

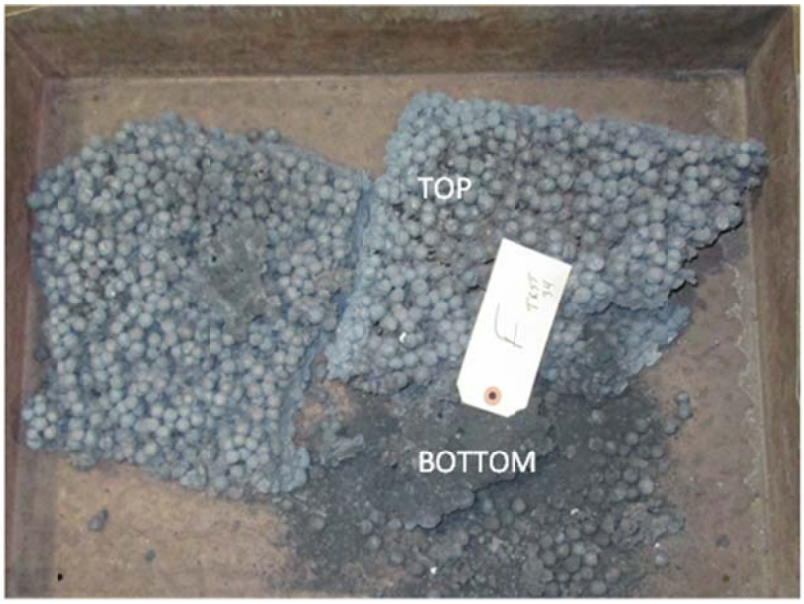

Figure 46. DRI produced at a furnace hot-zone temperature of 1400°C and residence time of 100 min. Dried greenballs which contain revert material (14-5) (molar C/O ratio = 1.1) were used as a feed material. The initial bed height of the dried greenballs was 7.6 cm. The DRI was cooled in the LHF cooler at a long residence time, and then was shoveled out to a tray and further cooled in nitrogen under the external hood.

Figure 47. DRI produced at a furnace hot-zone temperature of 1450°C and residence time of 50 min. Dried greenballs which contain revert material (14-5) (molar C/O ratio = 1.1) were used as a feed material. The initial bed height of the dried greenballs was 7.6 cm. The DRI was cooled in the LHF cooler at a long residence time, and then was shoveled out to a tray and further cooled in nitrogen under the external hood.

Figure 48. DRI produced at a furnace hot-zone temperature of 1450°C and residence time of 80 min. Dried greenballs which contain revert material (14-5) (molar C/O ratio = 1.1) were used as a feed material. The initial bed height of the dried greenballs was 7.6 cm. The DRI was cooled in the LHF cooler at a long residence time, and then was shoveled out to a tray and further cooled in nitrogen under the external hood.

Figure 49. DRI produced at a furnace hot-zone temperature of 1450°C and residence time of 100 min. Dried greenballs which contain revert material (14-5) (molar C/O ratio = 1.1) were used as a feed material. The initial bed height of the dried greenballs was 7.6 cm. The DRI was cooled in the LHF cooler at a long residence time, and then was shoveled out to a tray and further cooled in nitrogen under the external hood.

Figure 50. DRI produced at a furnace hot-zone temperature of 1500°C and residence time of 50 min. Dried greenballs which contain revert material (14-5) (molar C/O ratio = 1.1) were used as a feed material. The initial bed height of the dried greenballs was 7.6 cm. The DRI was cooled in the LHF cooler at a long residence time, and then was shoveled out to a tray and further cooled in nitrogen under the external hood.

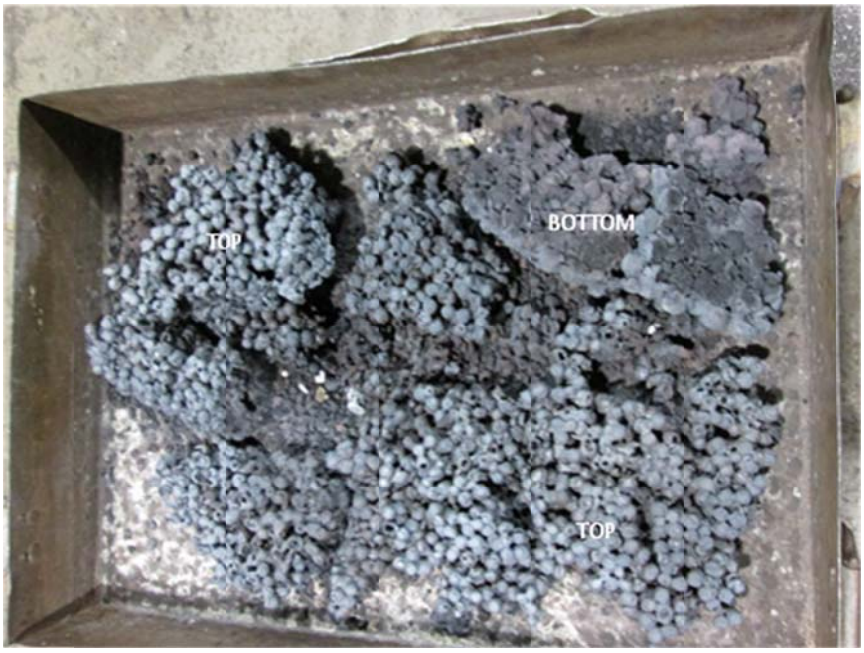

Figure 51. DRI produced at a furnace hot-zone temperature of 1500°C and residence time of 80 min. Dried greenballs which contain revert material (14-5) (molar C/O ratio = 1.1) were used as a feed material. The initial bed height of the dried greenballs was 7.6 cm. The DRI was cooled in the LHF cooler at a long residence time, and then was shoveled out to a tray and further cooled in nitrogen under the external hood.

The relationship between percent metallization of the DRI and furnace hot-zone residence times at a furnace hot-zone temperature of 1400°C (2552°F) is plotted in Figure 52, and the relationship between percent metallization of the DRI and various furnace hot-zone residence times at a furnace hot-zone temperature of 1450°C (2642°F) is plotted in Figure 53. It can be seen from Figures 52 and 53 that as the furnace residence time increases, the percent metallization at the top of the bed increases. For DRI produced at a furnace temperature of 1400°C, as the residence time increases, the percent metallization at the middle and bottom of the bed also increases.

However, for DRI produced at a furnace temperature of 1450°C, as the residence time increases, the percent metallization appears to decrease. This observation is deceiving. The majority of the fines generated throughout the experiments were observed to be at the middle and bottom of the bed. When the samples were collected, individual DRI balls at the top, middle, and bottom of the bed were sampled separately, and fines were sampled separately. Thus, it is projected that if representative samples of DRI and fines were sampled, an increase in the percent metallization with increasing residence time might have been observed. Further studies should be conducted to identify the conditions that favor fines generation, the effect on the reactions and heat transfer, and methods to eliminate the fines.

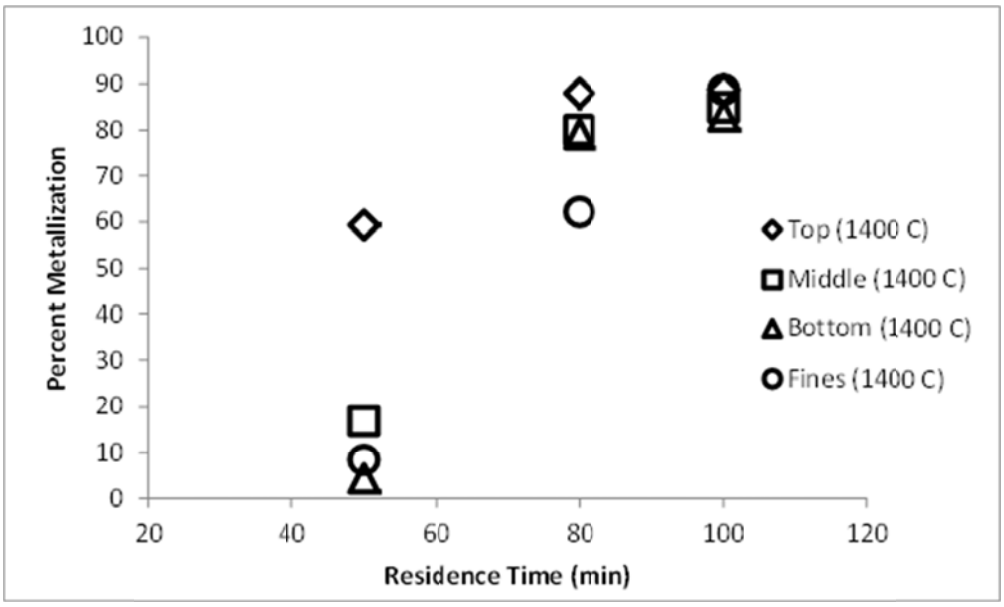

Figure 52 . Relationships between percent metallization and furnace hot-zone residence time for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at a constant furnace hot-zone temperature of 1400°C (2552°F). The initial bed height was 7.6 cm.

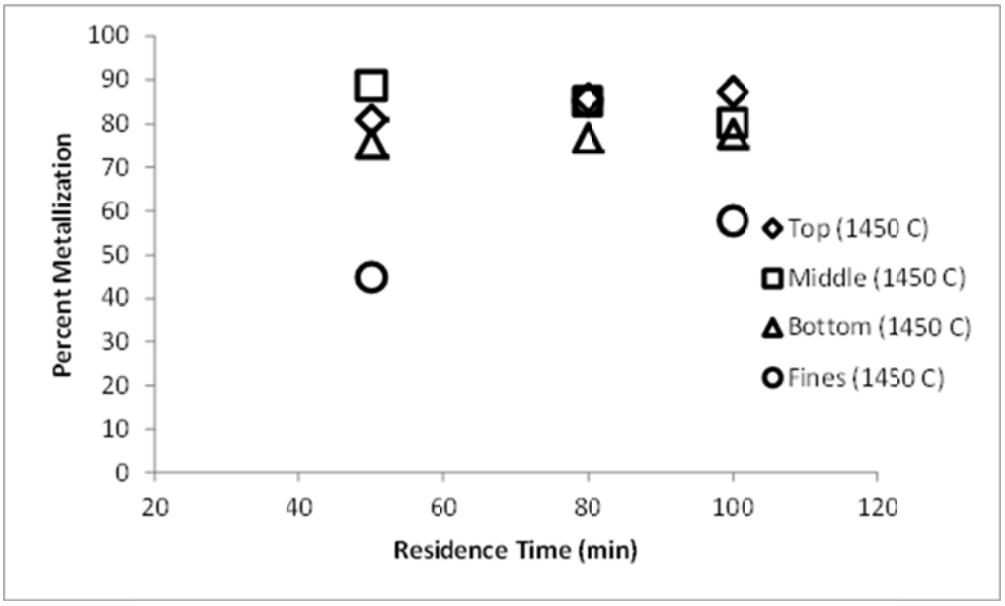

Figure 53. Relationships between percent metallization and furnace hot-zone residence time for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at a constant furnace hot-zone temperature of 1450°C (2642°F). The initial bed height was 7.6 cm.

4.5.2 Furnace Residence Time Required for High-Quality DRI Production

A series of experiments was conducted using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm, furnace temperatures of 1400°C, 1450°C, and 1500°C, and several residence times, to determine the optimum residence time required for production of high-quality DRI. Relationships between percent metallization of DRI located at the top, middle and bottom of the bed at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C and several furnace hot-zone residence times are plotted in Figures 54, 55, and 56 respectively. It can be seen from these figures that a considerable increase in the percent metallization for DRI located at the top, middle, and bottom of the bed was observed when the residence time was increased from 50 min to 80 min. On the other hand, the change in percent metallization as the residence time increased to 100 min was not as significant. Thus, it can be concluded that an 80 min hot-zone residence time is sufficient for production of high-quality DRI when the initial bed height is 7.6 cm.

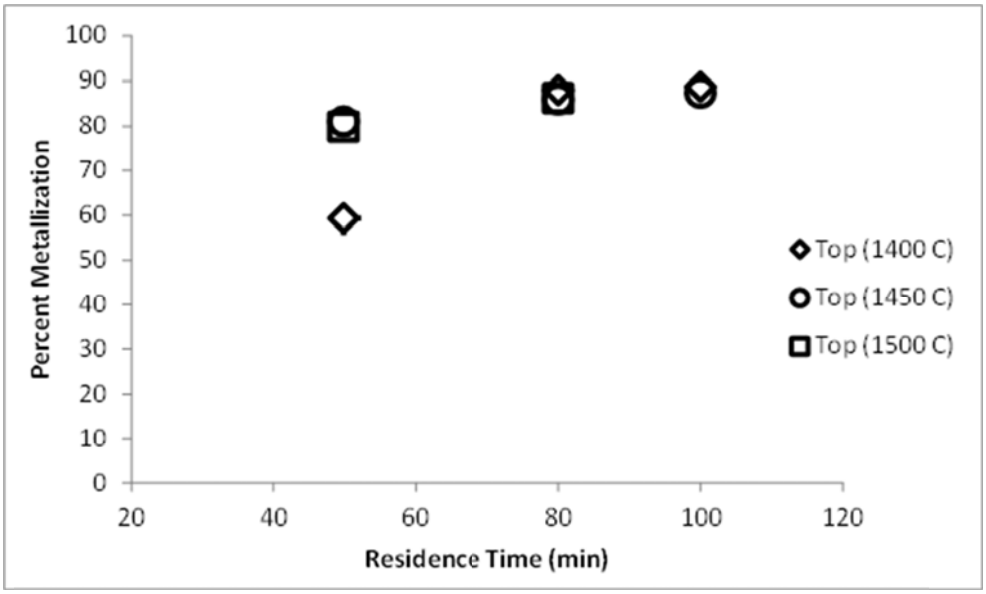

Figure 54 . Relationships between percent metallization of DRI located at the top of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C. The initial bed height was 7.6 cm.

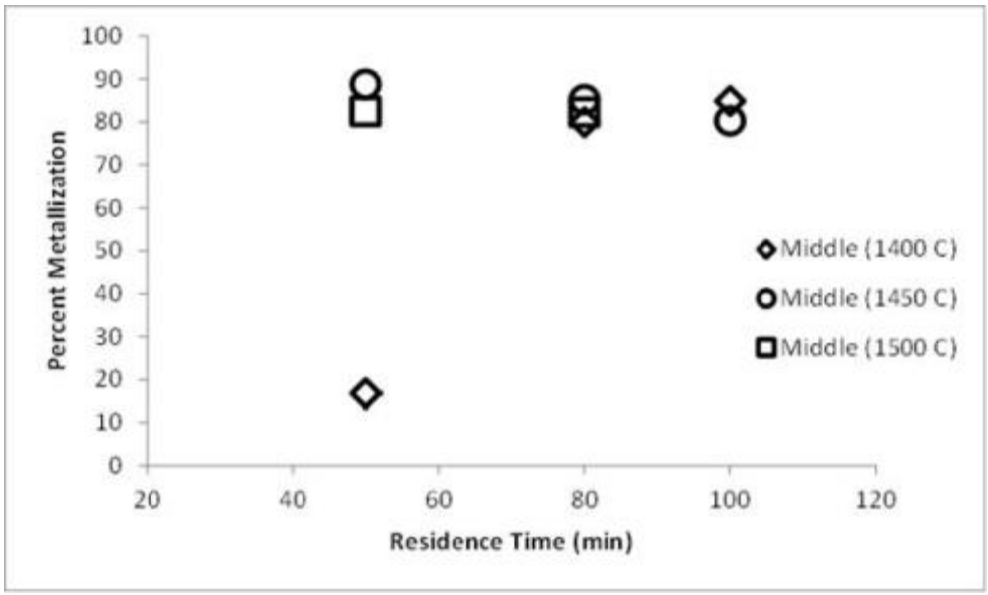

Figure 55. Relationships between percent metallization of DRI located at the middle of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C. The initial bed height was 7.6 cm.

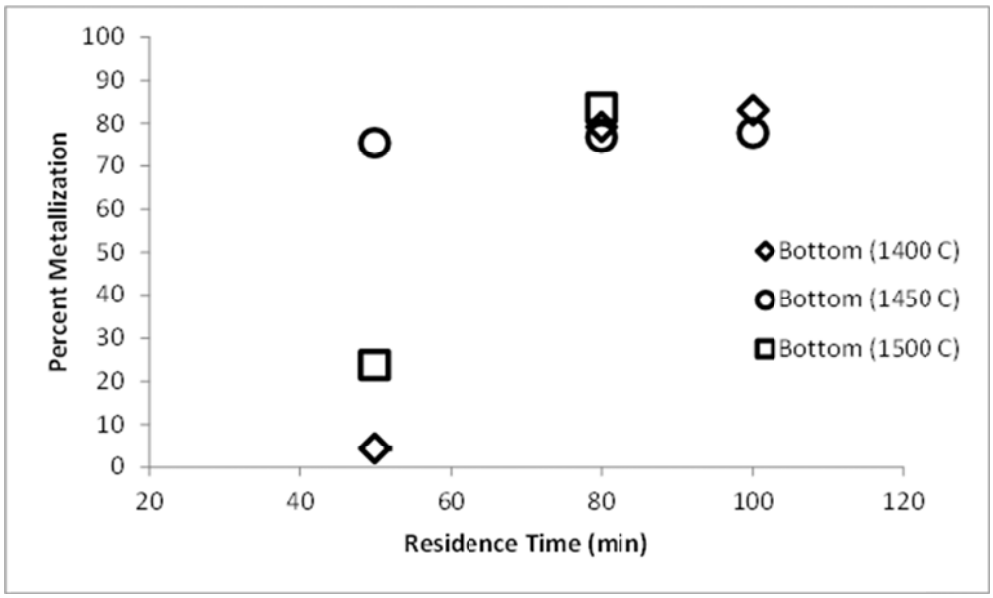

Figure 56 . Relationships between percent metallization of DRI located at the bottom of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C. The initial bed height was 7.6 cm.

4.5.3 Effect of Furnace Temperature on the DRI Quality

A series of experiments was conducted using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm, three furnace residence times of 50 min, 80 min, and 100 min, and several furnace temperatures, to investigate the effect of furnace hot-zone temperature on the quality of DRI produced. Relationships between percent metallization of the DRI and furnace hot-zone temperature at furnace hot-zone residence times of 50 min, 80 min, and 100 min are plotted in Figures 57, 58, and 59, respectively. It can be seen from Figure 57 that at 50 min furnace residence time, as the furnace hot-zone temperature increases from 1400°C to 1450°C, the percent metallization of DRI located at the top, middle and bottom increases. However, for residence times longer than 80 min, no significant increase in the percent metallization was observed as the furnace hot-zone temperature was increased.

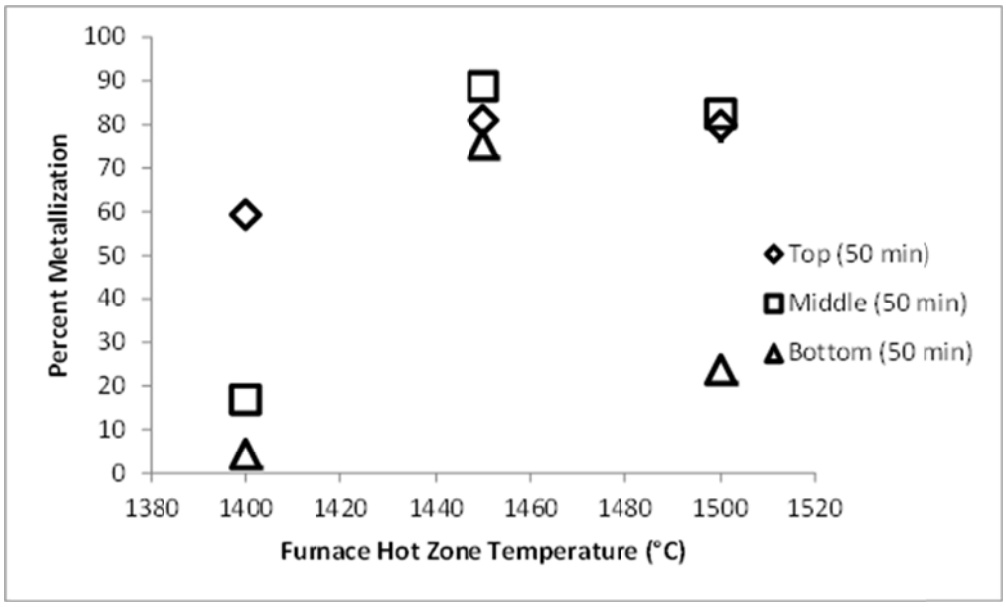

Figure 57. Relationships between percent metallization and furnace hot-zone temperature for DRI produced using dried greenballs which contain revert material (greenball recipe 14- 5) (molar C/O ratio = 1.1) at a constant furnace hot-zone residence time of 50 min. The initial bed height was 7.6 cm.

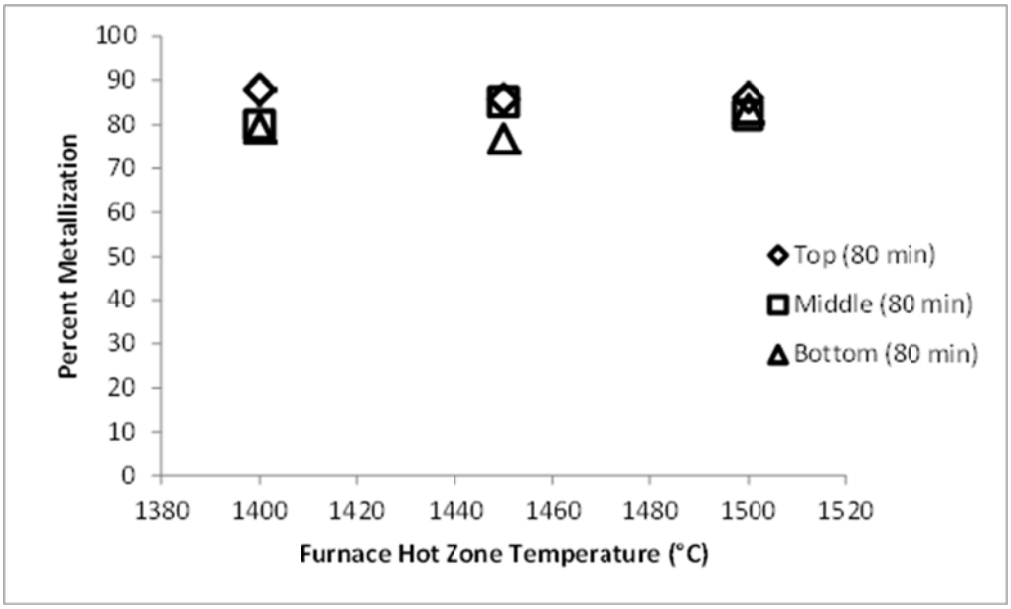

Figure 58 . Relationships between percent metallization and furnace hot-zone temperature for DRI produced using dried greenballs which contain revert material (greenball recipe 14- 5) (molar C/O ratio = 1.1) at a constant furnace hot-zone residence time of 80 min. The initial bed height was 7.6 cm.

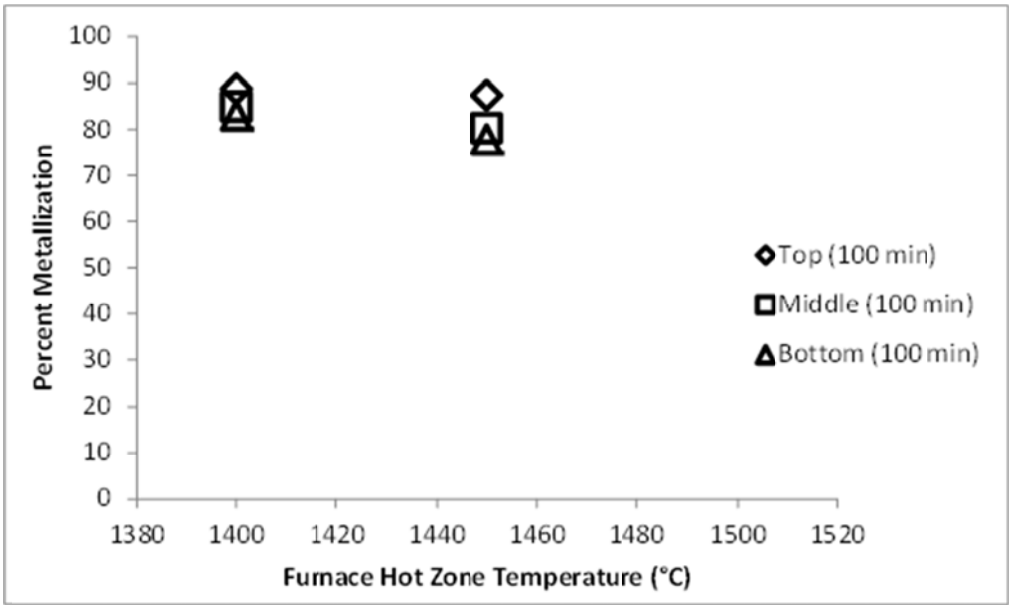

Figure 59 . Relationships between percent metallization and furnace hot-zone temperature for DRI produced using dried greenballs which contain revert material (greenball recipe 14- 5) (molar C/O ratio = 1.1) at a constant furnace hot-zone residence time of 100 min. The initial bed height was 7.6 cm.

4.5.4 Furnace Temperature Required For High-Quality DRI Production

A series of experiments was conducted using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at an initial bed height of 7.6 cm, furnace residence times of 50 min, 80 min, and 100 min, and various furnace hot-zone temperatures, to determine the optimum furnace hot-zone temperature required for production of high-quality DRI. Relationships between percent metallization of DRI located at the top, middle and bottom of the bed, at three furnace hot-zone residence times of 50 min, 80 min, and 100 min, and several furnace temperatures, are plotted in Figures 60, 61, and 62, respectively. It can be seen from these plots that a considerable increase in percent metallization for DRI located at the top, middle and bottom of the bed was observed when the furnace hot-zone temperature was increased from 1400°C to 1450°C. On the other hand, the change in percent metallization as the furnace temperature was increased from 1450°C to 1500°C was not as significant. Thus, it might be concluded that a 1450°C hot-zone temperature is sufficient for high quality DRI production when the initial bed height is 7.6 cm.

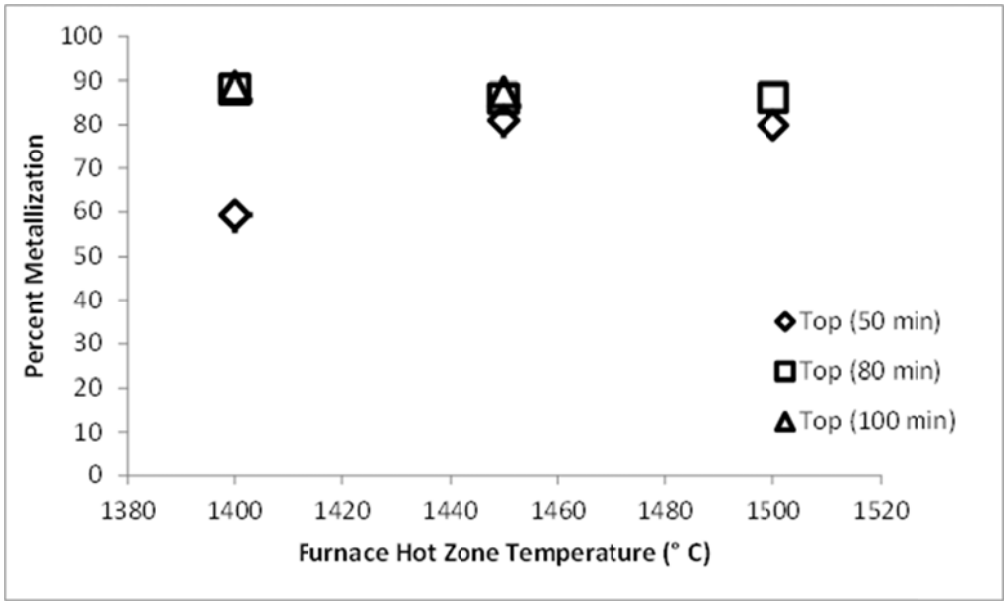

Figure 60. Relationships between percent metallization of DRI located at the top of the bed and furnace hot-zone temperature for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at furnace hot-zone residence times of 50 min, 80 min, and 100 min. The initial bed height was 7.6 cm.

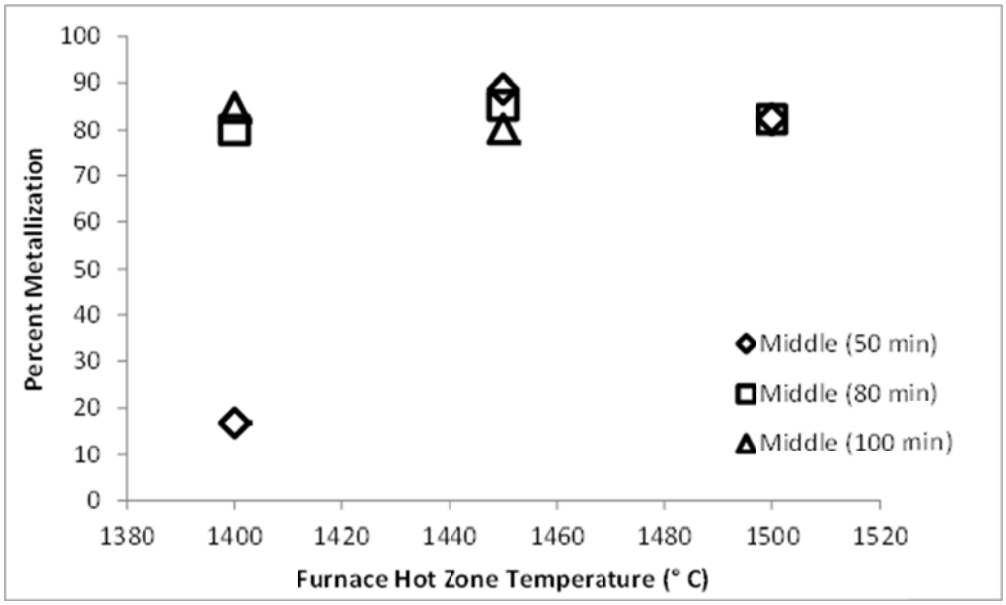

Figure 61 . Relationships between percent metallization of DRI located at the middle of the bed and furnace hot-zone temperature for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at furnace hot-zone residence times of 50 min, 80 min, and 100 min. The initial bed height was 7.6 cm.

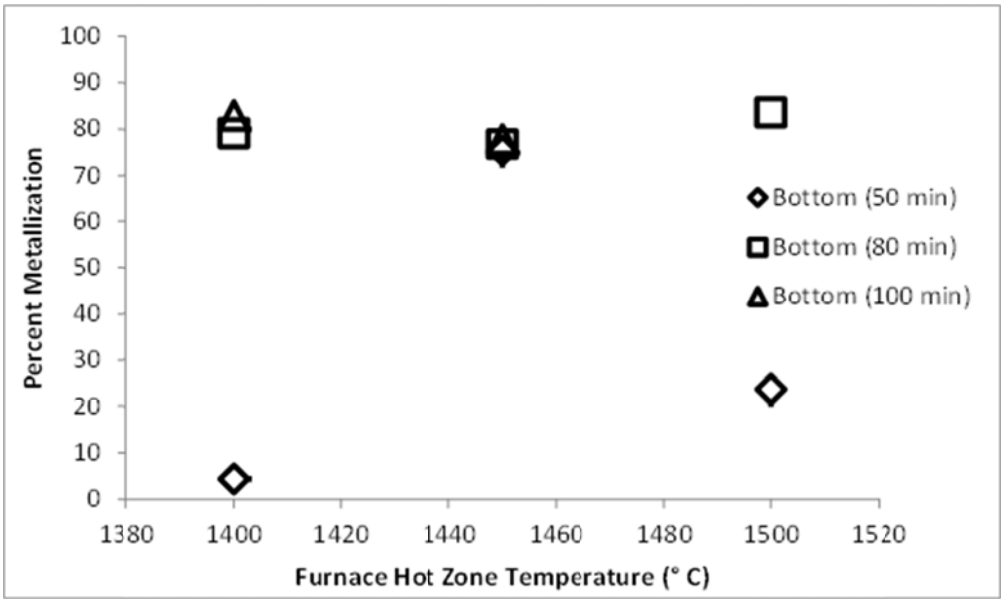

Figure 62 . Relationships between percent metallization of DRI located at the bottom of the bed and furnace hot-zone temperature for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at furnace hot-zone residence times of 50 min, 80 min, and 100 min. The initial bed height was 7.6 cm.

4.5.5 Effect of Dried Greenball Molar Carbon-to-Oxygen Ratio on DRI Quality

A series of experiments was conducted to determine the effects of dried greenball molar carbon-to-oxygen (C/O) ratio on the quality of DRI produced. The dried greenballs used for these experiments had either a 1.0 or 1.1 molar C/O ratio. Dried greenballs were heated at a furnace temperature of 1500°C and residence times of either 50 min or 80 min. The initial bed height was 7.6 cm. For these experiments, the DRI prduced was cooled in the LHF cooler at a long residence time, and then shoveled out to a tray and further cooled in nitrogen under the external hood. A summary of the experimental findings is given in Table XIV. Pictures of DRI produced at a furnace temperature of 1500°C and residence times of 50 min and 80 min are shown in Figures 63, and 64 respectively. The DRI samples shown in Figures 63 A and 64 A were produced using dried greenballs which had a molar carbon-to-oxygen ratio of 1.1 (greenball recipe 14-5), and the DRI samples shown in Figures 63 B and 64 B were produced using dried greenballs which had a molar carbon-to-oxygen ratio of 1.0 (greenball recipe 14-8).

Table XIV . DRI produced using dried greenballs which contain revert material, and a molar carbon-to-oxygen ratio of either 1.1 (greenball recipe 14-5) or 1.0 (greenball recipe 14-8) at a furnace temperature of 1500°C and residence times of 50 min and 80 min.
The initial bed height was 7.6 cm.

For the DRI sampled from the top of the bed,

Molar C/O ratio/ Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1.1 / 50 min	82.92	66.22	79.86	12.73	0.027	0.242
1.1 / 80 min	86.12	74.18	86.14	11.00	0.030	0.141
1.0 / 50min	86.37	62.60	72.48	19.33	0.029	0.080
1.0 / 80 min	87.63	70.89	80.90	15.60	0.037	0.154

For the DRI sampled from the middle of the bed,

Molar C/O ratio/ Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1.1 / 50 min	81.05	66.85	82.48	10.06	0.246	0.261
1.1 / 80 min	79.17	65.08	82.20	9.16	0.075	0.306
1.0 / 50min	80.54	68.95	85.61	5.94	0.210	0.290
1.0 / 80 min	85.21	74.40	87.31	8.76	0.769	0.181

For the DRI sampled from the bottom of the bed,

Molar C/O ratio/ Residence Time (min)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
1.1 / 50 min	56.84	13.51	23.77	33.83	13.10	0.260
1.1 / 80 min	79.19	66.22	83.62	9.11	0.123	0.330
1.0 / 50min	54.21	3.48	6.42	30.44	13.80	0.259
1.0 / 80 min	62.64	15.43	24.63	34.96	11.70	0.172

The relationships between percent metallization of DRI located at the top, middle and bottom of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which had molar carbon-to-oxygen ratios of either 1.1 (greenball recipe 14-5) or 1.0 (greenball recipe 14-8) are plotted in Figures 65, 66, and 67, respectively. It can be seen from these plots that higher percentages of metallization can be achieved while using dried greenballs which had the higher molar carbon-to-oxygen ratio of 1.1. It was observed that for DRI located at the bottom of the bed, the molar carbon-to-oxygen ratio of the greenballs had a significant influence on the increased percent metallization. It should be noted that for the current study, only two different levels of molar carbon-to-oxygen ratio were tested. Further studies should be conducted to determine the optimum molar carbon-to-oxygen ratio for the dried greenballs. In addition, the amount of fines generated with changing molar carbon-to-oxygen ratio should be studied.

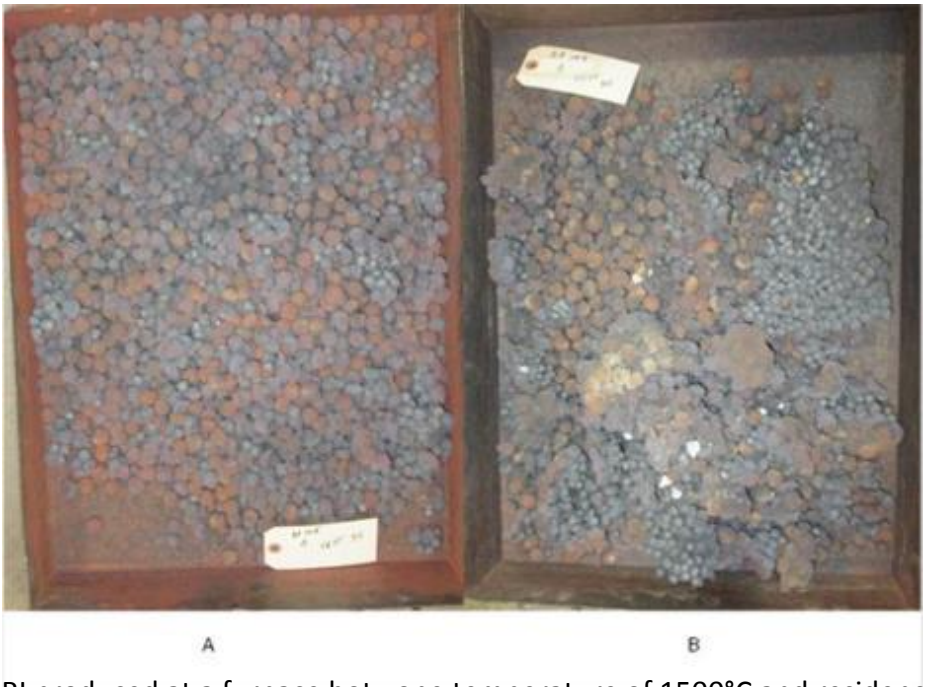

Figure 63 . DRI produced at a furnace hot-zone temperature of 1500°C and residence time of 50 min; the initial bed height was 7.6 cm. Sample A was produced using dried greenballs which had a molar carbon-to-oxygen ratio of 1.1 (greenball recipe 14-5), and sample B was produced using dried greenballs which had a molar carbon-to-oxygen ratio 1.0 (greenball recipe 14-8). For these experiments, the DRI produced was cooled in the LHF cooler at a long residence time and then shoveled into a tray and further cooled in nitrogen under the external hood.

Figure 64 . DRI produced at a furnace hot-zone temperature of 1500°C and residence time of 80 min; the initial bed height was 7.6 cm. Sample A was produced using dried greenballs which had a molar carbon-to-oxygen ratio of 1.1 (greenball recipe 14-5), and sample B was produced using dried greenballs which had a molar carbon-to-oxygen ratio of 1.0 (greenball recipe 14-8). For these experiments, the DRI produced was cooled in the LHF cooler at a long residence time and then shoveled into a tray and further cooled in nitrogen under the external hood.

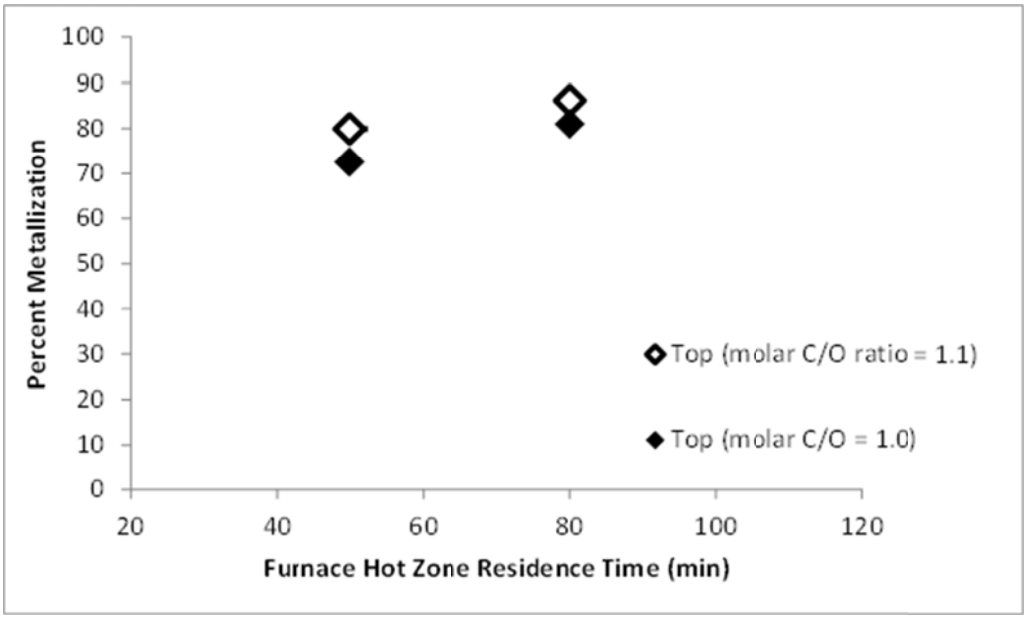

Figure 65 . Relationships between percent metallization of DRI located at the top of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which had molar carbon-to-oxygen ratios of 1.1 (greenball recipe 14-5) and 1.0 (greenball recipe 14-8). Initial bed height was 7.6 cm.

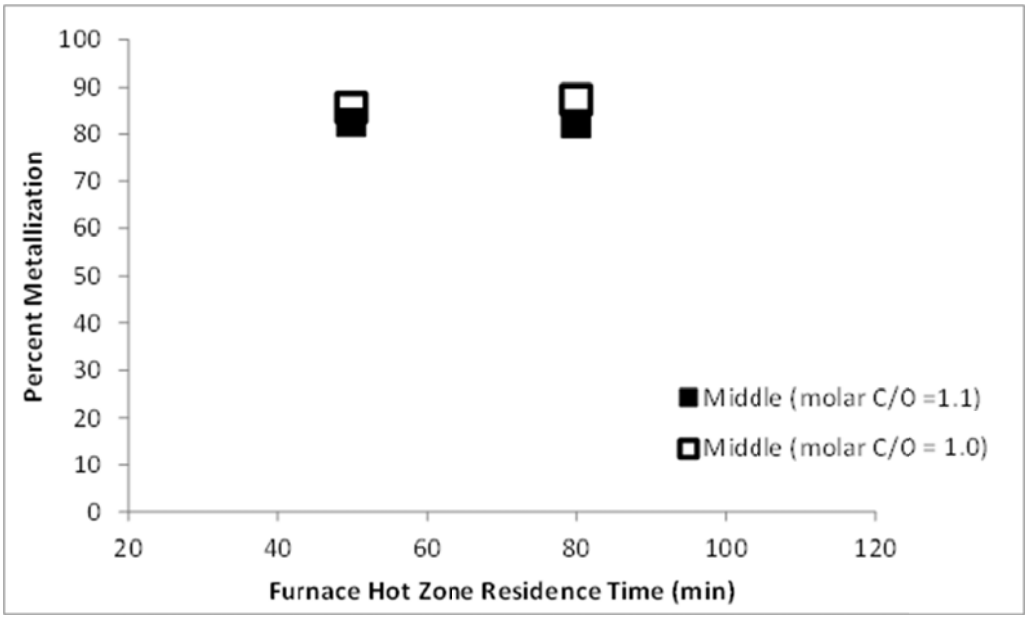

Figure 66 . Relationships between percent metallization of DRI located at the middle of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which had molar carbon-to-oxygen ratios of 1.1 (greenball recipe 14-5) and 1.0 (greenball recipe 14-8). The initial bed height was 7.6 cm.

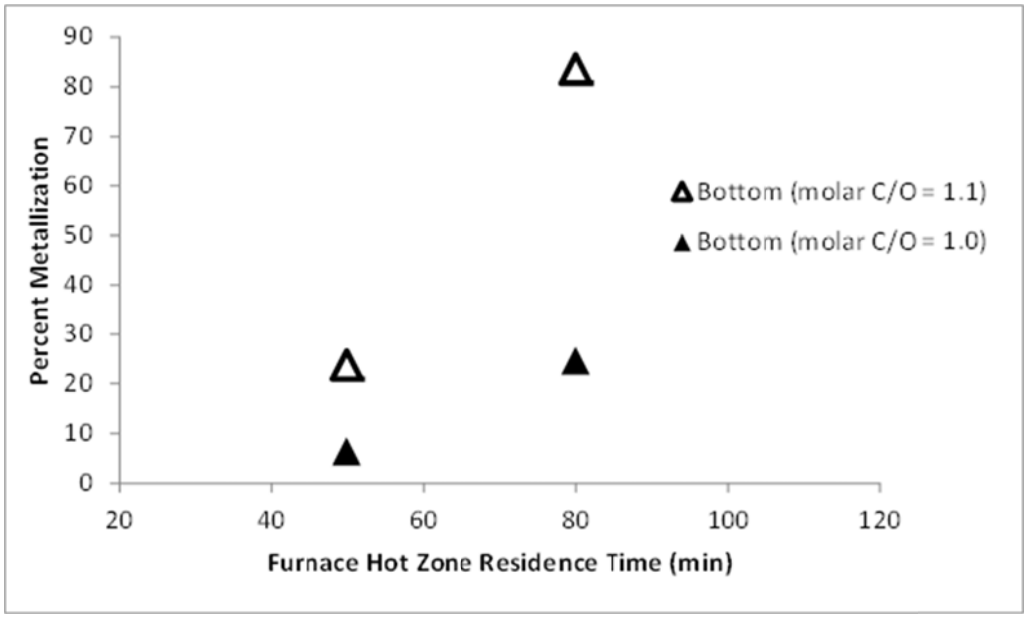

Figure 67. Relationships between percent metallization of DRI located at the bottom of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which had molar carbon-to-oxygen ratios of 1.1 (greenball recipe 14-5) and 1.0 (greenball recipe 14-8). The initial bed height was 7.6 cm.

4.5.6 Effect of Initial Bed Height on the DRI Quality

A series of experiments was conducted using dried greenballs which contain revert material (greenball recipe 14-8) (molar C/O ratio =1.0) at a furnace temperature of 1500°C and residence time of 80 min at various initial bed heights of 7.6 cm, 10.2 cm, and 12.7 cm. For these experiments, the DRI produced was cooled in the LHF cooler at a long residence time, shoveled out to a tray, and further cooled in nitrogen under the external hood. A summary of the experimental findings is given in Table XV. Pictures of DRI produced are shown in Figure 68. It was observed that as the initial bed height increased, the DRI fines generation was increased.

Figure 68 . DRI produced using dried greenballs which contain revert material (dried greenball recipe 14-8) (molar C/O ratio = 1.0) at a furnace temperature of 1500°C and residence time of 80 min at various initial bed heights. For these experiments, the DRI produced was cooled in the LHF cooler at a long residence time and shoveled into a tray and further cooled in nitrogen under the external hood.

Table XV . A summary of the experimental findings for DRI produced using dried greenballs which contain revert material (greenball recipe 14-8) (molar C/O ratio = 1.0) at a furnace temperature of 1500°C and residence time of 80 min. Three different initial bed heights were used when loading the dried greenballs in the furnace. These initial bed heights were 7.6 cm, 10.2 cm, and 12.7 cm.

For the DRI sampled from the top of the bed,

Initial Bed Height (cm)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
7.6 cm	86.88	73.83	84.98	11.17	0.029	0.162
10.2 cm	87.63	70.89	80.90	15.60	0.037	0.154
12.7 cm	84.42	75.74	89.72	6.26	0.024	0.231

For the DRI sampled from the middle of the bed,

Initial Bed Height (cm)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
7.6 cm	80.13	67.40	84.11	8.86	0.149	0.295
10.2 cm	85.21	74.40	87.31	8.76	0.769	0.181
12.7 cm	76.75	58.47	76.18	4.61	2.81	0.259

For the DRI sampled from the bottom of the bed,

Initial Bed Height (cm)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
7.6 cm	77.83	53.10	68.23	10.08	0.100	0.248
10.2 cm	62.64	15.43	24.63	34.96	11.70	0.172
12.7 cm	50.99	2.97	5.82	49.18	12.80	0.203

For the DRI fines sampled,

Initial Bed Height (cm)	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
7.6 cm	76.07	60.25	79.20	7.06	2.94	0.265
10.2 cm	74.33	53.61	72.12	7.11	2.55	0.295
12.7 cm	68.48	38.37	56.03	26.98	12.39	0.267

The relationship between percent metallization of the DRI and initial bed height for DRI produced at a furnace temperature of 1500°C and residence time of 80 min is plotted in Figure 69. It can be seen from Figure 69 that for DRI located on top of the bed, no significant change in percent metallization with increasing initial bed height was observed. However, for DRI located at the middle and bottom of the bed, a decrease in percent metallization with increasing initial bed height was observed. In addition, DRI produced at an initial bed height of 7.6 cm had more uniform percent metallization from top to bottom.

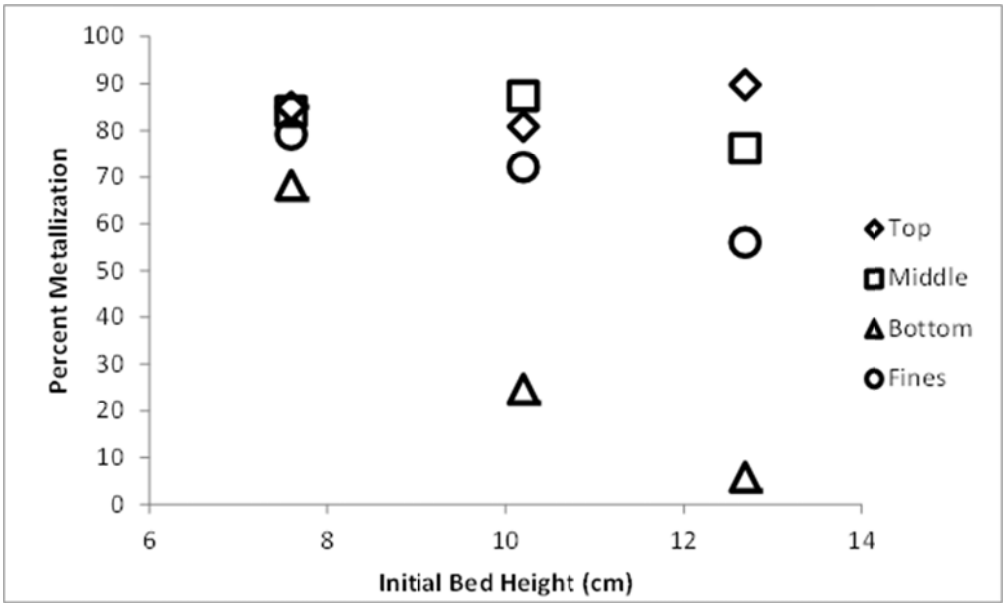

Figure 69 . Relationships between percent metallization of the DRI at initial bed heights of 7.6 cm, 10.2 cm, and 12.7 cm for DRI produced at a furnace temperature of 1500°C and residence time of 80 min. Dried greenballs which contain revert material (greenball recipe 14-8) (molar C/O ratio = 1.0) were used as feed.

An additional experiment was run at an initial bed height of 5.1 cm (2 inches) at a furnace temperature of 1500°C and residence time of 80 min. For this experiment, DRI produced was cooled in the LHF cooler at a long residence time. When the sample was removed, it was observed that the cooling of the DRI was more uniform than with deeper bed heights, and the bottom of the sample was not glowing or as hot. It was also observed that the DRI was removed cleanly from the hearth. Pictures of DRI produced are shown in Figure 70. It can be seen from Figure 70 that the DRI cake was fused together. It was difficult to separate the layers from each other. Thus, for this test, multiple samples which contained all the layers were collected across the DRI cake. These samples were collected equidistant from each other from one corner to the opposite corner. A summary of the findings is shown in Table XVI. It can be seen from Table XVI that the percent metallization for the samples collected varied, but no obvious pattern was observed. The average percent metallization for the sample was 74.21% +/- 6.6%. It appeared that no significant increase in the percent metallization was achieved by

decreasing the initial bed height from 7.6 cm to 5.1 cm. Thus, it can be concluded that an initial bed height of 7.6 cm is the preferred initial bed height for production of high-quality DRI.

Figure 70 . DRI produced using dried greenballs which contain revert material (dried greenball recipe 14-8) (molar C/O ratio = 1.0) at a furnace temperature of 1500°C and residence time of 80 min. For the DRI shown, the initial bed height was 5.1 cm.
The DRI was cooled in the LHF cooler at a long residence time.

Table XVI . A summary of the experimental findings for DRI produced using dried greenballs which contain revert material (greenball recipe 14-8) (molar C/O ratio = 1.0) at a furnace temperature of 1500°C and residence time of 80 min. The initial bed height was 5.1 cm (2 inches). This sample was cooled in the LHF cooler at a long residence time. Samples were collected equidistant from each other from one corner of the bed to the opposite corner. The average percent metallization for the sample is 74.21% +/- 6.6.

Samples obtained diagonally across the bed	% Fe (total)	% Fe (metallic)	% Metallization	% Fe^{++}	% C	% S
Sample 1	80.04	57.25	71.53	17.56	0.013	0.244
Sample 2	79.99	56.52	70.66	19.22	0.001	0.243
Sample 3	81.84	57.62	70.41	20.25	0.011	0.203
Sample 4	80.20	57.68	71.92	20.06	0.008	0.242
Sample 5	78.78	54.03	68.58	23.11	0.017	0.264
Sample 6	76.64	55.37	72.25	16.77	0.018	0.330
Sample 7	79.87	64.06	80.21	14.20	0.030	0.267
Sample 8	84.33	74.33	88.14	8.81	0.027	0.229

4.5.7 Zinc and Lead Content in DRI Produced Using Dried Greenballs Which Contain Revert Material

4.5.7.1 Effects of Furnace Residence Time and Temperature on the Zinc Content of the DRI

A series of experiments was conducted using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm, furnace temperatures of 1400°C, 1450°C, and 1500°C and several residence times to investigate the effect of furnace hot-zone residence time on the zinc and lead content of DRI produced. DRI produced in these experiments was cooled in the LHF cooler at a long residence time, shoveled into a tray, and further cooled under the hood. A summary of the experimental findings is given in Table XVII. It can be seen from Table XVII that the DRI with the lowest lead and zinc content was produced at a furnace temperature of 1400°C, residence time of 100 min, and an initial bed height of 7.6 cm.

It should be noted that the percent zinc removal throughout the experiments cannot be calculated effectively, due to the fact that the weight of DRI produced was not measured for the DRI cooled under the external cooling hood. DRI produced using dried greenballs containing revert material was cooled in the LHF cooler at a long residence time and shoveled into a tray placed under the external cooling hood. A considerable amount of fines was left in the cart as a result of removal by shovel. The fines weight was not measured nor tested for zinc content.

Table XVII . DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio = 1.1) at an initial bed height of 7.6 cm, at various furnace temperatures and residence times.

Furnace Temp (°C)/Residence Time (min)	% Pb (Top)	% Zn (Top)	% Pb (Middle)	% Zn (Middle)	% Pb (Bottom)	% Zn (Bottom)
1400°C / 50 min	0.005	0.105	0.006	0.079	0.037	2.889
1400°C / 80 min	0.005	0.041	0.006	0.114	0.004	0.081
1400°C / 100min	0.008	0.029	0.006	0.020	0.007	0.029
1450°C / 50 min	0.003	0.089	0.006	0.448	0.074	2.648
1450°C / 80 min	0.005	0.043	0.006	0.139	0.005	0.107
1500°C / 50 min	0.007	0.102	0.073	2.824	0.086	3.264
1500°C / 80 min	0.002	0.071	0.005	0.076	0.001	0.025

Relationships between weight percent zinc contained in DRI located at the top, middle and bottom of the bed and various furnace hot-zone residence times at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C, are shown in Figures 71, 72, and 73, respectively. It can be seen from these figures that as the furnace residence time increases, the zinc content of the DRI decreases. Further studies should be conducted to determine zinc removal kinetics.

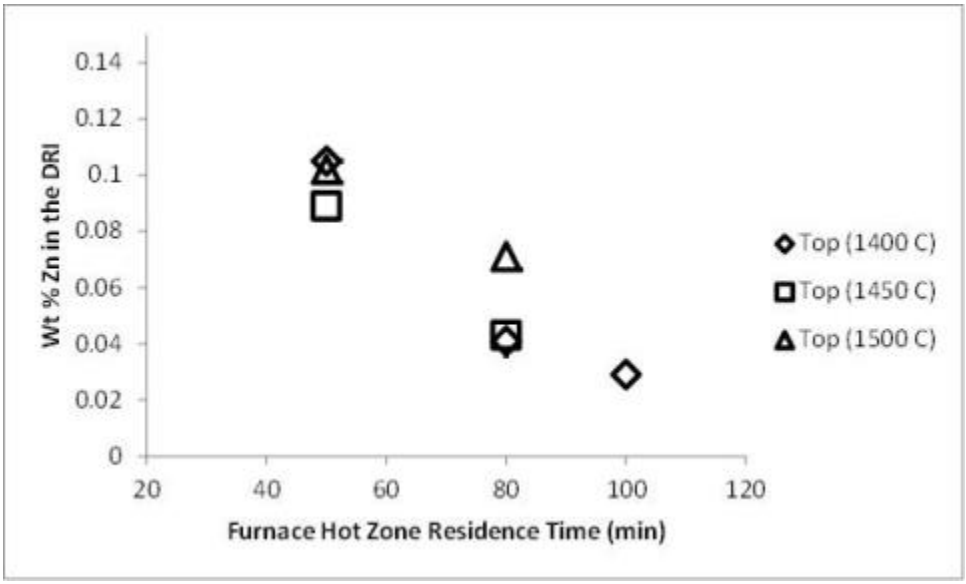

Figure 71 . Relationships between wt % Zn content of DRI located at the top of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C.

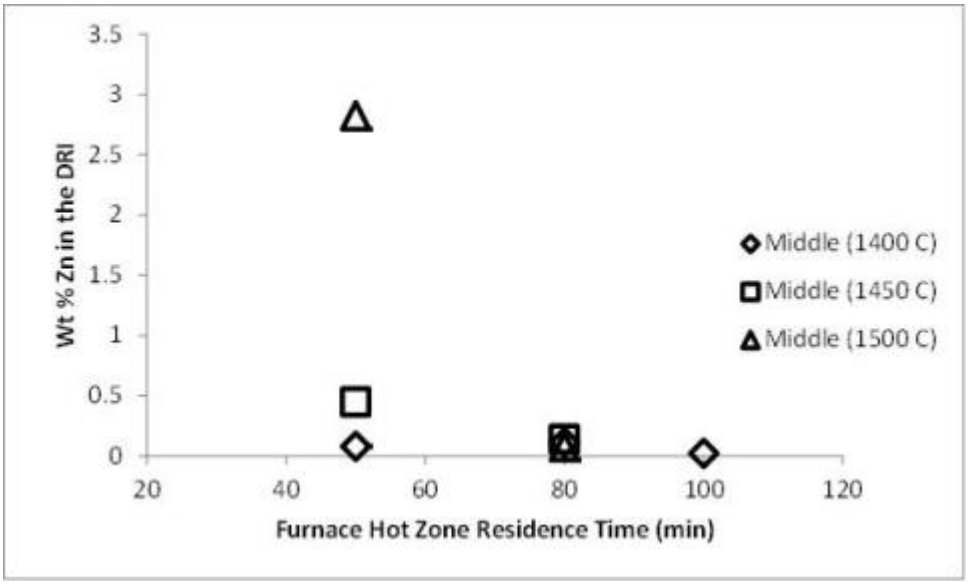

Figure 72 . Relationships between wt % Zn content of DRI located at the middle of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C.

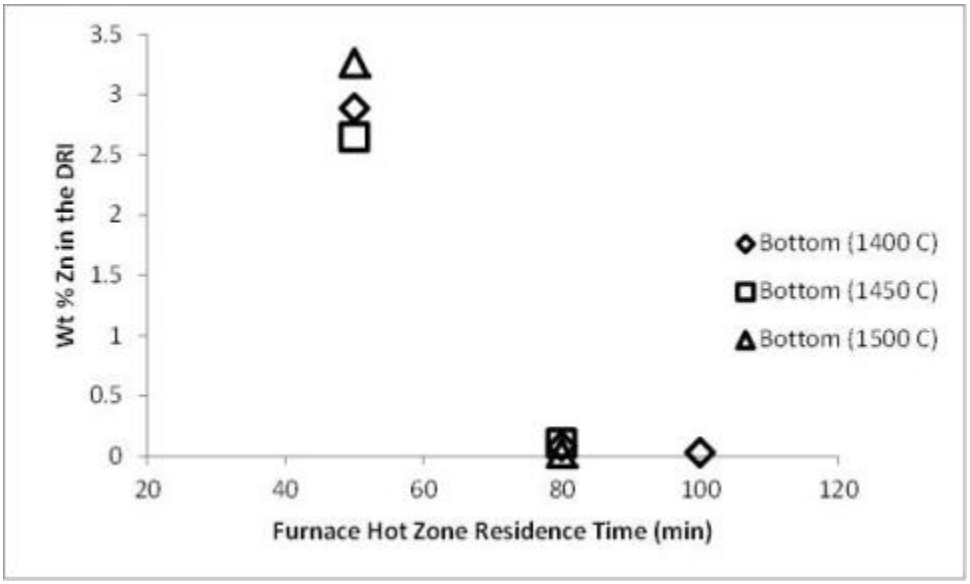

Figure 73 . Relationships between wt % Zn content of DRI located at the bottom of the bed and furnace hot-zone residence time for DRI produced using dried greenballs which contain revert material (greenball recipe 14-5) (molar C/O ratio =1.1) at furnace hot-zone temperatures of 1400°C, 1450°C, and 1500°C.

4.5.7.2 Effect of Initial Bed Height on the Zinc Content of the DRI

A series of experiments was conducted using dried greenballs which contain revert material (greenball recipe 14-8) (molar C/O ratio =1.0) at a furnace temperature of 1500°C and a residence time of 80 min, at various initial bed heights of 7.6 cm, 10.2 cm, and 12.7 cm. DRI produced throughout these experiments was cooled in the LHF cooler at a long residence time. A summary of the experimental findings is given in Table XVIII. It can be seen from Table XVIII that the DRI with high concentrations of zinc was produced at initial bed heights of 10.2 cm and 12.7 cm.

Table XVIII . A summary of the experimental findings, for DRI produced using dried greenballs which contain revert material (greenball recipe 14-8) (molar C/O ratio = 1.0) at a furnace temperature of 1500°C and residence time of 80 min. Three different initial bed heights were used when loading the dried greenballs in the furnace. These initial bed heights were 7.6 cm, 10.2 cm and 12.7 cm.

Initial Bed Height (cm)	% Pb (Top)	% Zn (Top)	% Pb (Middle)	% Zn (Middle)	% Pb (Bottom)	% Zn (Bottom)
7.6 cm	0.010	0.061	0.009	0.085	0.008	0.283
10.2 cm	0.009	0.025	0.010	0.108	0.085	3.104
12.7 cm	0.002	0.037	0.003	0.094	0.068	3.248

The relationship between weight % zinc (Zn) content of DRI located at the top, middle and bottom and initial bed height for DRI produced at a furnace temperature of 1500°C and residence time of 80 min, is plotted in Figure 74. It can be seen from Figure 74 that for DRI located at the bottom, significant zinc removal was achieved only when the initial bed height was 7.6 cm.

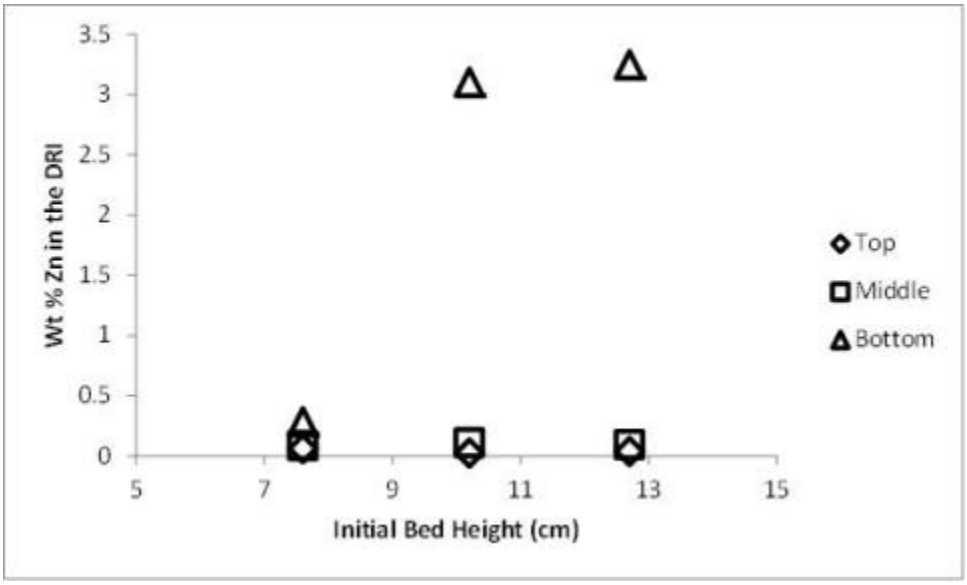

Figure 74 . Relationships between wt % Zn content of the DRI at initial bed heights of 7.6 cm, 10.2 cm, and 12.7 cm for DRI produced at a furnace temperature of 1500°C and residence time of 80 min. Dried greenballs which contain revert material (greenball recipe 14-8) (molar C/O ratio = 1.0) were used as feed.

4.5.7.3 Effect of Dried Greenball Molar Carbon-to-Oxygen Ratio on Zinc Content of the DRI

A series of experiments was conducted to determine the effects of dried greenball molar carbon-to-oxygen ratio on the quality of DRI produced. The dried greenballs used for these experiments had either a 1.0 or 1.1 molar C/O ratio. They were heated at a furnace temperature of 1500°C, and residence times of either 50 min or 80 min.

The relationships between wt % Zn content of DRI located at the top, middle and bottom of the bed, and furnace hot-zone residence time for DRI produced using dried greenballs which had molar carbon-to-oxygen ratios of 1.1 (greenball recipe 14-5) and 1.0 (greenball recipe 14-8) are plotted in Figures 75, 76, and 77, respectively. Further studies should be conducted to determine the effect of molar carbon-to-oxygen ratio on the zinc removal kinetics.

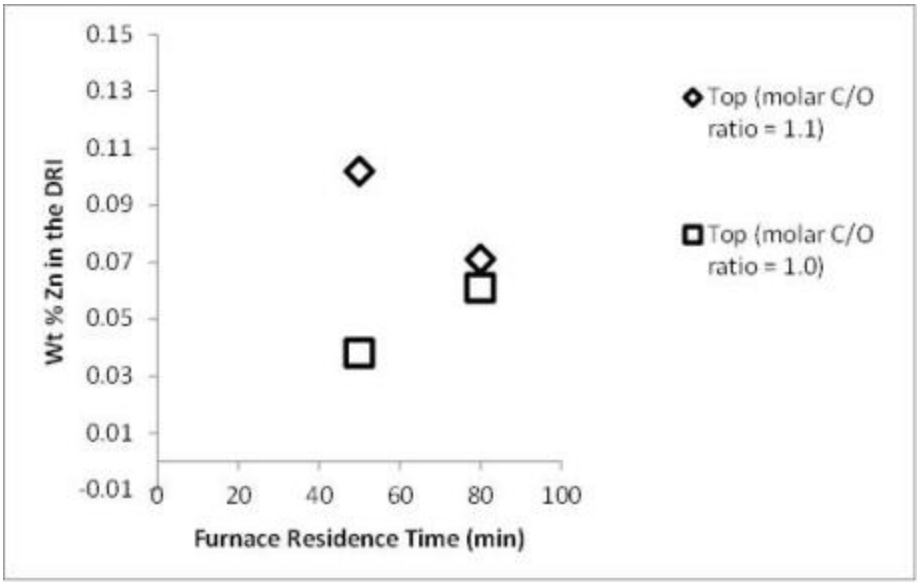

Figure 75 . Relationships between wt % Zn of DRI located at the top of the bed, and furnace hot-zone residence time for DRI produced using dried greenballs which had molar carbon-to-oxygen ratios of 1.1 (greenball recipe 14-5) and 1.0 (greenball recipe 14-8).

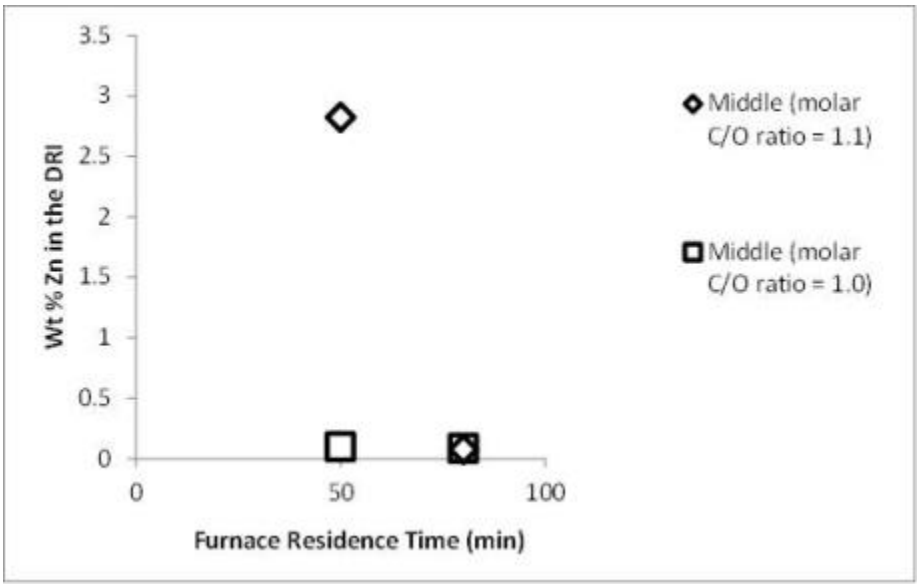

Figure 76 . Relationships between wt % Zn of DRI located at the middle of the bed, and furnace hot-zone residence time for DRI produced using dried greenballs which had molar carbon-to-oxygen ratios of 1.1 (greenball recipe 14-5) and 1.0 (greenball recipe 14-8).

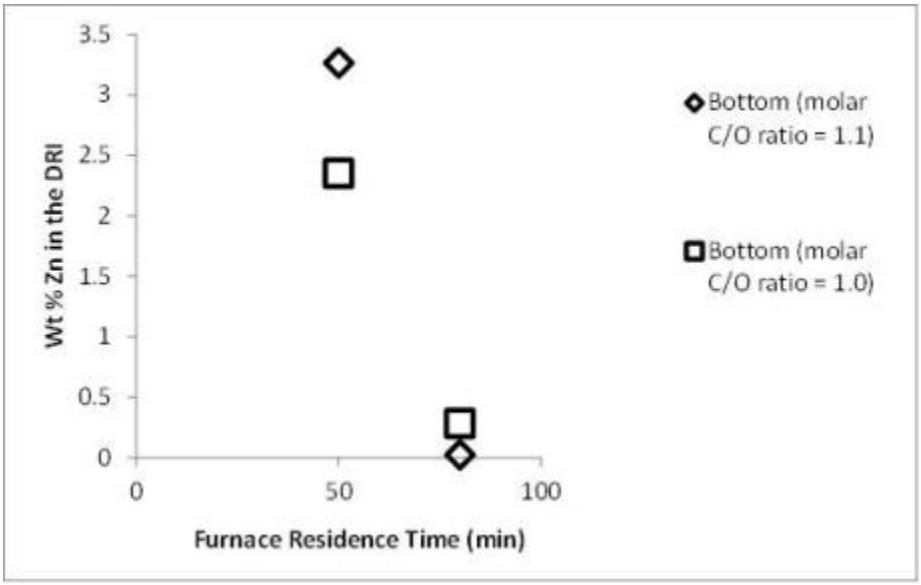

Figure 77. Relationships between wt % Zn of DRI located at the bottom of the bed, and furnace hot-zone residence time for DRI produced using dried greenballs which had molar carbon-to-oxygen ratios of (greenball recipe 14-5) 1.1 and 1.0 (greenball recipe 14-8).

4.6. Grate Factor

The grate factors were estimated for dried greenballs which contain magnetite concentrate and for dried greenballs which contain revert material. In both cases, the optimum bed depth where percent metallization was the highest in these experiments was identified as 7.6 cm (3 inches), and the optimum furnace hot-zone residence time was 80 minutes. The optimum molar carbon-to-oxygen ratio for the coal used was 1.1. The optimum furnace hot-zone temperature for production of DRI using dried greenballs which contain magnetite concentrate was 1500°C, but the optimum furnace hot-zone temperature for production of DRI using dried greenballs which contain revert material was lower, at 1450°C. The cart loading was 95.8 kg/m^2 for the dried greenballs which contain magnetite concentrate, so the grate factor would be 71.9 kg/m^2/h at 80 min furnace hot-zone residence time. For the dried greenballs which contain revert material, the loading was 105.45 kg/m^2, so the grate factor would be 79.1 kg/m2/h at 80 min at furnace hot-zone residence time.

It should be noted that in both cases, the hearth preheat temperature was 800°C. For these calculations, the residence time in Zone 1 and the cooling zone were not included. In addition, throughout the experiments, only three carts were loaded in the furnace.

5.0 Conclusions

Pilot-scale studies were conducted using the NRRI LHF to simulate one-half of the PSHF process. Dried greenballs which contained either magnetite concentrate or revert material (BOF dust) as an iron oxide source, high-volatile bituminous coal as a reductant, and bentonite as a binder, were used as a feed materials.

The studies were conducted in five (5) phases. These phases included:

- **Phase I** – Modified LHF to simulate the conditions required for the PSHF.

- **Phase II** – Identified LHF operational conditions.

    - The residence time required in the LHF cooler was identified. The DRI produced with a long residence time had less reoxidation, and high amounts of remaining carbon.

    - In order to minimize the amount of reoxidation, an external hood was constructed. The DRI cooled with a long residence time was shoveled out to trays and cooled under the external hood with nitrogen purge.

    - Some benefits on the percent reduction and horizontal shrinkage of the DRI were observed when using carts with alumina bricks installed at the sides.

- **Phase III** – Evaluated effects of furnace temperature, residence time, dried greenball molar carbon-to-oxygen ratio, and initial bed height on the reduction of dried greenballs containing magnetite.

    - Highest percent metallization when using dried greenballs which contain magnetite concentrate was achieved at a furnace temperature of 1500°C, a residence time of 80 min, an initial bed height of 7.6 cm, and a dried greenball molar carbon-to-oxygen ratio of 1.1. Percent metallization in the top, middle and bottom bed fractions was 89.22%, 87.32%, and 83.22%, respectively.

    - It was observed that for DRI produced using dried greenballs which contain magnetite concentrate, the furnace temperature had a greater impact on the percent metallization than did furnace residence time. When operating at furnace temperatures below 1450°C, the percent metallization achieved was considerably lower than 80%.

    - For DRI produced with dried greenballs which contain magnetite concentrate, a considerable increase in percent metallization was observed when the dried greenball molar carbon-to-oxygen ratio was increased from 1.0 to 1.1. However, a further increase in the dried greenball molar carbon-to-oxygen ratio to 1.2 did not seem to significantly affect the DRI quality.

    - For DRI produced with dried greenballs which contain magnetite concentrate, the percent metallization at the bottom of the bed decreased when the initial bed height increased.

- **Phase IV** – Involved simulation of continuous operation of one-half of the PSH furnace using the LHF. This experiment was not successful, due to increased temperatures in Zone 1, triggering the safety feature of the furnace.

- **Phase V** – Evaluated effects of furnace temperature, residence time, dried greenball molar carbon-to-oxygen ratio, and initial bed height on the reduction of dried greenballs containing revert material.

    - Highest percent metallization was achieved at a furnace temperature of 1500°C, a residence time of 80 min, an initial bed height of 7.6 cm, and a dried greenball molar carbon-to–oxygen ratio of 1.1. Percent metallization in the top, middle and bottom of the bed was 86.14%, 82.20%, and 83.62%, respectively.

- For DRI produced using dried greenballs which contain revert material, as the furnace temperature and residence time increased, the percent metallization in the top, middle and bottom of the bed increased.

- For DRI produced with dried greenballs which contain revert material, an increase in percent metallization was observed when the dried greenball molar carbon-to-oxygen ratio was increased from 1.0 to 1.1.

- The practical initial bed height for the reduction of dried greenballs which contain revert material was identified as 7.6 cm.

- The DRI with the lowest zinc content throughout the bed was produced at a furnace temperature of 1400°C and residence time of 100 min using dried greenballs which had a molar carbon-to-oxygen ratio of 1.1 at an initial bed height of 7.6 cm. Zinc content in the top, middle and bottom of the bed was 0.029%, 0.020%, and 0.029%, respectively.

The grate factors were estimated for dried greenballs which contain magnetite concentrate and for dried greenballs which contain revert material. For dried greenballs which contain magnetite concentrate, the cart loading was 95.8 kg/m^2, so the grate factor would be 71.9 kg/m^2/h at 80 min furnace hot-zone residence time. For the dried greenballs which contain revert material, the loading was 105.45 kg/m^2so the grate factor would be 79.1 kg/m^2/h at 80 min at furnace hot-zone residence time. These grate factors do not account for the preheat times nor any cooling times. It should be noted that in all tests, the hearth preheat temperature was 800°C.

6.0 Recommendations for Future Studies

6.1 Agglomeration

High-quality DRI production using the PSHF process is highly dependent upon both the heat transfer and the gas transfer within the bed. For DRI produced using dried greenballs which contain revert material, a considerable amount of fines generation was observed. The presence of these fine materials in the bed limits both the heat transfer and the gas transfer within the bed. Thus, further studies to improve balling of revert materials, and studies to eliminate fines generation during heating and reduction are recommended.

6.2 Coal as a Reductant

Throughout this study, only one type of coal, a bituminous coal with very high volatile matter, was used as a reductant. Additional studies should be conducted to determine the optimum type of coal needed for the specific iron oxide materials on hand. The effectiveness of the coal volatile matter for developing metallization throughout the bed should be investigated as a function of the furnace Zone 1 temperature, residence time, and preheat temperature of the cart hearth. In addition, a study should be conducted on the effect of coal volatile content on removal of both zinc and lead from the dried greenballs which contain revert material.

6.3 Optimum Molar Carbon-to-Oxygen Ratio

During this study, the optimum molar carbon-to-oxygen ratio for production of highly metallized DRI using dried greenballs which contain revert material was not identified. However, an increase in the percent metallization was observed for DRI produced using dried greenballs which contain revert material when the molar carbon-to-oxygen ratio increased from 1.0 to 1.1. Additional studies should be conducted to determine whether further improvement in the percent metallization can be achieved at higher molar carbon-to-oxygen ratios.

6.4 Cart Hearth Preheat Temperature

It was shown in a previous study conducted at NRRI that the temperature at the bottom of the carts prior to loading of the dried greenballs had a great impact on the percent reduction achieved at the bottom of the bed [6]. In the present study, the temperature at the bottom of the carts was 800°C. Since the highest achievable temperature at the bottom of the carts in this study was 800°C, additional laboratory-scale experiments should be conducted to identify the effects of both temperature and heat retention in the refractory at the bottom of the cart (or crucible in laboratory experiments) on the percent metallization attainable at the bottom of the bed with varying initial bed heights.

6.5 Cart Type

If further tests are performed on the LHF, a system to measure the temperature at the bottom of the bed in the carts during transit through the furnace should be devised. In this study, the initial hearth temperature of 800°C was measured at the cart bottom outside the furnace after preheating and prior to charging dried greenballs. In addition, further studies should be conducted with brick-sided carts to investigate the effects on the heat transfer and reduction kinetics.

6.6 Zinc Removal

Further studies should be conducted to identify zinc and lead removal kinetics and the effects of bed height and dried greenball molar carbon-to-oxygen ratio on the extent of zinc removal. This should include an investigation of the interaction of hearth preheat temperature and volatile matter from the coal. These studies can be performed in a laboratory furnace as previously described [6]. Findings from laboratory tests should be confirmed through additional pilot scale studies using the LHF.

6.7 Cooling

Methods to rapidly cool DRI while preventing re-oxidation should be investigated.

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Appendix A

Optical micrographs of DRI produced at the top, middle and bottom of the bed, using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio =1.0) at a furnace temperature of 1450°C, residence time of 80 min, and an initial bed height of 7.6 cm are shown in Figures A-1 through A-3 . This DRI was cooled in the LHF cooler at a long residence time. In these micrographs, the white areas represent metallized areas, light grey areas represent wustite, and dark grey areas represent slag phases. It can be seen from these micrographs that the phases across the DRI samples are not uniformly distributed. The amounts of slag and wustite phases at the bottom of the bed appear to be higher than at the middle or top of the bed.

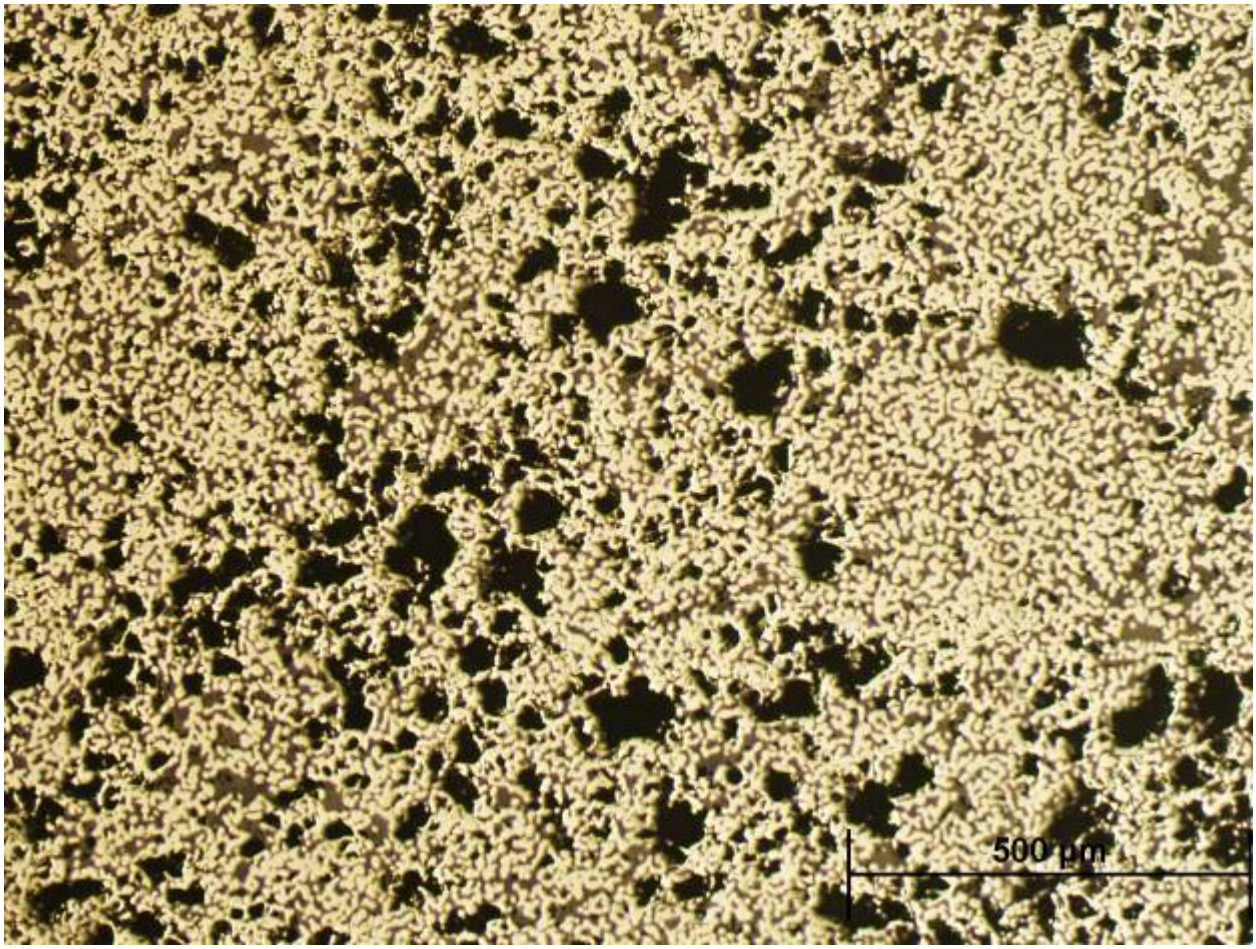

Figure A- 1 . Optical micrograph of DRI produced at the top of the bed using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio =1.0) at a furnace temperature of 1450°C, residence time of 80 min, and an initial bed height of 7.6 cm. The white areas represent metallized areas, light grey areas represent wustite, and dark grey areas represent slag phases.

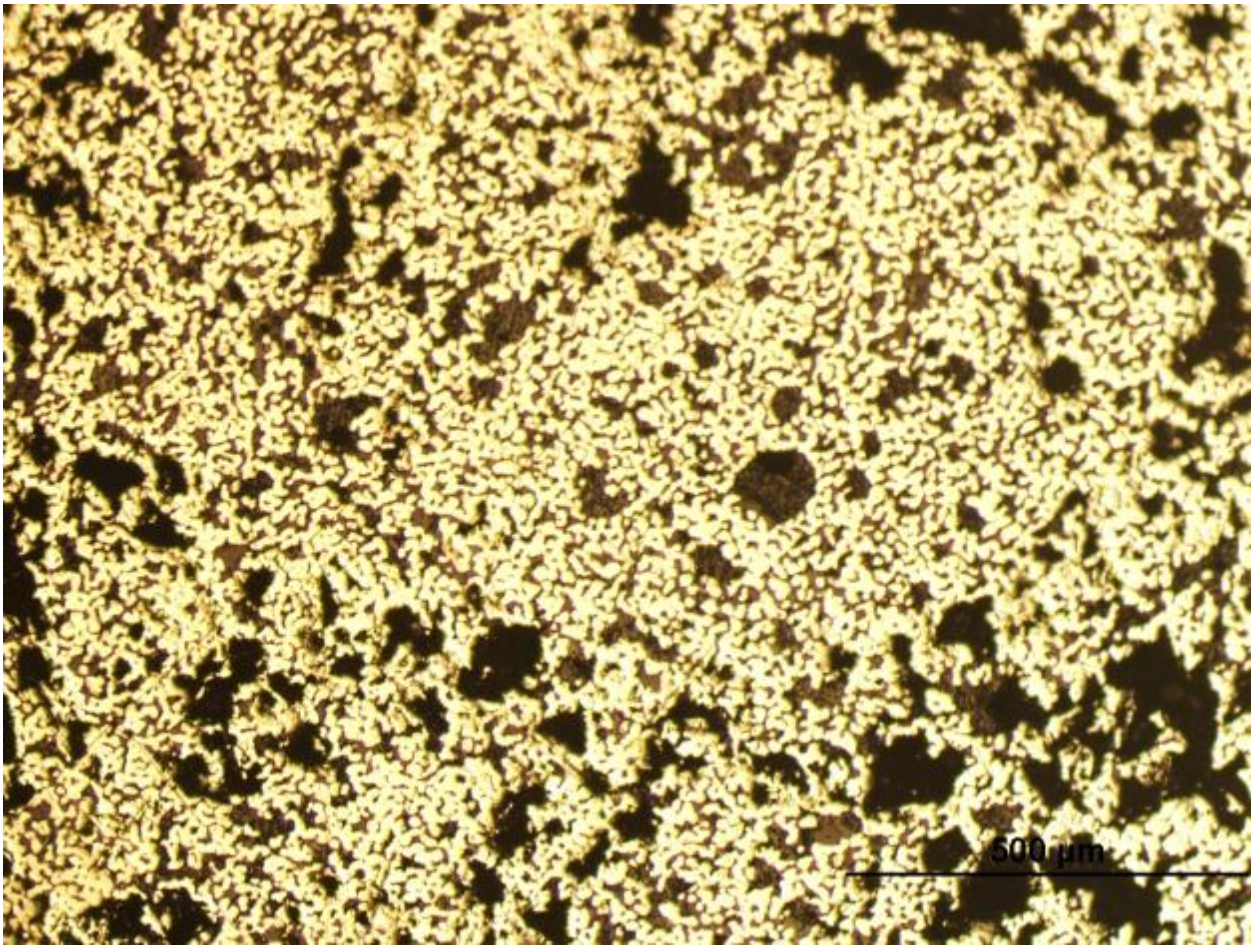

Figure A- 2 . Optical micrograph of DRI produced at the middle of the bed using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio =1.0) at a furnace temperature of 1450°C, residence time of 80 min, and an initial bed height of 7.6 cm. The white areas represent metallized areas, light grey areas represent wustite, and dark grey areas represent slag phases.

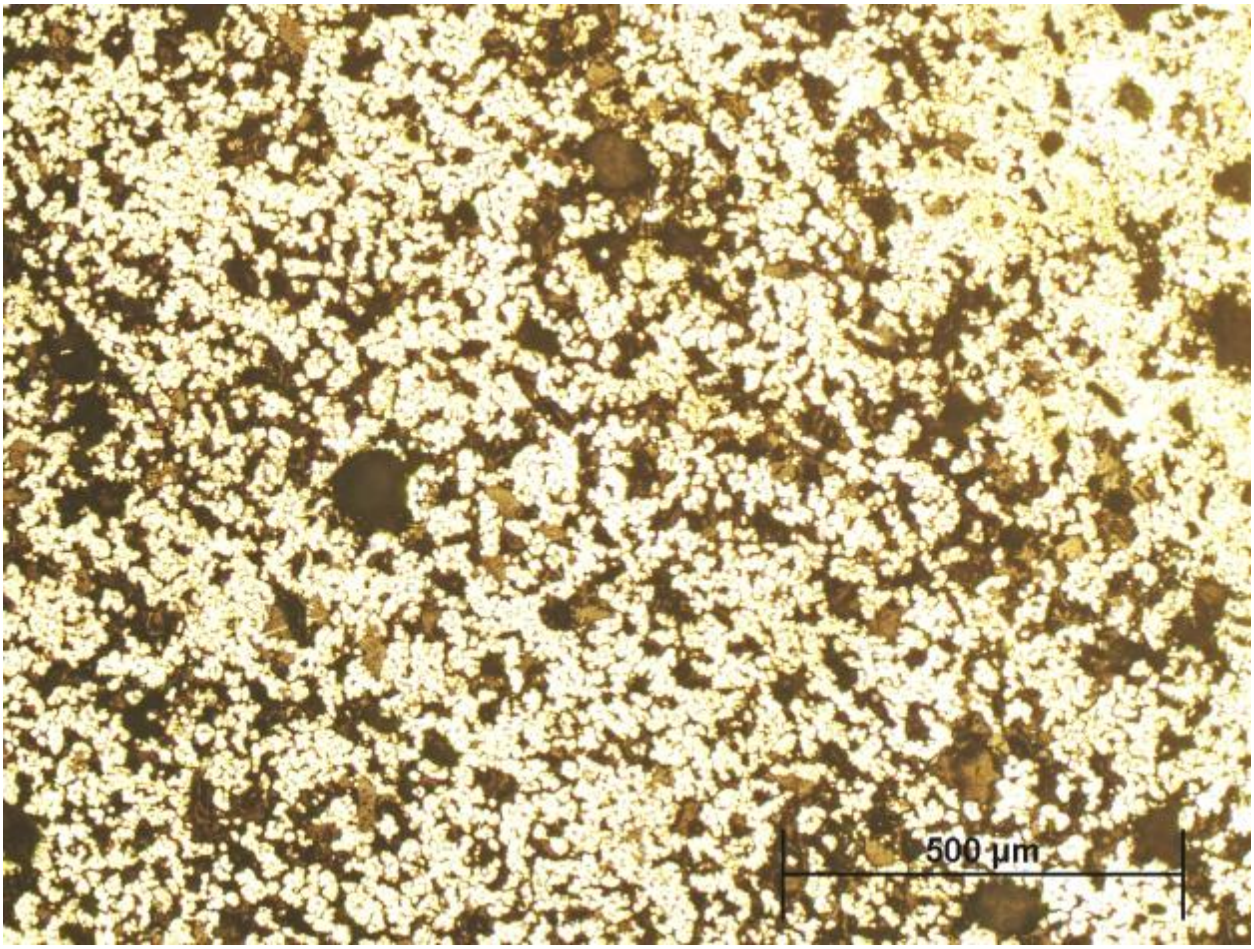

Figure A- 3 . Optical micrograph of DRI produced at the bottom of the bed using dried greenballs which contain magnetite concentrate (greenball recipe 13-1) (molar C/O ratio =1.0) at a furnace temperature of 1450°C, a residence time of 80 min, and an initial bed height of 7.6 cm. The white areas represent metallized areas, light grey areas represent wustite, and dark grey areas represent slag phases.

Optical micrographs of DRI produced at the top of the bed, using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio =1.1) at a furnace temperature of 1500°C, residence time of 80 min, and an initial bed height of 7.6 cm, are shown in Figures A-4 and A-5. The sample of DRI shown in the optical micrograph of Figure A-4 was cooled in the LHF cooler at a long residence time. The sample of DRI shown in the optical micrograph of Figure A-5 was cooled in the LHF cooler at a long residence time and then shoveled out to a tray and further cooled in nitrogen under the external cooling hood. In these micrographs, the white areas represent the metallized areas, light grey areas represent the wustite, and dark grey areas represent the slag phases. It can be seen from these micrographs that there is a thin layer of wustite on the shell of the DRI cooled in the LHF cooler at a long residence time.

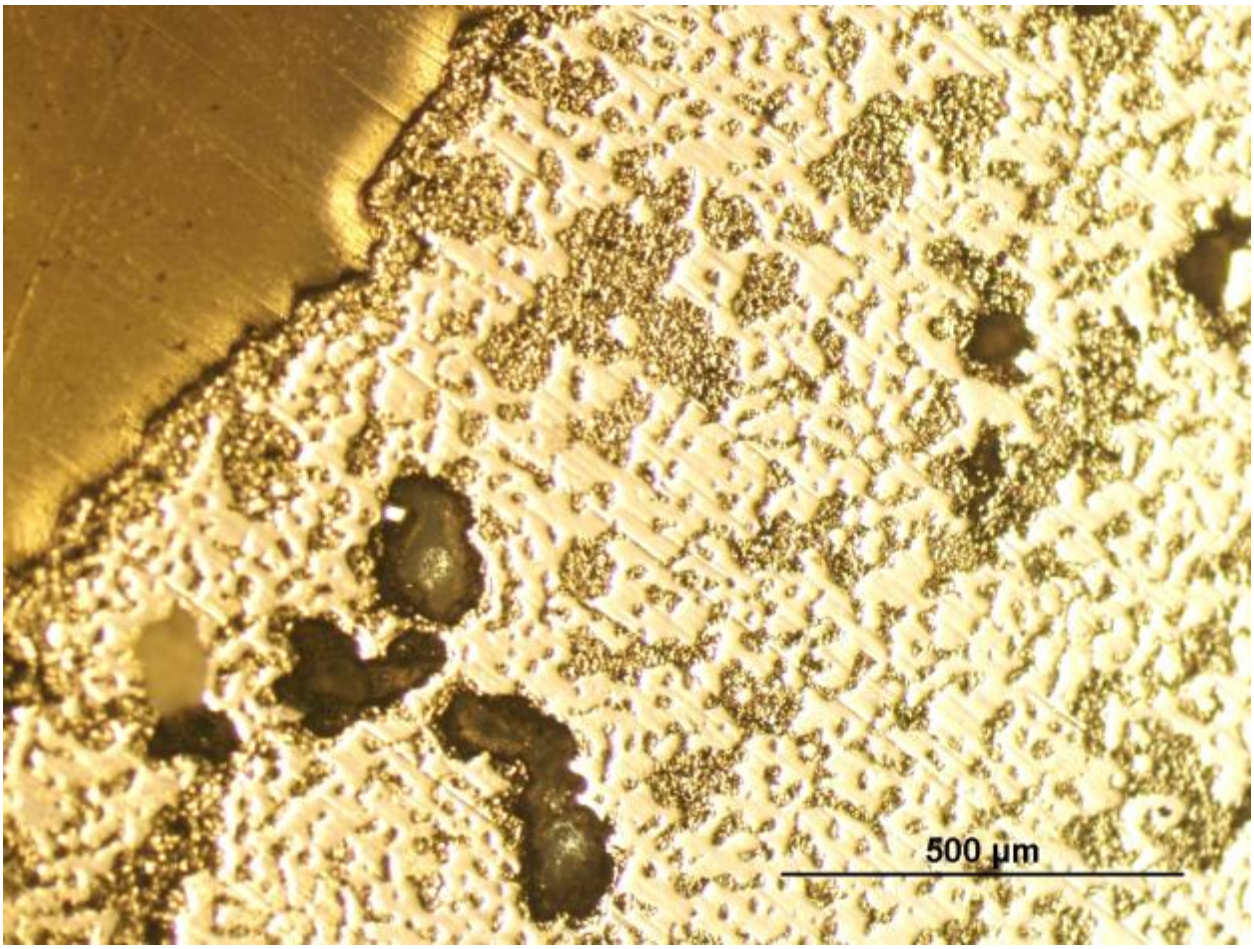

Figure A- 4 . Optical micrograph of DRI produced at the top of the bed using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio =1.1) at a furnace temperature of 1500°C, a residence time of 80 min, and an initial bed height of 7.6 cm. The white areas represent metallized areas, light grey areas represent wustite, and dark grey areas represent slag phases. This DRI was cooled at a long residence time in the LHF cooler.

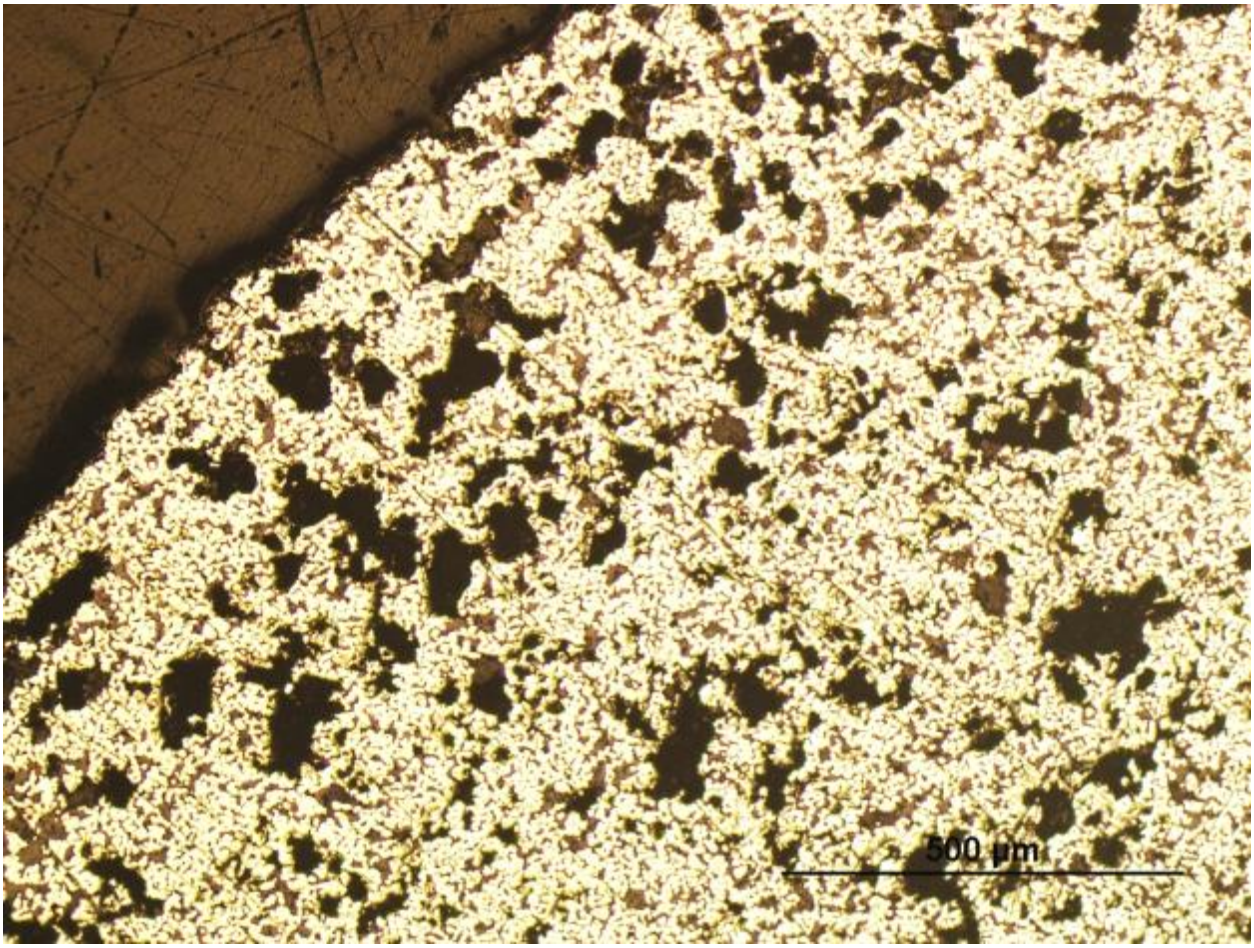

Figure A- 5 . Optical micrograph of DRI produced at the top of the bed, using dried greenballs which contain magnetite concentrate (greenball recipe 14-6) (molar C/O ratio =1.1) at a furnace temperature of 1500°C, a residence time of 80 min, and an initial bed height of 7.6 cm. The white areas represent metallized areas, light grey areas represent wustite, and dark grey areas represent slag phases. This DRI was cooled at a long residence time in the LHF cooler then shoveled out to a tray and further cooled in nitrogen under the external hood.