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AISI/DOE Technology Roadmap Program for the Steel Industry
TRP 9941: A New Process for Hot Metal Production at Low Fuel Rate

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Abstract

This project is a part of the continuing effort supported by the American Iron and Steel Institute and the United States Department of Energy to develop a coal-based and cokeless hot metal production process. A demonstration plant of the Paired Straight Hearth (PSH) furnace is intended to test the core outcomes of the technology developed in an earlier project (TRP 9810) for the production of hot direct reduced iron (DRI) at 95% metallization. The pilot facility is proposed to be built at the facilities of INMETCO in Ellwood City, PA. The process will combine the Paired Straight Hearth furnace with a stripped down version of the oxy-coal converter developed in an AISI project on Direct Steelmaking. The oxy-coal converter is suitable for the melting of hot direct reduced iron (DRI) to be refined into hot metal of low sulfur and nitrogen content. Further testing of the converter is not necessary. Therefore, it will not be a part of the demonstration plant project.

This project has been divided into two phases: Phase 1 - Feasibility and Preliminary Engineering and Phase 2 - Detailed Engineering, Construction and Operations. This document is reporting on Phase I work done by McMaster University and Bricmont, Inc.

The Bricmont, Inc. report and the McMaster University analysis conclude that it is feasible with current technology and construction practices to design, build and operate a demonstration plant of the Paired Straight Hearth furnace with a capacity of 42,000 mtpy of DRI for an estimated cost of \$16,729,000.

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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 Wei-Kao Lu
Professor Emeritus
McMaster University**

February 1, 2006

EXECUTIVE SUMMARY

This project is a part of the continuing effort supported by the American Iron and Steel Institute and the United States Department of Energy on the development of a coal-based and cokeless hot metal production process. The demonstration plant of the Paired Straight Hearth Furnace which has been proposed to be built at Ellwood City, Pa. is intended to test the core outcomes of TRP-9810 technology (the production of hot direct reduced iron (DRI) at 95% metallization). The stripped down version of the oxy-coal converter developed in an earlier AISI project on Direct Steelmaking is suitable for the melting of hot direct reduced iron (DRI) to be refined into hot metal of low sulfur and nitrogen content. Further testing of the converter is not needed. Therefore, it will not be a part of the demonstration plant. This project has been divided into two phases. This document is reporting on Phase I work done in the last 16 months through the interactions of personnel from McMaster University and Bricmont, Inc.

The TRP-9810 methodology of making hot metal has a lower coal rate in comparison with other alternative ironmaking processes because of thermodynamic and kinetic advantages. In the conventional Rotary Hearth Furnace (RHF), such as that at INMETCO and Iron Dynamics, and the modified form at ITmk3, the bed height is less than two layers thick. In the later stage of reaction, in order to limit the extent of re-oxidation of the nascent sponge iron, the furnace productivity and energy consumption are sacrificed by limiting the oxidizing potential of the combustion products. The temperature is maintained around 1300 °C; the CO/CO₂ ratio is maintained at greater or equal to 2.0; and carbonaceous reductants are composed of low volatile matter content to avoid the heat of de-volatilization. In contrast, the new technology developed at McMaster University is based on having a tall bed (up to 8 layers of composite pellets and a height of 120 mm) under a fully oxidized flame at 1600 °C. The higher temperature leads to a much faster rate of radiative heat transfer which limits the rate of reduction, thus, higher furnace productivity results. Full oxidation of combustibles in the reduction zone allows the complete liberation of the chemical heat in the fuel therefore, lower energy consumption is realized. The creative idea, of course, is in the way the nascent sponge iron on the top of DRI bed is protected from the gas of very high oxidizing power flowing above. It is the shrouding effect of gaseous reaction products rising from the bed which has been patented by McMaster University and provides the background technology to the TRP-9810 project. The tall bed makes the flow of shrouding gas steady over a longer time and the use of high volatile coal makes it stronger. The greater degree of densification of DRI at higher temperature results in shrinkage of DRI located in upper positions of the bed. Therefore, it widens the passages for radiative heat flux to reach further down in the pellet bed, layer by layer.

Based on the Final Report submitted by Bricmont, Inc. on the "PAIRED STRAIGHT HEARTH (PSH) FURNACE FEASIBILITY STUDY " (Appendix II) and comments and discussions presented herein the following conclusions may be reached.

- 1) Bricmont reported that it is feasible to design, build and continuously operate the Paired Straight Hearth Furnaces with a capacity of 46,300 tpy (42,000 mtpy) of DRI of 95% metallization. The cost to engineer, manage, and install the facility is estimated to be \$16,729,000.
- 2) In the preliminary design, Bricmont included several precautionary measures to ensure that the shrouding of the top layer of DRI by the gas rising from the bed provided protection against re-oxidation of the sponge iron by combustion products flowing above.
- 3) Successful shrouding will lead to productive and efficient operations. For the demonstration plant to be built at INMETCO, Ellwood City, Pa. Bricmont's estimation of energy consumption per ton of DRI of 95% metallization includes high volatile coal of 564 lb/nt (282 kg/mt) and natural gas of 3.45 MMBtu/nt (0.96 MMkcal/mt). In our opinion, the baffle wall and the flue in Bricmont's preliminary design should be moved to the region of lower temperature and closer to the charging end. With the temperature of the exit gas lowered and counter-current gas/solid movement, the natural gas consumption would be significantly lower than 3 MMBtu/nt.
- 4) For the gas released at the stack of the Ellwood City plant, the emission rates are estimated to be 8.00 lb/hr (3.63 kg/hr) for SO_x at a concentration of 117 mg-SO_x/Nm³ flue gas; and 5.89 lb/hr (2.69 kg/hr) for NO_x at a concentration of 87 mg-NO_x/Nm³ flue gas. With the use of an afterburner, the elimination of CO in flue gas would be complete by all practical measurements.
- 5) For an Ellwood City, Pa. plant location based on domestic raw materials, the cost of production is estimated by Bricmont to be \$193.86/nt (\$213.63/mt) of DRI of 95% metallization, including the delivery cost of \$75/nt (\$82.67/mt) of iron ore concentrate from Minnesota.
- 6) Considering differences in operating conditions assumed by Bricmont and the preferred industrial scheme as depicted on the flow sheet in Table 2, the potential energy consumption in the production of hot metal should be reassessed. According to Table 2 the total coal rate is 791 lb/nt (396 kg/mt) of high volatile coal. Using a conservative estimate for the demonstration plant with simple ancillary equipment (with flue gas leaving the PSH furnace at the peak temperature of the system, low preheating temperature of combustion air and large energy loss to cooling water) more coal has to be burned to generate more fuel gas for the PSH Furnace. Our heat and mass balances calculation suggest that the likely upper limit of the range to be 930 lb/nt (465 kg/mt) for hot metal production. Therefore, the total coal rate would have a range of 791-930 lb/nt (396-465 kg/mt) of high volatile coal per ton of hot metal production, by the all-coal TRP-9810 technology.

- 7) In the "Final Technical Report" of the Mesabi Nugget Research Project by Larry Lehtinen, the energy consumption consists of natural gas - 5.30 MMBtu/nt and low volatile coal - 11.34 MMBtu/nt of nuggets. Using a conversion factor 13,000 btu/lb, the coal rate (in addition to natural gas) would be 872 lbs low volatile coal per ton of nuggets.

RECOMMENDATION

A new proposal should be prepared for the construction and operation of a demonstration plant of the Paired Straight Hearth Furnace at INMETCO in Ellwood City, Pa for further development of TRP-9810 Technology.

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The writer wishes to acknowledge the contribution of Dr. D. Frank Huang of the Research and Development Center of Mittal Steel, East Chicago, Indiana. Frank has made important contributions by participating in technical discussions in meetings held in Pittsburgh and Hamilton as well as debates through telecommunication channels with personnel at Bricmont and McMaster University throughout the course of work on this project. The cooperation from the management of Mittal Steel's R&D Center in allowing Dr. Huang the freedom to pursue these activities is greatly appreciated.

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1. INTRODUCTION

For blast furnace ironmaking, the fuel rate per ton of hot metal varies from furnace to furnace and from time to time. For 1997 ~ 1998, Stubbles^[1] reported the energy intensity (good practice) of hot metal production was 15.48 MBTU/NTHM in the U. S. steel industry. Hot metal production is the key operation in integrated plants and accounts for 72% of the overall energy intensity, 14.88 to 20.66 MBTU/shipped ton of steel in an integrated plant in 1998^[1]. 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 need of a more environmental-friendly and more economical way to make hot metal in general is recognized all over the world. In particular a coal-based and coke-free process is needed. Substantial efforts have been made toward achieving this goal in both sub-sectors of the U.S. steel industry, i.e. the AISI smelting reduction process and the rotary hearth furnace/submerged arc furnace process at Iron Dynamics, Inc and ITmk3 process for making nuggets.

In Project TRP-9810, the development work on a new all coal ironmaking process has been supported by AISI and DOE. It consists of two steps: (1) making DRI from ore/coal composite agglomerates in a tall bed in a PSH Furnace and (2) melting hot DRI in a oxy-coal converter to produce low sulfur and low nitrogen hot metal with controlled amounts of carbon at an energy consumption of two thirds of the amount of a good blast furnace operation.

The present work focuses on building a demonstration plant to test the TRP-9810 technology with particular emphasis on materials handling and energy consumption that could not be investigated in the laboratory or the pilot facility that was used in Genova, Italy. A copy of the proposal is attached here as Appendix I. This report is a summary of work done in Phase I of the project, Preliminary Engineering. The bulk of the work is in the form of interactions with engineers from Bricmont Inc. throughout 2005 on a "Feasibility Study" of using a Paired Straight Hearth Furnace to produce DRI which is the core technology of the TRP-9810 new ironmaking process.

2. FUNDAMENTAL ADVANTAGES IN THE REDUCTION OF GREEN BALLS OF ORE/COAL MIXTURES OVER BLAST FURNACE IRONMAKING

In order to eliminate cokemaking and high temperature iron ore agglomeration, to lower capital and operating costs and to avoid the generation of pollutants in these processes, it is desirable to use iron ore and coal directly. There are two ways to achieve this goal. In smelting reduction, they are charged to the vessel separately. Another approach is to mix iron ore fines or concentrate and pulverized coal, then, to heat the composite to complete the reduction of iron oxide. The latter is more appealing because the rate limiting steps of chemical reactions and mass transfer can be eliminated and replaced by heat transfer which has much higher limiting values. The rate of reduction of iron oxide in the green balls of ore/coal mixtures is determined by the heating rate. At

high temperature, the radiative heat flux is proportional to T^4 . Therefore, the speed of the process can be increased dramatically by the increase of furnace temperature.

In a blast furnace, carbon is burned to CO first with molecular oxygen in the raceways to generate heat and reductants for the process. The drawback is that in the exit gas of the blast furnace there are approximately equal amounts of CO and CO₂ due to thermodynamic limitation. Ignoring the solution-loss reaction ($\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$), it takes two molecules of CO to remove one atom of combined oxygen to give a mixture of equal amounts of CO and CO₂ in the exit gas. The other extreme case is making sponge iron in a retort with external heating where carbon is used first as a reductant to form CO when its reducing potential is highest inside the retort, then, as the fuel, CO is burned to CO₂ externally with all the chemical energy released to sustain the process. The theoretical carbon rate with simplifying assumptions, in the number of oxygen atoms in iron oxide to be removed by each atom of carbon, is 1.0 for retort and 0.5 for blast furnace.

Following the procedure of Fruehan et al.^[2], the theoretical minimum energy of this proposed process which is similar to a retort without the solid wall, in direct comparison with the blast furnace for liquid iron production has been presented in detail in the Final Report of TRP-9810. The results are reproduced here in Table I. The lower carbon rate in the TRP-9810 process is mainly due to the fact that less energy is carried away in the exit gas. As shown in the table, the energy consumptions are comparable.

Table I: Absolute theoretical minimum carbon and energy requirements per tonne of liquid iron at 1600°C (From the TRP-9810 Final Report)

Process	Blast Furnace	TRP-9810 Technology	
		Hematite	Magnetite
Carbon Rate, kg/T.Fe	404	259	238
Energy Requirement, MJ/T.Fe	8673 ^[2]	8482	8387

3. FUNDAMENTAL ADVANTAGES OF TRP-9810 TECHNOLOGY OVER THE ROTARY HEARTH FURNACE (RHF) FOR DRI PRODUCTION.

In the search for a process with a lower coal rate, the right approach appears to be to go along the route indicated in the last section. Carbon should be used first as the reductant in the direct reduction of iron ore, with its full reducing power under a reducing atmosphere. The reaction products are metallic iron and carbon monoxide. In order to sustain the endothermic reaction of metallization, heat may be supplied by burning CO to CO₂ under an oxidizing atmosphere. Currently two types of processes are being pursued to achieve the goal of low carbon rate toward the limits listed in Table I. (i) With the use of a smelting reduction vessel, the difficulty encountered with respect to energy consumption is that there is little space to serve as the oxidizing compartment and very little opportunity to transfer the heat to where it is needed, i.e., the reducing compartment of the system. (ii) With the use of a rotary hearth furnace, the set-up is more suitable for

the intended purpose because there are actually two regions in the system: the space occupied by ore/coal composite pellet is the reducing region and the oxidizing region is where CO and H₂ are oxidized, in the free-board above the pellet bed.

The reacting system of the RHF is shown in Figure 1. It is equivalent to a retort without the benefit of the wall to separate the shallow pellet bed for reduction and free board above for heat generation. The most unfortunate consequence is that the oxidants (CO₂, H₂O and O₂) in the flame can reach sponge iron in the later stage of the process and re-oxidize it back to iron oxide. In general, current RHF operators utilize the following "Rules of Thumb" to minimize the extent of re-oxidation.

- (i) The bed height of agglomerates is about 20-25 mm, less than two complete layers of pellets.
- (ii) The space above the pellet bed where fuel is burned to generate heat and is kept at about 1300 °C and the CO/CO₂ ratio in gaseous phase is equal to or greater than 2.0.
- (iii) Carbonaceous materials of low volatile matter content are preferred as the reductant.

The kinetics of reduction of iron ore oxide in the chemically self-sufficient ore/coal pellets (briquettes) has been confirmed to be heat transfer limited. Thermal conductivity of both the sponge iron layer (due to very high porosity) and the raw materials are both very low. In order to speed up the chemical kinetics controlled by radiative heat transfer, the process temperature has to be raised above that in a conventional RHF. The amount and composition of gaseous product generated by chemical reactions inside the pellet have also been studied. Suddenly, an interesting picture appears. The higher process temperature leads to faster iron oxide reduction and stronger gas flow from the bed of green balls of ore/coal mixtures. The gas flow could shroud the top layer of sponge iron and prevent its re-oxidation by the oxidants from the flame. A schematic diagram is shown in Figure 2. In 1998, the three "Rules of Thumb" of RHF operations were challenged simultaneously, not individually, in the Howe Memorial Lecture of the the Iron and Steel Society and in a research proposal submitted to American Iron and Steel Institute (AISI) and the U.S. Department of Energy. The challenge was based on preliminary data obtained by heating chemically self-sufficient ore/coal agglomerates (pellets or briquettes of a certain shape) in an electrically heated muffle furnace in an air atmosphere.

For further investigations and development in a pilot/demonstration plant, the following values of process parameters were recommended in the Final Report of TRP-9810:

- Pellet bed height 120 mm (old Rule #1, 20-25 mm)
- Flame and refractory surface temperature 1600-1650°C (old Rule #2, about 1300°C)
- Composition of combustion product CO/CO₂ = 0 (old Rule #2, CO/CO₂ ≥ 2.0)
- Volatile matter content in carbonaceous materials about 30% (old Rule #3, coke and anthracite are preferred)

Experimental results obtained at McMaster University with the use of the specially designed natural gas-fired furnace (see Figure 3) of a heat size of 6-7 kg of green balls were excellent under the conditions stated in the previous section. Green balls have relatively low coal addition in comparison with the RHF practice and the DRI has good chemical (95% degree of metallization) and physical (denser than molten slag for easy melting) properties. For an independent confirmation, the pilot plant of CSM Combustion Laboratory in Genova, Italy was chosen and five weeks of trials were conducted to repeat the results with taconite ore obtained on campus, as well as testing hematite ore from Brazil, BOF sludge, mill scales, mixtures of BOF sludge and EAF dust. In general, the experimental results from the pilot plant are better than those obtained on campus, except for the bottom layer of the pellet bed because of the excessive cooling due to nearby water-cooling tubes. Two important conclusions were reached: (i) the equipment on campus can be used to produce meaningful results and (ii) waste oxides from carbon steel plants may be recycled using this technology.

It should be pointed out that the unit of productivity often expressed in weight of DRI per unit area of hearth and per unit time, even with the degree of metallization specified, is not proper because in this calculation gangue in the ore, ash in the coal and oxygen in the iron oxides are counted as product. For ironmaking, it should be the amount of metallic iron produced per unit area per unit time. Detailed comparisons with typical RHF practice have been documented in the Final Report of TRP-9810.

4. THE TRP-9810 TECHNOLOGY

The non-proprietary version of the Final Report of TRP-9810 is available at AISI's TRP website, www.steel-trp.org. Conclusion #1 of the Report is reproduced below:

“The thermo chemical aspect of the process is well established. The process is stable and tolerant to operational errors and in principle; there is practically no risk in scale-up with respect to thermo chemical reactions. DRI are of excellent qualities, physically and chemically. The material handling aspects of the process and the exact energy savings have to be established in a pilot/demonstration plant designed for such tests. ”

The flow sheet of the all-coal operation based on TRP-9810 technology for hot metal production is shown in Table 2, including items from the heat and mass balances. It should be compared with the energy intensity of the Blast Furnace (Good Practice) at 15.48 MMBTU/NTHM according to Stubbles(Ref. #1) and at 16.64 MMBTU/NT Nugget for ITmk3 estimated for a commercial plant at 550,000 mtpy by Larry Lehtinen^[3] (Final Technical Report of MESABI NUGGET RESEARCH PROJECT to DOE).

Table 2 Energy consumption of hot metal production

Items	Consumption	MBTU /NTHM
Coal	791 lb	9.89
Oxygen	3072SCF	0.17 (0.54*)
Lime	190lb	0.61
Electricity	54 kwh	0.18(0.57*)
Gas credit (from hearth furnace)		-0.96
Total		9.89(10.64*)

* including the losses for the generation and transmission of electricity, following Stubbles^[1]

The above flow sheet of the duplex process represents the most energy efficient means to produce hot metal from iron ore and coal ever proposed. DRI of 95% metallization at an average temperature of 2550°F (1400°C) in a hearth furnace will be charged to the AISI Oxy-Coal Converter for melting and refining. The oxy-coal vessel for smelting reduction was developed in the AISI DIRECT STEELMAKING Project and it was designed for the capability of the reduction of wustite to iron and the gasification of about one ton of coal per one ton of hot metal produced. It is well known that in all smelting reduction processes, the concentration of iron oxide in slag which is high enough to be viable for the required kinetics of ironmaking, would lead to a serious problem of refractory corrosion. Also, the generation of large amounts of gas creates the control problems of the foaming slag. The work load assigned to the oxy-coal converter in the above flow sheet in terms of that in a smelting reduction operation is only 5% with respect to metallization and 10% for coal gasification. In the absence of problems of refractory corrosion, slopping, and the impossible task of post combustion/heat transfer, the oxy-coal converter can be operated as controllable as a BOF for melting and refining to produce hot metal of consistent temperature and much lower sulfur and nitrogen contents in comparison with blast furnace hot metal. The efficiency of de-sulfurization by slag depends on slag volume (which is mainly determined by gangue and ash in the raw materials), temperature and the basicity of the slag. In comparison with the blast furnace, the oxy-coal converter should be much more effective for de-sulfurization because the slag and metal are stirred, and the slag is of higher basicity. Basicity of slag in the blast furnace is limited because a more basic slag (which is more effective for de-sulfurization) will promote the cycling of alkalis leading to serious operational problems. Based on the amount of heat required and the amount of carbon to be gasified per ton of hot metal produced, the productivity of the converter should be closer to that of BOF

rather than any smelting reduction vessel. For these reasons, the Oxy-Coal Converter in TRP-9810 Technology is not considered to be a part of the demonstration plant.

5. THE NEW HEARTH FURNACE IN TRP-9810 TECHNOLOGY

The experimental successes at McMaster University and in the pilot plant in Genova, Italy have demonstrated the validity of the thermal-chemical part of the process in a batch type operation. On the other hand, for commercial operation it has to be in a continuous process. Furthermore, materials handling, for example charging and discharging needs to be tested, energy consumption needs to be verified and emissions must be monitored before the commercialization of this new ironmaking process. Our next step is to have the critical assumptions and the new DRI production unit tested at pilot/demonstration plant scale.

Contrary to the rotary hearth furnace (RHF) which is charged with two to three layers of pellets (20 - 23 mm) (see Figure 1) and uses a screw discharger to remove the substantially cooled DRI, the new Paired Straight Hearth (PSH) furnace is charged with 120 mm of pellets (see Figure 2). Due to the breakthrough (sketched in Figure 2) of the protection of sponge iron from re-oxidation in the PSH furnace with a tall bed of pellets, the equipment productivity, energy intensity and DRI quality can be greatly improved with the use of a fully oxidized atmosphere of higher temperature and the use of high volatile coal.

6. BRICMONT'S FEASIBILITY STUDY

The contract with Bricmont, Inc., proposed that this project to be divided into 2 phases:

Phase I. PRELIMINARY ENGINEERING to be performed by Bricmont with assistance from McMaster University and INMETCO.

- (1). Conduct a kick off meeting with all involved personnel.
- (2). Computer modeling of process
- (3). Demonstration scale furnace mechanical design
- (4). Demonstration scale process design
- (5). Computer modeling of reaction zones of the furnace and combustion capacity
- (6). A location plan including preliminary arrangement drawings
- (7). Capital cost estimate for the facility and utility cost
- (8). Final report/follow-up presentation.

Phase II. DETAIL ENGINEERING, INSTALLATION AND COMMISSIONING OF THE FACILITIES.

The facility to be built at INMETCO (Ellwood City, Pa) will have an annual capacity of 42,000mtpy of DRI of 95% degree of metallization from taconite concentrate and high volatile coals.

7. BRICMONT'S FINAL REPORT FOR PHASE I OF THE PROJECT

The Report submitted to AISI on November 8, 2005 is enclosed herewith as Appendix II. Bricmont engineers have done extensive mathematical modeling to translate the McMaster University data obtained in batch processes to continuous operations and exercise their professional judgment based on their experience of decades working on rotary hearth furnaces for re-heating of steel and reduction of iron ore. Preliminary design of the PSH Furnace and ancillary equipment for the demonstration plant and environmental considerations are documented in Appendix II. Even though TRP-9810 Technology is based only on coals of high volatile contents, in the demonstration plant, natural gas will be used because the oxy-coal converter will not be built. Bricmont recognized that the goal of the demonstration plant is to test the "core mechanism" of the process shown in Figure 2, devise equipment for materials handling, environmental protection, energy consumption, etc. Commercial viability of the tall pellet bed theory and the PSH furnace concept depends on results of the continuous operations and tests performed in the demonstration plant. The energy consumption in the demonstration plant will always be higher per unit of output than that in the subsequently built commercial unit because the latter has greater size and improvement in the design of process equipment. It should be noted that Bricmont's estimate of energy consumption in the demonstration plant is essentially the same as that marked on the flow sheet in Table 2, recognizing the differences in conditions assumed. This subject will be discussed later.

The major points of the Bricmont Report are:

- i. The process is indeed feasible to be built and to be operated on a continuous basis.
- ii. All estimations are based on a demonstration plant to be built at INMETCO in Ellwood City, Pa. with a designed capacity of 42,000 mtpy (46,300 tpy) of DRI at 95% metallization.
- iii. The system is expected to produce fully metallized DRI with a natural gas consumption of 0.96 MMkcal/metric ton of DRI (3.45 MMBtu/ton of DRI).
- iv. The cost of production at Ellwood City using domestic raw materials is about \$213.63/metric ton DRI (\$193.86/ton) including the shipping cost of iron ore concentrate from Minnesota at \$82.67/metric ton of concentrate (\$75/ton).
- v. The cost to engineer, construct and operate the facility in Ellwood City is estimated to be \$16,729,000.
- vi. The gas to be emitted from the stack is expected to contain:
SO_x at 3.63 kg/hr (8.00 lb/hr) and 117 mg-SO_x/Nm³-flue gas
NO_x at 2.69 kg/hr (5.89 lb/hr) and 87 mg-NO_x/ Nm³-flue gas
The afterburner will eliminate any trace amount of CO in the flue gas.

8. COMMENTS ON BRICMONT'S REPORT

It must be stated at the beginning that it is a feasibility study and the design is preliminary given the limited resources we provided to Bricmont, Inc. McMaster University has been working on this process for quite a long time and has learned many lessons that could not be fully incorporated into the Bricmont knowledge base in such limited time. The comments given below are on the points that either deserve further emphasis or need additional explanation.

(i) The shrouding of sponge iron from re-oxidation

The features of Bricmont's design such as roof-mounted burners, a higher than normal roof, two rows of air ports and the avoidance of excessive turbulence creation, all contribute to the certainty that the mechanism of shrouding shown in Figure 2 will function even more successfully than we experienced in the laboratory and pilot plant where there were none of these precautionary measures.

(ii) The location of flue and hanging baffle wall in PSH Furnace

Figure 5 is a reproduction of *Figure 10* from the Bricmont Report. This is provided to enable easy comparison with Figure 4.

In Figure 4, the paired furnaces are shown twice, once to depict pellet (solids) flow and once to indicate the energy-efficient, counter-current nature of the gas flow. Note that the flue of the furnace is located near the hanging baffle wall and the charging end so that the flue gas will leave the furnace from the lower temperature zone and with lower sensible heat carried away. A significant portion of volatile matter from the pellet bed is introduced through an interconnecting flue from where it is not all needed (Zone 1 defined by Bricmont) to the discharging end (Zone 4) of the paired furnace where the gaseous fuel from the DRI bed is diminishing. This will contribute to the efficient use of gaseous fuel. From chemical kinetics and the rate of heat consumption point of view, more heat should be provided at high temperature for faster heat transfer in Zones 2 & 3 to sustain the high productivity of the process. On the other hand, in Zone 4, reduction of iron ore is approaching practical completion (95% metallization) and the most significant change is densification of DRI. Therefore, the atmosphere in Zone 4 may not be fully oxidized because of the low heat requirement of the process. Down the stream of gas flow in Zones 2 & 3, there is very little risk of re-oxidation of sponge iron because of strong shrouding, therefore, fully oxidized atmosphere will ensure the complete liberation of chemical energy of combustibles for the process where it is needed.

In Figure 5 which is Bricmont's preliminary design, the gas flow pattern is very significantly different from what we reported to AISI & DOE in the project TRP-9810 and in the documents made available to Bricmont at the beginning of project TRP-9941, including Figure 4 as described in last paragraph. In this preliminary design by Bricmont, Figure 5, the flows of gas and solid are co-current. The flue and

baffle wall are located at spots where the temperature is highest according to their calculations. The design shown in Figure 5 has been described as “counter intuitive” by Bricmont but consistent with their mathematical model. Unfortunately there was no time remaining to correct this flaw. However, it does not invalidate the feasibility study.

In Bricmont's estimation the system shown in Figure 5 will be function properly and serve the intended purpose of making DRI of 95% metallization with the lowest energy consumption ever reported.

If the baffle wall and flue are moved to locations in the lower temperature zone and closer to the charging end (somewhat similar to Figure 4), the potential benefits would include the following:

- less sensible heat carried away by flue gas
- less heat loss and maintenance of baffle wall
- more thermal efficiency due to counter-current flows
- less turbulence and oxidizing potential of the gas phase in the discharging end

We are confident that in the final design process, mathematical models with updated conditions will confirm the baffle wall and flue locations similar to Figure 4.

(iii) The energy consumption estimates

The energy consumption estimates for the production of hot metal and the portion for the manufacturing of DRI by TRP-9810 Technology have been documented in detail in the Final Report of TRP-9810 and to a limited extent in the proposal for this project (see Appendix I). In the University laboratory as well as in the pilot plant in Genova, Italy all process variables were studied over specific ranges, for example, the ore/coal ratio, reaction time, temperatures. The median values were chosen for analysis as shown in the flow sheet in Table 2. We are very comfortable with the values of heat and mass balances shown here which are very close to Bricmont's estimate for the operation of the demonstration plant, with the differences in conditions specified. In this comparison, the amount of electricity used to power fans and pumps, etc. in both cases are excluded because they are very similar and minor in magnitude.

For the production of DRI in the PSH furnace there are three major energy inputs, coal in the composite pellets, sensible heat in preheated combustion air and gaseous fuel (natural gas in the Ellwood City plant and in the flow sheet of Table 2, gas from the oxy-coal melter). In terms of coal consumption per ton of DRI of 95% metallization, the amount shown in the flow sheet of Table 2 and the amount reported in *Table 6* of Bricmont's Report are essentially equal. Furthermore, solid products are assumed to leave the furnace at the average temperature of 2552 °F (1400°C) in both cases. For comparison, we should focus on the temperature of the combustion air and the exit gas, and the amount of gaseous fuel needed.

Temperature	Bricmont Report	Table 2 Flow Sheet
Exit Gas	2732°F (1500 C)	2012 F (1100 C)
Combustion air	850 F (454 C)	1562 F (850 C)
Gaseous fuel	3.45 MMBtu/ton natural gas	1.52 MMBtu/ton melter gas

From Bricmont's Report (*Figure 11*, all numbers shown are for per hour and per furnace) there is 3.2 MMBtu per ton of DRI of sensible heat in the exit gas at the temperature shown above. Simplistically, one may say that in this configuration practically all the energy in the natural gas used will be carried away by the exit gas. By re-locating the flue, for example, the temperature of the flue gas is lowered by 500F (260 C) and the amount of natural gas will be cut down to 2.87 MMBtu/ton DRI for the Ellwood City Plant. We have considered the worst case by burning more coal in the oxy-coal melter to generate more gaseous fuel for the PSH furnace under the operating conditions specified by Bricmont and the results of our mathematical model show that the total coal consumption will increase by 132 lb/ ton of hot metal (66 kg/metric ton), to a overall total of 930.2 lb of coal per ton (465.1 kg/ metric ton) of hot metal, from ore and coal at ambient temperature to liquid products.

(iv) The cost of production

The estimated cost of \$ 213.63/metric ton DRI (\$ 193.86/ton) is certainly eye catching. The details are in *Table 6* of Bricmont's Report, entitled 'Operating Cost Estimates'. In this *Table*, the estimated cost of energy (electricity and natural gas) and raw materials are listed. It should be pointed out that operating labor cost is not included. Note that the delivery cost of iron ore from mines in Minnesota is very high at \$82.67/metric ton of iron ore concentrate. This severely impacts the production cost estimate and it is directly related to the Ellwood City, Pa location and unrelated to the specific production process. For each potential user of this technology, the location sensitive items in *Table 6* must be reestimated with their own relevant data.

(v) Similarities and differences between PSH Furnace and existing metallurgical equipment

Both the RHF and the PSH Furnace are “hearth furnaces” which is most suitable for heating the mechanically weak and chemically self-sufficient ore/coal composite agglomerates. With respect to scientific phenomena, the similarity is mainly in heat transfer and the mechanism of reduction. The difference is mainly in gas flow immediately above the DRI bed. Because of these considerations, Bricmont was chosen to perform the feasibility study and we offer the comments stated above.

With respect to the hearth structure and movement and the charging and discharging operations, the similarity between the PSH Furnace on one hand and the straight grate for pellet induration and the sintering machine for iron ore, is striking except for the path of the gas flow. In the straight grate and sintering machine cases, the gas flow goes vertically through the pellet or sinter bed and of course, the hearth. In the PSH Furnace, the hearth is impermeable and the main path of the gas is above the pellet or DRI bed. Due to the limitations in resources and time imposed on the feasibility study, the preliminary design of the charging and discharging operations will require improvement. In the "detail design" phase the assistance of experts on pellet plant equipment will be required.

(vi) The philosophy of making it work first and improving it later

Through many discussion sessions with Bricmont engineers, we appreciate their wisdom in setting up the priorities. All ancillary equipment should be reliable and easy to operate so that our attention will be focused on the PSH Furnace. The technologies in air preheating, pelletization, gas cleaning, air emissions monitoring are all well developed to satisfy our potential needs in the future. The PSH Furnace in a way has been over designed to allow the movement of the hearth in a wide range of speeds and corresponding rates of energy input, and more than adequate water cooling to protect the structures. Even though equipment productivity and energy consumption are the facts that potential users of this technology want to establish, the designer and the operator want to make sure the "brand new furnace" is functioning first. Only after achieving stable operation, can efficiency parameters, productivity and energy intensity have the significance that we predict. Bricmont has designed the furnace based on the median values of each parameter we provided. While conservative, the approach is acceptable. In our opinion, it is very probable that Bricmont's operational design can yield the results in productivity and energy intensity as estimated in their Report.

9. OTHER ALTERNATIVE IRONMAKING PROCESSES

In the spring of 2005, AISI established a project on TECHNOLOGY SURVEILLANCE – IRONMAKING with the participation of eight member companies and McMaster University. A White Paper on the subject was prepared by this writer to overview and assess the current state of the development in this area. Among the emerging ironmaking processes, four technologies have passed the pilot stage and were selected for further study and onsite visits. FINEX, HIs melt and ITmk3 were chosen as alternative processes to the blast furnace and OxyCup was chosen for the recycling of in-plant scrap and waste oxides. Three of these processes are briefly reviewed below. The comparison of process efficiency and product quality between ITmk3 and the TRP-9810 Technology is developed in more detail.

A. HIs melt , FINEX and OxyCup

Among smelting reduction processes; DIOS, AISI, etc., the lone survivor today is HIs melt. The improvements such as in the design of the vessel and injection units, the addition of a fluidized bed to preheat the fine ore, etc., will lead to more reliable operation, but the fundamental problem originating in the process thermodynamics remains. When the vessel is used for the reduction of iron oxide in the slag at an adequate rate, the rate of refractory attack by the same slag is appreciable because the concentration of iron oxide in the slag determines both effects. In order to have the coal rate lowered to an acceptable level, there must be an oxidizing compartment for post-combustion as well as conditions for transferring the heat generated in the oxidizing compartment to the reducing compartment (slag/metal/carbon reacting mass). Among all the designs of smelting reduction vessels proposed, HIs melt included; the space for post-combustion and heat transfer is inadequate; therefore, the very high coal rate and the slopping of melts will continue to be problematic.

When the shaft furnace of COREX is replaced by a train of four fluidized beds for preheating and reduction, it becomes FINEX. COREX is a well established commercial technology while none of the smelting reduction processes has reached that status yet. The high temperature unit in COREX is used for gasification of coal and melting of DRI. The stated motivation of the development of FINEX is that the fine ore to be used in FINEX is cheaper than the pellets and crushed ore for COREX. It should be noted that after metallization the powdery sponge iron has to be hot briquetted, before charging to the gasifier/melter. Operationally, there are two issues with the FINEX technology. Safety is the first concern in the handling of large amount of hot and dirty reducing gas circulating in the plant. The second challenge is to maintain a stable operation of “directly” coupled continuous reactors with counter-current movement of gas and solids through four fluidized beds and the gasifier/melter.

For OxyCup the feed materials are both the sized in-plant scrap and cold bonded “bricks” made of mixtures of carbonaceous materials and waste oxides as well as a certain amount of coke for permeability. Metallurgically, the reactor behaves somewhat like both a low-shaft furnace as well as a cupola, depending on the nature of feed

materials. It is designed as a recycling unit for an integrated plant. It can not be and should not be considered as an alternative to the blast furnace because of its inferior efficiency.

B. ITmk3

ITmk3 is a modified RHF with an added melting zone of higher temperature located after the reduction zone to liquefy the partially reduced DRI , an ore/coal composite. After the separation of liquid metal and slag, iron nuggets and solid slag are made in the subsequent cooling zone. ITmk3 shares the advantage of using composite pellets with TRP-9810 Technology for lower energy consumption than processes based on smelting reduction. However, there are significant differences in energy consumption and quality of product and similarity in the rate-controlling mechanism in these two processes as outlined in following paragraphs.

(i). Energy Intensity`

The major differences between the ITmk3 and TRP-9810 Technology are listed in the following table. Two figures for energy consumption under TRP-9810 are shown. The larger figure includes the losses for generation and transmission of electricity.

	ITmk3	TRP-9810
Product	solid nuggets "pig iron"	liquid hot metal
Raw materials, coal natural gas	low volatile coal yes	high volatile coal no
Energy consumption ** per ton of product	coal 11.34 MMBtu <u>natural gas 5.30 MMBtu</u> sub-total 16.64 MMBtu	coal 9.89(10.64) MMBtu <u>natural gas 0.00</u> sub-total 9.89(10.64) MMBtu
Layers of agglomerates	less than one layer	eight layers in the bed

** Data for ITmk3 are from "Final Technical Report" of Mesabi Nugget Research Project by Larry Lehtinen (DE-FC36-02ID14280). For TRP-9810 Technology using an oxy-coal melter, the details of the energy estimation have been documented in the proposal of this project (Appendix I). For comparison, the energy intensity for the blast furnace (good practice) 1997-1998 is 15.48 MMBtu according to John Stubbles based on AISI data.

(ii). Product Quality

DRI made from ore/coal composite agglomerates retains all the gangue in ore and the ash in coal as well as a substantial portion of the sulfur from the raw materials. Without the step of de-slagging and de-sulfurization in the molten state, the amount of such DRI to be used for making quality steel will be limited, particularly for steelmaking furnaces that lack the space for holding slag. Assuming with the same raw materials, the quality of the product is determined and limited by the conditions of the melting and refining.

Since the conditions of slag/metal reactions in ITmk3 and TRP-9810 Technology are very different, some definite comparisons may be made. In ITmk3, we believe that judging by the size and the shape of the nuggets, there are many separate small pools of reacting slag and iron in the melting zone. Each of the small pools may have originated from single and isolated green agglomerate in order to avoid the formation of very large "nuggets" that would create a problem in discharging by the existing equipment. In the RHF of ITmk3, DRI is made in the reduction zone and becomes molten in the subsequent melting zone without the opportunity to add fluxes for chemical and physical considerations. In the design of the green agglomerate, a compromise between the optimum composition for reduction on one hand and that for melting and refining on the other has to be made. Most likely the latter would be considered of secondary importance. To be concise, the other relevant conditions are listed below.

Slag/metal System	ITmk3	TRP-9810 Tech.
Temperature	around 1400 C	1500 to 1600 C
system size	tens of grams	hundreds of tons
intensity of stirring	very weak, if any	extremely intensive
slag composition	fixed in the composite	controlled by adding flux to converter
reaction time	short	longer
gas over liquid iron	nitrogen-CO-CO2	CO-CO2

Based on the conditions listed above, attention should be given to the following issues.

- Nitrogen pick-up by the Fe-C melt from the atmosphere in ITmk3 will take place.
- In the converter with a strong carbon-boil and little nitrogen source, the nitrogen content in the hot metal should be very low.

--- With conditions of higher temperature, more basic slag, better mixing and longer reaction time, the de-sulfurization reaction in the converter should have greater sulfur capacity in the slag and the sulfur content of the hot metal should be closer to its thermodynamic equilibrium value. The blast furnace is known to be very efficient in de-sulfurization. However, the converter under consideration should do much better with more basic slag and more stirring. The basicity of the blast furnace slag is limited in order to control the cycling of alkalis which is not operative in the converter.

(iii). Environment, Scale-Up and Capital Cost of Commercial Plant

The overall rate-control step in both ITmk3 and TRP-9810 Technology is heat transfer mainly from the freeboard to the chemically self-sufficient composite in the vertical direction. It has been established in the laboratory and in a pilot plant that the capacity of a hearth furnace for ironmaking is proportional to the area of the hearth under the same thermal conditions. It has been a good guidance in the scale-up of these types of furnaces. From our point view, it is fortunate that the development of the ITmk3 is one step ahead of TRP-9810 technology. Due to the similarity in combustion conditions, the air emissions of pollutants from the stack would be similar. A table from Lehtinen’s ITmk3 Report is reproduced below.

	<u>BF Route</u>	<u>ITmk3</u>	<u>% Reduction</u>
CO	9.40	0.38	96.0
NOX	2.57	0.90	65.0
PM10	0.84	0.33	60.5
SO ₂	0.84	0.19	77.7
VOC	0.29	0.04	86.5
CO ₂	2251	1320	41.4

(Emissions are in Kg per metric tones of steel products)

The success of the ITmk3 would be advantageous to the advancement of the TRP-9810 Technology. Several engineering companies have indicated that for the same hot DRI production capacity, the capital cost of ITmk3 and the PSH furnace are comparable. Recently, Mesabi Nugget LLC of Minnesota announced that the construction of the \$150-million project which will produce 600,000 tonnes of iron nuggets annually, will start early in 2006.

(iv) Remarks

With the use of the all-coal TRP-9810 Technology hot metal of very low sulfur and nitrogen contents may be made at a low energy intensity based on high volatile (cheaper) coals, in comparison with hot metal from the blast furnace or nuggets from ITmk3. Other benefits are in environmental protection because less CO₂ and other pollutants are generated and emitted. In comparison with ITmk3, the TRP-9810 Technology includes

an oxy-coal melter at additional capital cost to produce gaseous fuel and high quality hot metal for the benefit of steelmaking operation, particularly the EAF shops.

10. CONCLUSIONS

Based on the Final Report submitted by Bricmont, Inc. on the "PAIRED STRAIGHT HEARTH (PSH) FURNACE FEASIBILITY STUDY ", TRP-9941, and comments and discussions presented above, the following conclusions may be reached.

- 1) Bricmont reported that it is feasible to design, build and continuously operate continuously the Paired Straight Hearth Furnaces with a capacity of 46,300 tpy (42,000 mtpy) for the production of DRI of 95% metallization. The cost to engineer, install, and operate the facility is estimated to be \$16,729,000.
- 2) In the preliminary design, Bricmont included several precautionary measures to positively ensure that the top layer of the DRI bed be shrouded by the gas rising from lower in the bed and that the shroud effect be adequate for the protection of sponge iron from re-oxidation by combustion products flowing above.
- 3) Successful shrouding will lead to productive and efficient operations. For the demonstration plant to be built at INMETCO, Ellwood City, Pa. Bricmont's estimation of energy consumption per ton of DRI of 95% metallization includes high volatile coal of 564 lb/nt (282 kg/mt) and natural gas of 3.45 MMBtu/nt (0.96 MMkcal/mt). In our opinion, the baffle wall and the flue in Bricmont's preliminary design should be moved to the region of lower temperature and closer to the charging end. With the temperature of the exit gas lowered and a gas/solid counter-current movement, the natural gas consumption would be significantly lower than 3 MMBtu/nt.
- 4) For the gas released in the stack of the Ellwood City plant, the emission rates are estimated to be 8.00 lb/hr (3.63 kg/hr) for SO_x at a concentration of 117 mg-SO_x/Nm³ flue gas; and 5.89 lb/hr (2.69 kg/hr) for NO_x at a concentration of 87 mg-NO_x/Nm³ flue gas. With the use of an afterburner, the elimination of CO in flue gas would be complete by all practical measurements.
- 5) At the location of Ellwood City, Pa. based on domestic raw materials, the cost of production is estimated by Bricmont to be \$193.86/nt (\$213.63/mt) of DRI of 95% metallization, including the delivery cost of \$75/nt (\$82.67/mt) of iron ore concentrate from Minnesota.

- 6) Considering differences in operating conditions assumed by Bricmont for the demonstration plant and the recommended industrial situation as marked on the flow sheet in Table 2, the potential energy consumption in the production of hot metal should be re-assessed. Shown in Table 2 the total coal rate is 791 lb/nt (396 kg/mt) of high volatile coal. Using a conservative estimate for the demonstration plant with simple ancillary equipment (with flue gas leaving the PSH Furnace at the peak temperature of the system, low preheating temperature of combustion air and large energy loss to cooling water) more coal has to be burned to generate more fuel gas for the PSH Furnace. Our heat and mass balances calculation suggested that the likely upper limit of the range to be 930 lb/nt (465 kg/mt) for hot metal production. Therefore, the total coal rate would have a range of 791-930 lb/nt (396-465 kg/mt) of high volatile coal per ton of hot metal production, by the all-coal TRP-9810 Technology
- 7) In the "Final Technical Report" of the Mesabi Nugget Research Project by Larry Lehtinen, the energy consumption consists of natural gas 5.30 MMBtu/nt and low volatile coal 11.34 MMBtu/nt of nuggets. Using a conversion factor 13,000 btu/lb, the coal rate (in addition to natural gas) would be 872 lbs low volatile coal per ton of nuggets.

11. RECOMMENDATIONS

A new proposal should be prepared for the construction and operation of a demonstration plant of the Paired Straight Hearth Furnace at INMETCO in Ellwood City, Pa to advance the development of TRP-9810 Technology.

12. REFERENCES

1. John Stubbles, "Energy Use in the U.S. Steel Industry: An Historical Perspective and Future Opportunities", September, 2002, An Energetics Inc., report to U.S. Department of Energy.
2. Fruehan, R. J.; Fortini, I.; Paxto, H. W.; and Brindle, R.; "Theoretical Minimum Energies to Produce Steel for Selected Conditions", Sept., 2000, Office of Industrial Technologies, Department of Energy, Washington DC, USA, page 4.
3. Larry Lehtinen, "FINAL TECHNICAL REPORT of Mesabi Nugget Research Project" DOE Awards No: DE-FC36-021D14280, date of publication 03/31/05

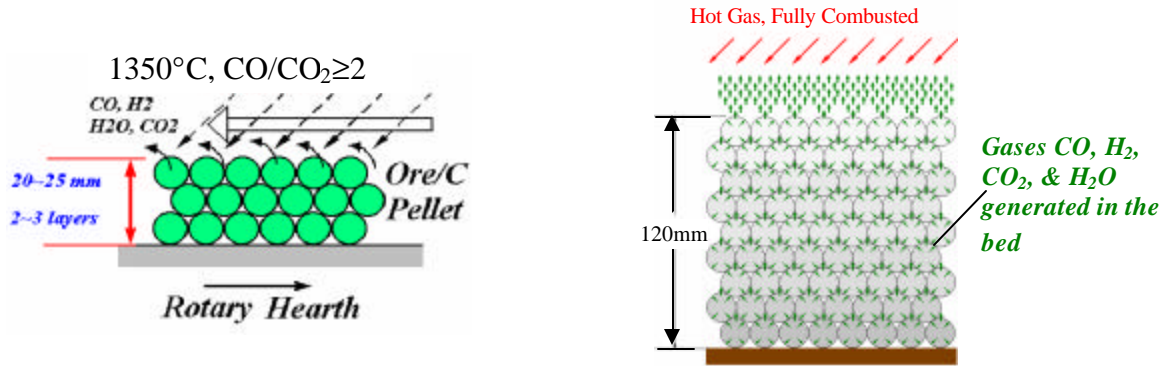


Fig. 1 The shallow bed of pellets in conventional RHF operation. Fig. 2. The rising gas stream pushes back the combustion products which contains CO₂, H₂O and possibly O₂

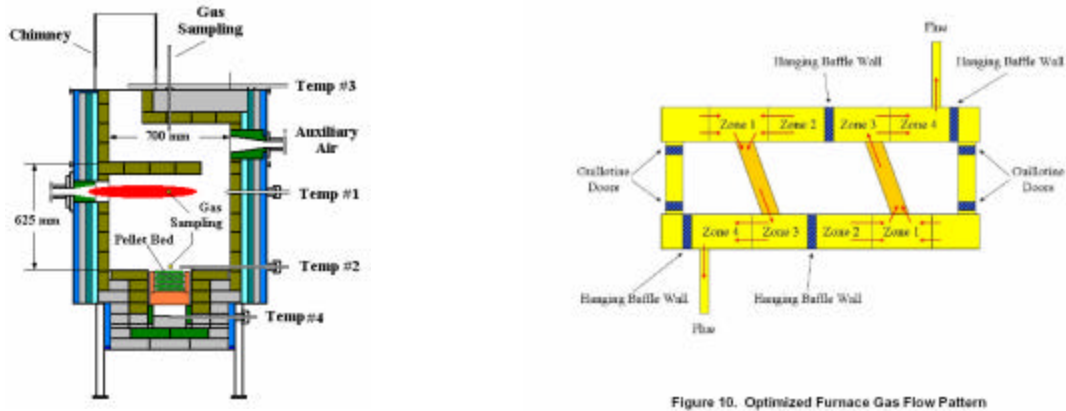


Fig. 3. The design of gas-fired furnace at Fig. 5 A figure reproduced from Bricmont's McMaster University Report

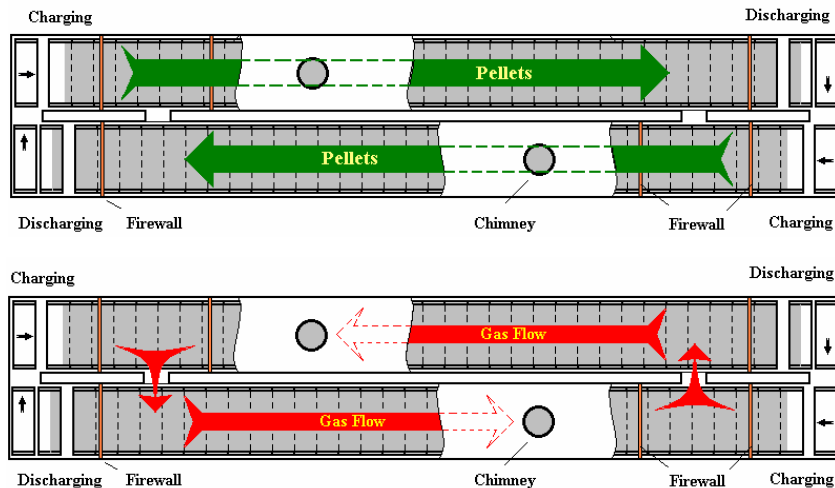


Fig. 4 The top view of a PSH furnace and movements of solid and gas

Appendix I

Research Proposal of the Project TRP-9941

“A New Process for Hot Metal Production at Low Coal Rate”

Submitted by W-K Lu, Professor Emeritus, McMaster University, Nov. 13, 2003

Appendix II

The Final Report

“Paired Straight Hearth Furnace Feasibility Study“

Submitted by Bricmont, Inc.. to American Iron and Steel Institute, Nov. 8, 2005

TRP 9941

A New Process For Hot Metal Production At Low Fuel Rate

APPENDIX I

Proposal for TRP - 9941

American Iron and Steel Institute

R & D Proposal Summary Page

1. Name of Proposing Organization(s): **McMaster University, Hamilton, Ontario**

2. Date: **November 13, 2003**

Descriptive Project Title: **A NEW PROCESS FOR HOT METAL PRODUCTION AT LOW FUEL RATE**

4. Total Project Cost: **US\$11,385,330**, Duration: **3.25 years**

Phase I Cost: **US\$83,600**, *Duration:* **0.50 year**

Phase II Cost : **US\$11,301,730**, *Duration:* **2.75 years**

% of Total Cost Contributed by Proposer(s): **NIL**

5. Provide the objective and brief description of the proposed project

The development of a new hot metal production process using American iron ore and coal by the construction and operation of a demonstration plant in Ellwood City, Pa.

6. Briefly describe the energy saving arising out of the proposed research.

Aging blast furnace plants may be replaced by the proposed process and maintain the BOF operations. They may also be replaced by a new EAF operation with hot metal additions. Using "Project Evaluation Tool" provided by AISI, the energy savings are computed to be 85.3 and 482 trillion BTU for 2010 and 2015, respectively.

7. Briefly described the environmental benefits of the proposed research

Using "Project Evaluation Tool" provided by AISI, from the reduction in carbon equivalent consumption, the reduction in CO₂ emission is computed to be 6.56 and 37.0 MMT/year for 2010 and 2015, respectively.

8. Briefly describe other benefits of using the developed technology (e.g. productivity, quality).

For integrated plants, coke and sinter plant may be eliminated, blast furnaces are replaced with low capital cost. For EAF-based companies, the availability of inexpensive hot metal on site will lead to operational efficiency and resumption of fast rate of expansion.

9. Contact Name: **Prof. W-K. Lu**

Contact Address: **Department of Materials Science and Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario, L8S 4L7**

11. Contact Phone: **(905)525-9140, ext. 24976/24984**

E-Mail: **luweikao@mcmaster.ca**

Signature of W-K. Lu and Date

EXECUTIVE SUMMARY

The trend of decreasing energy intensity (the average energy consumed per shipped ton) continues in the U.S. steel industry, but it has been forecasted for a slower rate in the next decade unless there is major structure change or a new “disruptive” technology emerges. Stubbles^[1] attributes the success in the past fifty years to new technologies, i.e., pellets in ironmaking, BOF, continuous casting and the growth of EAF sector. He suggests that in the coming decade if there is significant lowering of energy intensity for the whole steel sector, it would be in blast furnace fuel rate, re-heating efficiency and further increase in the fraction of steel shipped from EAF-based plants. In this application, the building and operating of a demonstration plant for the commercialization of a new coal-based, coke-free process to produce hot metal at much lower fuel rate and higher yield is proposed. This process has the potential to replace the blast furnace to gain economic and environmental advantages and to provide hot metal on-site resulting in operational efficiency of EAF shops.

Further developmental work with a Paired Straight Hearth (PSH) Furnace at demonstration plant scale proposed here is a continuation of the very successful DOE/AISI Technology Roadmap Program (TRP) project-9810, completed in 2001 and the final report accepted in September, 2002. The proposed process has two steps, i.e., the reduction of iron ore/waste oxides in solid state by coal, followed by melting to remove gangue, ash and sulfur from the hot metal. Project TRP-9810 is about heating chemically self-sufficient green balls of iron ore and coal mixtures. For gains in energy efficiency, furnace productivity and DRI quality, a tall bed of green balls (120 mm) can be processed under a fully combusted flame at 1600 to 1650°C. It is fundamentally different from conventional operation of the rotary hearth furnace with respect to temperature, furnace atmosphere and bed height. The energy intensity of hot metal production from ore and coal in three different ways may be compared as follows:

Blast furnace (Good Practice) 1997-1998 ^[1] :	15.48* MBTU/NTHM
TRP-9810 Technology & Oxy-Coal Melter:	10.64* MBTU/NTHM
TRP-9810 Technology & Electric Melter:	12.14* MBTU/NTHM

This proposal is developed jointly by McMaster University (the center of research and education for ironmaking technology in North America), INMETCO (well known for the first rotary hearth furnace for waste oxide recycling and for its continuing success in this business) and BRICMONT (a well known furnace builder including the largest rotary hearth furnace in the world) and in consultation with a number of steel companies. The program consists of two phases: (i) Preliminary engineering to develop a design for further assessment of the technology of DRI production and pricing of the demonstration plant and estimating operation expenses. (ii) The design and construction of the demonstration plant at INMETCO, Ellwood City, PA and collecting data for the design of full size commercial plants for iron ore reduction as well as for waste oxide recycling. It should be a continuous operation with the following features: (i) automated charging and discharging; (ii) counter-current mode of solid and gas flows; and (iii) a choice of designs of combustion system for efficient use of burner fuel and the combustible gases from the pellet bed during reduction with low turbulence at the top of the pellet bed. The melting of hot (1400°C) DRI of 95% degree of metallization produced in the proposed process in a stripped down version of AISI Smelting Reduction Vessel needs no further study and is not a part of this program. Melting of such kind DRI in the oxy-coal reactor is much less challenging in comparison with smelting reduction. The reasons are: (i) DRI is of high degree of metallization and denser than slag; (ii) slag of low FeO content is not corrosive to the lining; and (iii) post combustion needs not to be high because of low energy intensity of melting and the exit gas will be used in DRI production.

* In the conversion of power to the unit of BTU, following Stubbles^[1], the losses of generation and transmission of electricity are included.

1. INTRODUCTION

For blast furnace ironmaking, the fuel rate per ton of hot metal varies from furnace to furnace and from time to time. For 1997 ~ 1998, Stubbles^[1] reported the energy intensity (good practice) of hot metal production was 15.48 MBTU/NTHM in U. S. Steel Industry. Hot metal production is the key operation in integrated plants and contributes to 72% overall of energy intensity, 14.88 to 20.66 MBTU/shipped ton of steel in integrated plant in 1998^[1,2]. For EAF operations, the availability of hot metal on-site will bring advantages in power consumption, tap-to-tap time and stability in operation and in cost, as well as, energy intensity. The need of a better way to make hot metal in general and coal-based and coke-free process in particular is recognized all over the world. For this goal substantial efforts have been made in both sub-sectors of U.S. steel industry, i.e. the AISI smelting reduction process and the rotary hearth furnace/submerged arc furnace process at Iron Dynamics, Inc.

2. FUNDAMENTAL ADVANTAGE IN THE REDUCTION OF GREEN BALLS OF ORE/COAL MIXTURES

In order to eliminate raw materials preparation steps, i.e., cokemaking and high temperature iron ore agglomeration, it is desirable to use iron ore concentrate and coal directly. In smelting reduction, they are charged to the vessel separately. Another approach is to mix iron ore concentrate and pulverized coal, then, to heat the composite to complete the reduction of iron oxide. The rate of reduction of iron oxide in green ball of ore/coal mixtures is determined by the heating rate. At high temperature, the radiative heat flux is proportional to T^4 so that the process can be speed up greatly by the increase of furnace temperature.

It should be noted that the source of carbon in the proposed process is coal and that for blast furnaces is mostly coke. The advantage of using taconite ore from the Great Lakes region is not only in lower carbon requirement but also in lower swelling during reduction.

3. A COMPARISON BETWEEN RHF AND A RETORT

The wall of the retort in which sponge iron are made from carbon and iron ore, plays two important roles in retort process.

- (a) it separates two sub-systems of very different atmosphere, i.e., inside the retort strongly reducing and outside the retort strongly oxidizing.
- (b) It is the medium of heat transfer by conduction. Heat is generated by combustion outside the retort and is consumed by endothermic reactions inside.

The reacting system of RHF furnace is shown in Fig.1 It is equivalent to a retort without the benefit of the wall to separate the shallow pellet bed for reduction and free board above for heat generation. The most unfortunate consequence is that the oxidants (CO_2 , H_2O and O_2) in the flame can reach sponge iron in the later stage of the process and re-oxidize it back to iron oxide. Current RHF operators, in general, observe the following rules of thumb:

- (i) The bed height of agglomerates is about 20-25 mm, with 2 to 3 layers of pellets.
- (ii) The space above the pellet bed where fuel is burned to generate heat, is kept at about 1300 °C and CO/CO_2 ratio in gaseous phase equal or larger than 2.0.
- (iii) Carbonaceous materials of low volatile matter content are preferred.

4. THE BACKGROUND OF PROJECT TRP-9810

There are several Ph.D. theses on the general subject of reduction of ore/coal composite submitted to McMaster University under the supervision of the applicant in 1980s and 1990s. The higher process temperature leads to faster iron oxide reduction and stronger gas flow from the bed of green balls of ore/coal mixtures. The gas flow could shroud the top layer of sponge iron and prevent the re-oxidation by the oxidants from the flame. A schematic diagram is shown

in Fig.2 In 1998, the three Rules of Thumbs of RHF operations were challenged simultaneously, not individually, in the Howe Memorial Lecture of Iron and Steel Society^[3] and in the research proposal submitted to American Iron and Steel Institute (AISI) and the U.S. Department of Energy.

In the Final Report of TRP-9810, for the next stage of development, i.e., in a pilot/demonstration plant, the following values of process parameters were recommended:

- Bed height 120 mm (old Rule #1, 20-25 mm)
- Flame and refractory surface temperature 1600-1650°C (old Rule #2, about 1300°C)
- Composition of combustion product $\text{CO}/\text{CO}_2 = 0$ (old Rule #2, $\text{CO}/\text{CO}_2 \geq 2.0$)
- Volatile matter content in carbonaceous materials about 30% (Old Rule #3, coke and anthracite are preferred)

5. THE RESULTS OF PROJECT TRP-9810

The non-confidential version of the Final Report of this Project is available to AISI members from AISI office or from the applicant. Conclusion #1 is reproduce below:

“The thermochemical aspect to the process is well established. The process is stable and tolerant to operation errors and in principle, there is no risk in scale-up. DRIs are of excellent qualities, physically and chemically. The material handling aspect of the process and the exact energy savings have to be established in a pilot/demonstration plant designed for such tests.”

At about the halftime of the project, experimental results obtained on campus with the used of the specially designed natural gas-fired furnace, see Fig. 3, at a heat size of 6-7 kgs of green balls were excellent under the conditions stated in last section. Green balls have very low coal addition in comparison with RHF practice and DRI have good chemical (95% degree of metallization) and physical (denser than molten slag for easy melting) properties. The project committee decided to move the target further down the road. In a hurry, the pilot plant of CSM Combustion Laboratory in Genova, Italy was chosen and five weeks of trials were scheduled to repeat the results with taconite ore obtained on campus, as well as testing hematite ore from Brazil, BOF sludge, millscale, mixtures of BOF sludge and EAF dust. The work was carried out by a team of 4 workers led by 2 young combustion engineers in the pilot plant which located inside an old steelworks. Dr. Frank Huang of McMaster University served the role of quality control person by specifying the green ball properties and furnace conditions. In general, the experimental results are better than that obtained on campus, except the bottom layer of pellet bed because the excessive cooling due to nearby water-cooling tubes. Two important conclusions were reached: (i) Equipment on campus can be used to produce meaningful results (ii) waste oxides from carbon steel plants may be recycled by this technology.

Back in America, two challenges were proposed in a series of project committee meetings (i) organizing the experimental findings in a user-friendly form for technology transfer (ii) examining the possibility of modifying one of the existing RHF to apply our tall bed technology. A series of systematic experimentation, according to a statistical design, using raw materials supplied by U S Steel, were carried out to result in a number of regression equations. From those equations of multiple variables, optimization in operating condition and DRI properties can be made to meet a set of particular objectives for individual companies. An example is given in Fig.4. It should be pointed out that the unit of productivity expressed in weight of DRI per unit area of hearth and per unit time, even with degree of metallization specified, is not proper because the operation with high gangue raw materials and low degree of reduction will become more productive. For ironmaking, it should be the amount of metallic iron produced per unit area per unit time.

Through a series of lively debates, the answer to the possibility of modifying an existing RHF for tall bed and high temperature technology is negative because the metallic screw discharger would not survive. The new technology is independent of the size, shape and movement of hearth so that the “rotary” part of the furnace does not present a problem in itself. In the Final Report of TRP-9810, heat and mass balance under various conditions have been presented.

6. TECHNICAL HURDLES TO BE OVERCOME

The commercial process should be continuous with automated charging and discharging operations. These features could not be tested in the equipment on campus nor in the pilot plant in Genova, Italy.

7. THE FLOW SHEETS, HEAT AND MASS BALANCES

Two flow sheets, with different type melters and slightly different green balls, operating conditions and DRI properties are proposed in Tables 1 & 2, and shown in Fig.4.

Table 1 Energy Consumption of hot metal production

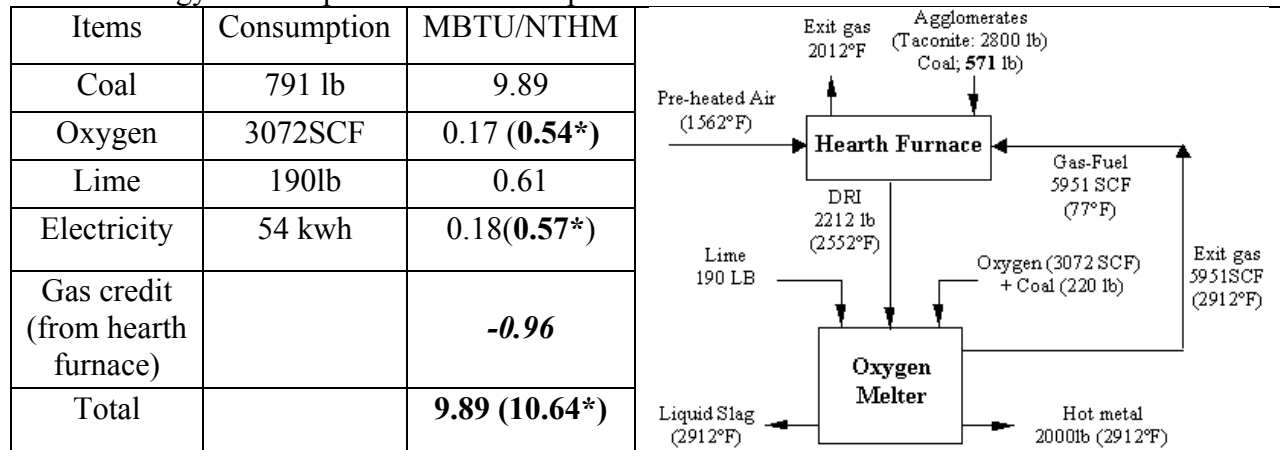
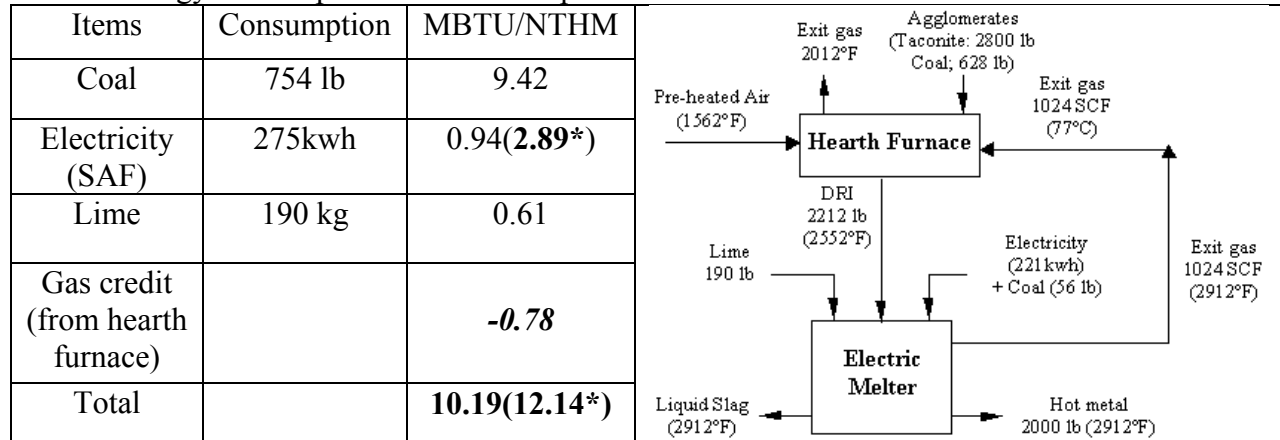


Table 2 Energy consumption of hot metal production



* including the losses for generation and transmission of electricity, following Stubbles^[1]

8. YIELD IMPROVEMENTS

From “Barriers and Pathways for Yield Improvements” prepared by Energetics, Inc. dated October 7, 2003 the yield loss of Fe (iron) in current practice is about 20% due to the creation of home scrap and waste oxides. Home scrap causes the operation to be less efficient; on the other hand, the loss in waste oxides (without the use of a sinter plant) is permanent. In a local steel

company with both integrated operation as well as EAF shop, for 4.2 million NT steel produced there are 157,000 NT Fe in dust and sludges (3.6% of Fe in the feedstock) and 56,000 NT Fe in slags (1.3% of Fe in the feedstock) mainly in steelmaking slags.

In the proposed ironmaking process, as shown in the data obtained in the pilot plant, the improvement in yield of Fe can be realized in two ways:

- (i) Waste oxide generated in steelplants, including those containing volatile heavy metals and oil-coated scales, can be processed to eliminate the permanent loss of 157,000 NT Fe in this plant and to gain a yield of 3.6% in terms of Fe in the feedstock.
- (ii) Steelmaking operation is chemically for the removal of C, S, and to a lesser extent P. The Blast furnace cannot be used to remove sulfur to the level needed by the melt shop because of limitations in temperature and slag composition required by casting operation. In the melter of DRI, high basicity slag which contains very little iron oxide well mixed with metal, will lead to a new process making hot metal with very low sulfur and relatively low carbon, e.g., 3% instead of 4.5%. In North America, phosphorus in hot metal could be very low without recycling steelmaking slag because of low P raw materials. This situation resembles the “slagless steelmaking” practice developed in Japan years ago. Of course, a very small amount of slag is needed to suppress the vaporization of iron. On the other hand, in the EAF shop there is limited potential in lowering slag weight because of uncertainty in the composition of purchased scrap. One could suggest that a substantial portion of 56,000 NT Fe (1.3%) loss in slag and the step of external desulphurization could be avoided.

In terms of total Fe in feedstock coming to the steelworks, in the proposed process for hot metal production, the yield of Fe in steel products will be higher by 4%, or higher, in comparison with a current practice of very good standing.

9. THE NEW FURNACE FOR OVERCOMING TECHNICAL HURDLES

As shown in Fig. 5, the Paired Straight Hearth Furnace (PSH) Furnace^[4,5] which is in many ways similar to straight grate machine for iron ore pellet production and sintering machine, would allow us to have counter-current solid and gas flows to achieve high fuel efficiency and the elimination of the risk of re-oxidation of sponge iron, as well as, higher furnace availability by off-line maintenance of the hearth.

Bricmont proposes this project to be divided into 2 phases:

Phase I. PRELIMINARY ENGINEERING to be performed by Bricmont with assistance from McMaster University and INMETCO, over a period of 16 weeks.

- (1). Conduct a kick off meeting with all involved personnel.
- (2). Computer modeling of process
- (3). Demonstration scale furnace mechanical design
- (4). Demonstration scale process design
- (5). Computer modeling of reaction zones of the furnace and combustion capacity
- (6). A location plan including preliminary arrangement drawings
- (7). Capital cost estimate for the facility and utility cost
- (8). Final report/follow-up presentation.

The Bricmont price of the service of phase I is US\$59,300 plus taxes and fee \$

Phase II. DETAIL ENGINEERING, INSTALLATION AND COMMISSIONING OF THE FACILITIES, over a period of 18 months.

The facility to be built at INMETCO (Ellwood City, Pa) will have an annual capacity of 4,200 mtpy of DRI of 95% degree of metallization from taconite concentrate and coals.

The PSH furnace itself will have a combined effective hearth of 65 m² split between two furnace chambers that will be 1.75m wide by 17.5 m long. Adding for the length of charge and discharge equipment, and access between furnace chambers, the overall area of the furnace installation will be approximately 7.5 m by 32 m. This excludes space for the recuperators and other ancillary equipment.

There will be 8 zones of temperature control (four per furnace chamber) utilizing hot air wickets and natural gas fired burners mounted on the sidewalls of the furnaces. Temperature will be controlled through zone thermocouples that will be monitored through a Level I control system. Preheated combustion air and gas valves to the zones will be modulated accordingly to maintain proper zone temperatures. Ductwork and firewalls are included to direct volatile laden gas to areas where it can best be utilized.

The hearth will be broken into 1250 mm long segments which ride on individual pallets. There will be 14 pallets in each active hearth with curbs at the edges to retain the product bed.

The pellets will be fed into the furnace with an electrically driven charge system that will funnel the pellets down to a charge chute through the furnace roof. The chute will direct the pellets to the furnace entry pallets and distribute pellets on the pallets with a uniform bed height. When the pallets moves to the discharging end, the products will be discharged by a means other than a screw discharger, after discharging, the emptied pallets will be shifted to the charging end of opposite furnace chamber to received dried green balls.

Products of combustion will exit the furnace chambers through separate uptakes and will be directed into recuperators. This will cool the gases sufficiently to allow installation of the furnace pressure control dampers. The gas streams will then be combined into a single duct for NO_x abatement utilizing a Selective Non-Catalytic Reactor (SNCR) system. This system will remove approximately 50% of NO_x emissions through chemical reaction with a urea reagent. A sidestream of gases will be sent to the dryer, then returned to the system. The gases will then pass through a baghouse, ID Fans and wet scrubber for removal of particulate and SO_x. There will be a short stack on top of the SO_x scrubber.

10. THE DEMONSTRATION OF THE NEW TECHNOLOGY

After the successful commissioning by Bricmont, the demonstration plant will be operated by a crew from INMETCO under a superintendent appointed by INMETCO and a technology/quality control person from McMaster University, under the supervision of the project committee. INMETCO will also provide general service through their business office, such as purchasing, transportation, etc. The task is to manufacture DRI of good quality from American raw materials (taconite concentrates and medium/high volatile coals) under a stable operating conditions so that economical, technological, and environmental evaluations can be done.

For technology development, the facility will be pushed to its limits to establish operations for maximum productivity, minimum energy consumption, DRI quality, optimum economical advantages under a given market condition, etc. The establishment of relations for the trade-off among various requirements are important for business plans to construct larger facilities. There will be 2 periods of 6 months each to carry out the demonstration tasks. The first period is aimed to establish stable and efficient operation to produce quality product. The periods of continuous operation will increase gradually to last 4 to 6 weeks. The second period will be devoted to assess the vitality of this new technology under extreme conditions for a particularly demanding performance.

To test iron ore other than taconite concentrate or waste oxides from steel plants in this demonstration plant is anticipated in a later date, but not a part of this project.

11. RISK ANALYSIS AND MARKET PENETRATION

The risks in scale-up of this thermal-chemical process has been investigated in Project TRP-9810 and concluded that for this one dimensional process (for heat and mass fluxes) the process should be independent of the size, shape and movement of the hearth. Other size and configuration-dependent factors such as positioning of burners, charging (same as in pellet plant) and discharging (similar to the pellet/sinter plants) will be dealt with in the demonstration plant. The risk of this new process in the scale-up and commercialization with respect to technology is very low.

For last two decades, most major integrated steel companies in the world, at one time or the other, wished that ironmaking facility could be modernized by switching to a hot metal production process which is environment-friendly and low in capital cost. Smelting reduction and COREX do not meet these requirements. The proposed process meets these requirements as well as very low energy consumption. For EAF-based companies, the resumption of a fast rate of expansion must be based on a quantum jump in process efficiency to assure business success. Inexpensive hot metal available on-site will result in lower power consumption and tap-to-tap time, and bring in stability in steelmaking operations and product quality. Proposed process is fundamentally superior to conventional RHF. The process ITmk3 is basically a RHF with two additional zones, the melting zone after reduction and followed by a cooling zone. Extra time needed for cooling will lower the furnace productivity. More sacrificial carbon is needed in the melting zone to raise the carbon above the level of conventional RHF. The effectiveness of the de-sulfurization, without stirring/mixing in liquid phases is another factor of concern.

As the proposed process will satisfy the well established needs of both sub-sector of U. S. steel industry, the market penetration will be at a very fast rate.

12. THE RESULTS GENERATED BY THE “PROJECT EVALUATION TOOL”

The market is assumed to be 50 million tons steel shipped from integrated plants and equal amount from EAF-based works. The market penetration curve chosen is the one for low risk cases, after first full scale plant starts in 2008. There are two scenarios:

A. Replacing aging blast furnace plants

Year	2010	2015
Energy Savings (trillion BTU)	41.34	233.8
Pollution Reduction, carbon MMTCE/yr)	0.769	4.35

B. New EAF-Based plants with (1/3 hot metal & 2/3 scrap) replacing aging B.F. plants

Year	2010	2015
Energy Savings (trillion BTU)	43.88	248.2
Pollution Reduction, carbon MMTCE/yr)	1.02	5.78

TOTAL (A+B)

Year	2010	2015
Energy Savings (trillion BTU)	85.3	482
Pollution Reduction, carbon MMTCE/yr)	1.79	10.1

13. THE MANAGEMENT OF THE PROJECT

As the person who submits the proposal, through McMaster University, the applicant will be responsible for the whole project, working under the guidance of an AISI project committee which is made of AISI project managers and representatives of sponsoring companies, as we had for TRP-9810. During different stages of this project, sub-committees will be set up under this AISI project committee, for example, one on “Engineering Design and Construction’ with

members from Engineering Department of sponsoring companies and the other on “Operations and Quality Control” including specialists from sponsoring companies. The superintendent of the demonstration plant should be appointed by INMETCO and the leader of quality control efforts would come from McMaster University, but working on site most the time. McMaster staff will work closely with Bricmont, INMETCO, Project Committee and sub-committees.

The applicant and McMaster University do not have the industrial experience and knowledge to negotiate business contracts with suppliers. It is our wish that business contracts will be done through AISI office. Budget of this project will be separated: (i) Expenses on campus and University staff (ii) Contracts with suppliers and expenses for the operation of demonstration plant.

14. MILESTONES AND BUDGET

MILESTONES:

- A. July 1, 2004: The purchase order of phase I, preliminary engineering, delivered to Bricmont Inc., Pittsburgh
- B. Nov. 3, 2004: Follow-up presentation of Phase I Final Report
- C. Jan. 1, 2005: The purchase order of phase II, Detail Engineering, Installation and Commissioning of the Demonstration Plant, in INMETCO, Ellwood City, Pa. delivered to Bricmont Inc.
- D. July 1, 2006: Delivery of the Demonstration Plant on turn-key basis to AISI Project Committee and INMETCO.
- E. Dec. 31, 2006: The Demonstration of hot DRI production from American raw materials under stable and efficient conditions will be completed.
- F. June 30, 2007: The Demonstration of hot DRI production from American raw materials under particular conditions for maximum productivity, or minimum energy consumption, or special properties of DRI will be completed.
- G. Sept.30, 2007: Project Final Report will be submitted. It will summarized demonstration plant results and make recommendation for full scale plants.

BUDGET IN US CURRENCY

(i) MCMMASTER UNIVERSITY

July 1, 2004 – June 30, 2005

Salaries and benefits (part-time) Lu (14,400) and an assistant (10,400):	24,800
Supplies (5000), Travel (5000) and Overhead (13,920):	23,920
<u>Subtotal:</u>	<u>48,720</u>

July 1, 2005 – June 30, 2006

Salaries and benefits Lu (28,800, part-time) and an assistant (62,000):	90,800
Supplies (5000), Travel (24,000) and Overhead (47,920):	76,920
<u>Subtotal:</u>	<u>167,720</u>

July 1, 2006 – Sept. 30, 2007

1.25@167,720:	209,650
<u>Total (McMaster University):</u>	<u>US\$426,090</u>

(ii) OFF CAMPUS ACTIVITIES

Bricmont: 59,300(Phase I) and 8,500,000(Phase II) US\$8,559,300

Operation of Demonstration Plant: 5000 tonne of DRI will be produced with about 10,000 tonne concentrate and 2,000 tonne of coal shipped to a nearby steelworks by rail first, then by truck to INMETCO. The costs for raw materials and operation of the plant:

Raw materials/transportation	900,000
------------------------------	---------

Operation (utilities, maintenance, mobile equipment, etc)	1,500,000
Personnel (700,00), Service(180,000) and Building Renovation (500,000):	*1,380,000
* contribution to be made by INMETCO as in-kind.	
<hr/>	
Subtotal (in cash):	US\$2,400,000
Total cost for phase I, Preliminary Engineering (July 1 – Dec. 31, 2004)	
59,300(Bricmont) and 24,300 (McMaster):	83,600
Total cost for phase II, Detail Engineering, Demonstration Plant, and Operation of the Plant:	
8,500,000 (Demo Plant), 2,400,000 (operation, etc) and 401,730 (McMaster):	11,301,730
PROJECT TOTAL:	US\$ 11,385,330

Due to insufficient time in the preparation of this proposal the cost for the construction of the demonstration plant and the operation of the plant will be refined.

15. CREDENTIALS OF THE LEADING PERSON OF THE PROJECT

Professor Wei-Kao Lu received his Ph.D. from the University of Minnesota in 1964 and became a faculty member at McMaster University, Hamilton, Ontario in 1965 and appointed Stelco Professor, 1973-1992. After the early retirement in 1997, he continues his research work on full-time basis at McMaster University. Professionally, he has been recognized as the leading scholar in blast furnace ironmaking and alternative ironmaking processes in North America and received highest honours from Iron and Steel Society, AIME, CIM (Canada) and JISI (Japan). He is the founder of the intensive short course of “Blast Furnace Ironmaking” in 1977 and McMaster Symposium on Iron and Steelmaking, 1973. For AISI Smelting Reduction Program (Direct Steelmaking), he was the leader of a group consultants from McMaster and McGill universities responsible for process analysis for the work done at the demonstration plant in Pittsburgh. Currently, he is working with Canadian Steel Industry using industrial data and laboratory modelling to improve the efficiency of blast furnace ironmaking.

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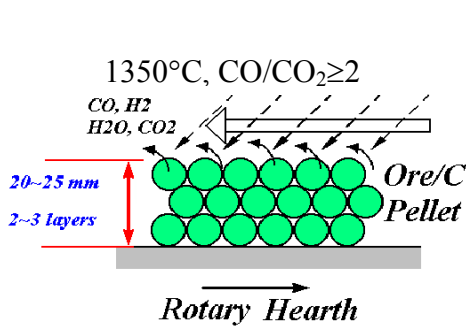


Fig. 1 The shallow bed of pellets in current RHF operation

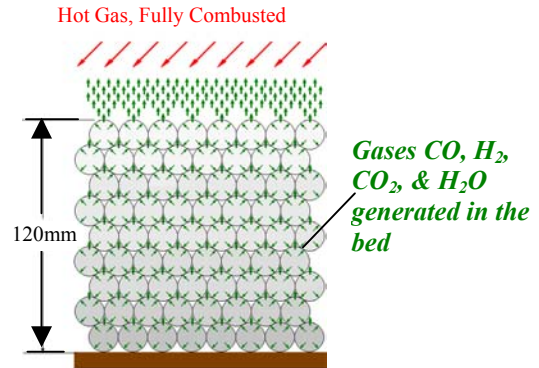


Fig. 2. The rising gas stream pushes back the combustion products which contains CO₂, H₂O and possibly O₂

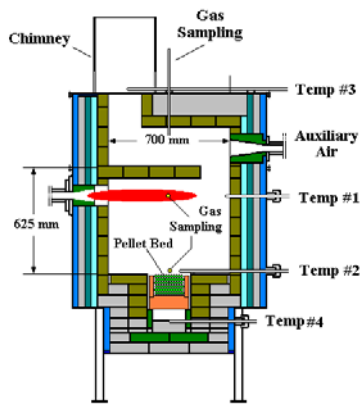


Fig. 3. The design of gas-fired furnace at McMaster University



Fig.4. The appearance of a DRI cake made at McMaster. (Weight ratio of ore to coal = 5.0, initial bed height =120 mm, degree of Metallization >95%, density 3.2 g/cm³, productivity: 125kg-DRI/m²h or 99kg-Fe^o/ m²h)

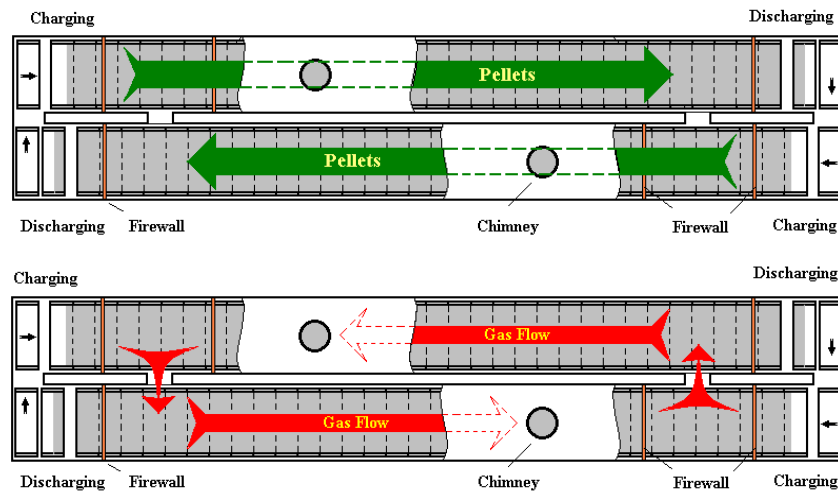


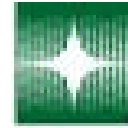
Fig. 5 The top view of a PSH furnace and movements of solid and gas

TRP 9941

A New Process For Hot Metal Production At Low Fuel Rate

APPENDIX II

**Bricmont's Final Report:
Paired Straight Hearth Furnace Feasibility Study**



**American
Iron and Steel
Institute**

AMERICAN IRON AND STEEL INSTITUTE

PAIRED STRAIGHT HEARTH FURNACE FEASIBILITY STUDY

November 8, 2005

**BRICMONT, INC.
CONTRACT NO. 421**

Revision 2

EXECUTIVE SUMMARY

Bricmont, Inc. was commissioned to complete a study to assess the feasibility of a Paired Straight Hearth (PSH) furnace system to produce Direct Reduced Iron (DRI). Among the steps taken were a computer modeling effort, basic design and engineering of a pilot furnace facility, and cost estimation of the facility.

It was found that the process is indeed feasible on a continuous basis. The process heating time required for full metallization was determined to be 70 minutes. When allowing for space for charge and discharge equipment, the total furnace residence time was found to be 85 minutes.

The system is comprised of refractory -lined pallets that convey the green pellets as they are reduced to metallic iron. The pallets are pushed hydraulically to a discharge position. From that position, the pallet is separated and then raked clean of pellets. Another hydraulic pusher transfers the empty pallet of one furnace to the charge end of the other furnace. A waste gas treatment system for the furnace includes an afterburner, a spray water quench, a dust settling chamber, a recuperator, an induced draft fan, and a stack.

An analysis of the anticipated performance and economics of a demonstration plant that would produce 42,000 mtpy (46,300 tpy) of DRI was then completed. It was assumed that the facility would be built at INMETCO in Ellwood City, PA.

The system is expected to produce fully metallized DRI with a natural gas consumption of 0.96 MMkcal/metric ton (3.45 MMBtu/ton). This fuel rate is higher than that for a full -scale system, which will have improved economies of scale. The system was designed to control criteria pollutant emissions, including NO_x, SO_x, CO, and particulates. The cost of the production using this system is about \$213.63/metric ton (\$193.86/ton). These costs include natural gas costs of \$28.66/metric ton (\$25.86/ton) at a price of \$29.85/MMkcal (\$7.50/MMBtu). It also includes an iron ore shipping cost of \$82.67/metric ton (\$75/ton), which, depending on the facility location, could be reduced to half of that.

The floor space needed for the system measures 16.8 m (55 ft) by 68.6 m (225 ft). This includes the raw material storage and pelletizing equipment, the furnaces, and the waste gas treatment system.

The cost to engineer, manage, and install the facility, is estimated to be \$16,729,000.

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INTRODUCTION

At the present time, most ironmaking worldwide is performed using blast furnace technology. Blast furnace technology utilizes a cupola to hold alternating layers of iron ore and coke derived from coal, to reduce the iron ore to metallic iron. Due to the high capital costs and environmental concerns, a search for new and improved ironmaking technology is ongoing.

A new coal-based process was developed at McMaster University. This process utilized a bed of pellets made of iron ore and coal (instead of coke). The premise of the concept was that when supplied with sufficient external heat, the carbon in the coal would reduce the iron ore to metallic iron. Also, because some of the gases formed would also be reducing, the gases would contribute to the iron ore reduction. In addition, the volatiles in the coal could be consumed as fuel to minimize the need for supplemental fuel sources. Therefore, the process would be much more environmentally friendly than blast furnace technology.

A test program was completed at McMaster University and at a test facility in the combustion laboratory of CSM in Genoa, Italy. Using batch-type furnaces, sample pellets beds measuring 8 layers deep, produced high quality DRI under a fully oxidized natural gas flame.

Following up on the successes of the batch trials, the next phase of the development of this ironmaking process was to find a way to convert the batch test process into a continuous industrial process.

Similar competing coal-based technologies had already existed in the form of a rotary hearth furnace (RHF). The RHF concept provided a means to convey, heat, and reduce pellets to metallic iron. In fact, some full-scale facilities are in operation at the present time. However, the RHF does not provide the means for a pellet bed more than one or two layers deep, as this type of furnace design cannot provide side curbs that would prevent the pellets from falling off the side of the hearth. This is a weakness in light of the determination that the pellet bed height allows for a continuous flow of reducing gases flowing upward from the bed, which protect the DRI against re-oxidation.

Therefore, a new furnace concept was developed which would overcome the disadvantages of a rotary hearth furnace for deep pellet beds. The new concept involved Paired Straight Hearth (PSH) furnaces. The concept is sketched in Figure 1. This concept utilizes twin straight hearths made up of discrete pallets. The pallets would include side curbs to

contain a full pellet bed. As the pellets would proceed through one of the furnaces, the pellets would be reduced to metallic iron. At the discharge end, the pellets would be removed from the pallets. At that time, the empty pallet could be conveyed laterally to the charge end of the other furnace, thus providing a closed-loop system.

Bricmont, Inc. was contracted by the American Iron and Steel Institute to provide a feasibility study of the Paired Straight Hearth (PSH) direct reduced iron furnace to be installed at the INMETCO plant in Ellwood City, PA. The main purpose of the study was to determine the feasibility of the tall bed, green ball reduction pilot facility. The facility was to include iron ore and coal processing equipment, the PSH furnace, and DRI transport equipment. It was to be sized to produce 42,000 mtpy (46,300 tpy) of DRI.

The study began with a kickoff meeting to discuss the system concepts. Next, Bricmont reviewed data from test work that was performed at McMaster University and at a test facility in Genoa, Italy. This data was then used to calibrate Bricmont's transient finite-difference DRI computer model for baseline performance. A part of this modeling effort was a tracking of pellet compositions, temperatures, and a balance of the heat and mass flowing through the system. Next, preliminary engineering began to identify the most appropriate methods of transporting the DRI pellets, sealing the PSH furnaces, redirecting the volatiles, distributing combustion capacity, handling the flue gases, abating emissions, and handling the DRI. With the resultant design concept, the original DRI model was then used as a testing tool to validate the pilot facility design. Finally, preliminary arrangement drawings of the facility were drafted and capital and operating costs for the system were estimated.

ANALYSIS

Engineering analysis tools utilized in defining the PSH furnace design include finite difference models and heat and mass balances.

Finite Difference Models

Bricmont has developed a finite difference model for calculation of the temperature and metallization distribution for a variety of coal based reduction reactions. The model utilizes an explicit method to calculate the condition of the product bed as it passes through the PSH furnace. The model breaks the bed into a series of layers of pellets through the bed depth, with the pellets broken into 30 nodes each, made of 5 radial increments and 6 circumferential increments. The model geometry is set forth in Figure 2.

Shrinkage must be accounted for in the model as it affects the bed thermal conductivity. The shrinkage and apparent density define the porosity of the bed. The more porous the bed is, the lower its thermal conductivity will be. The effect of porosity on conductivity was accounted for using the following relation:

$$\frac{K_{comp}}{K_{cont}} = \frac{np^{2/3} + 1 - p^{2/3}}{n(p^{2/3} - p) + 1 - p^{2/3} + p}$$

where: K_{comp} = conductivity of the composite
 K_{cont} = conductivity of continuous phase
 ν = ratio of gas conductivity to continuous conductivity
 p = volume fraction of voids

The conductivity of the continuous phase was taken as the volume weighted average of the thermal conductivities of the individual bed chemical constituents. The specific heat was taken as the mass weighted average of the individual bed chemical constituents. The conductivity of the void gas phase was based on the conductivity of air. Conductivity, void fraction and specific heat are recalculated at each time step since the composition of the bed varies with time.

The primary mechanism whereby the bed is heated is radiation. Radiation heat flux in the PSH furnace is defined, as it is for any process, by the relation:

$$\Phi = H_{\text{rad}} / A = f e s (T_f^4 - T_s^4)$$

where: H_{rad} = Heat to surface from radiation [W]
 A = area of surface [m^2]
 f = view factor of surface to furnace
 e = product of emissivities
 s = Stefan - Boltzman constant [$\text{W} / \text{K}^4 \text{m}^2$]
 T_f = furnace temperature [K]
 T_s = surface temperature [K]

In this case the surface on which the radiation is incident is the product bed. The pellet surface nodes have view factors that are dependent on their layer, the pellet diameter, and their location on the pellet surface. Because of this, a correlation was developed using geometry calculations based on the experimental data from McMaster University and the Genoa Pilot. When all view factors are summed, the total view factor of the pellet bed to the surrounding furnace is 1.0.

The emissivity of the bed is approximately 0.95. The remainder of the furnace is lined with refractory with an emissivity of 0.9 for a product of emissivities of 0.855.

$$\Phi = (1.0)(0.855)(5.6705 \times 10^{-8} \text{W} / \text{m}^2 \text{K}^4) \{ (1773)^4 - (373)^4 \}$$

$$\Phi = 478,157 \text{ W} / \text{m}^2$$

The node temperature for radiation is the surface node temperature. The surface node is massless and its temperature is determined iteratively based on a heat balance between the heat radiated from the furnace to the surface and the heat conducted from the surface to the center of the pellet.

Conduction between the true nodes of the pellets is based on the relation:

$$cond = A \Delta T / (L_1 / k_1 + L_2 / k_2)$$

Where: H_{cond} = Heat to node from conduction [kcal]
 k = conductivity of node [kcal/mm-C]
 L = length to node interface [mm]
 ΔT = temperature difference between nodes [C]
 A = node interface area [mm^2]

Here the lengths and areas are as required for spherical coordinates.

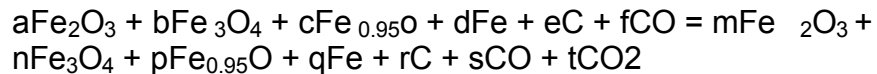
Despite the fact that it constitutes less than one percent of the heat passing through a given node, the heat from dissociation of coal was included in the model for completeness. The general relation for heat of dissociation is:

$$H_{vol} = M h_{evap}$$

where: H_{vol} = Heat from dissociation
 M = molar volatile flux [gmol / s]
 h_{evap} = heat of vaporization [kcal/gmol]

The model allows that the volatiles evaporate at a variable rate. The heat of dissociation was calculated as the difference between the heat of reaction of coal and its net heat of combustion.

Modeling of the chemical reactions followed the general reaction equation:



This equation provides three species balance equations, one each for Fe, O, and C. As there are seven unknowns, n through t, and only three equations, additional assumptions had to be made. The first of these dealt with the reaction rate determination. The reaction rate was set up based on the rate of change of the oxygen to iron ratio derived from pilot scale testing. It is assumed to be a function of temperature and the extent of reduction:

$$R_{O/Fe} = (O / Fe)Ae^{-b/T}$$

where: $R_{O/Fe}$ = Rate of change of O/Fe ratio (1/min)
 (O/Fe) = O/Fe Ratio (mol/mol)
 T = bed Temperature (K)
 A, b = constants derived from pilot scale tests

The second assumption is that the reduction proceeds in a stepwise fashion from Fe_2O_3 to metallic iron. Thus, for a given node, there are no lower reduction reactions to metallic iron in the presence of higher oxides. With these two assumptions and the original three species balances, the reaction was defined.

This paves the way for calculation of the heat of reaction according to the relation:

$$H_{\text{reaxn}} = \sum M_i h_f - \sum M_f h_f$$

where: H_{reaxn} = heat of reaction from node [Kcal]
 M_i = initial mols of species [gmol]
 M_f = final mols of species [gmol]
 h_f = heat of formation of species [Kcal/gmol]

Finally, the change in node temperature can be calculated from the relation:

$$M_n C_p \Delta T = H_{\text{rad}} + H_{\text{con}} + H_{\text{vol}} + H_{\text{reaxn}}$$

where: M_n = the node mass (g)
 C_p = the node specific heat (Kcal/g C)
 ΔT = node temperature increase (C)

The new node temperatures and compositions thus calculated become the starting point for the next time step. The process is repeated until the full residence time within the furnace is modeled.

The pallet hearth temperature will cycle through the movements governed by the PSH furnace. This temperature cycle is modeled by the finite difference program by modeling the heat conducted from the bottom layer of pellets to (or from) the hearth and then through the hearth to ambient. Sufficient iterations are performed by the program such that the initial hearth temperature profile at charging into the furnace matches the profile at the time it is re-charged into the other furnace with a new charge (this, after a heat-up in the first furnace), indicating convergence of the hearth temperature calculation.

While the model contains a substantial amount of the driving physics of the process, there are several mechanisms that are not explicitly incorporated. For instance, the model does not include a module to react the gaseous CO with solid iron oxides. Also, the model does not reverse any of the iron reduction reactions to result in a re-oxidation. Despite the fact that these specific mechanisms are not explicitly modeled, they are implicitly included, albeit on a limited basis, because the model was tuned to empirical data.

Where the limitations may be revealed is when modeled cases extend beyond the range of data used in tuning the model. So, when parametric studies have been performed with the model, a necessary caveat is included that states that one must be careful with how the results are interpreted and utilized. However, the majority of the cases performed using the model will remain within the appropriate range to provide accurate results.

Heat and Mass Balance

Heat and mass balance analysis is performed on a control volume bounded by the combustion space above the bed in the PSH furnace. The heat and mass into and out of this control volume are balanced by varying the amount of secondary air and/or burner input. Thus the heat and mass balance program calculates the amount of heat which will meet the needs of the DRI process.

The finite difference program totalizes the heat radiated to the bed, and this is passed to the heat and mass balance program. This approach is necessary since the heat supplied to the bed varies as the bed composition changes during reduction. Losses through refractory walls are calculated off line and inputted to the program. The heat leaving with the flue gases are calculated based on the enthalpy of the individual flue gas components. Since the flue gas heat is dependent on the air injection and burner firing rate, the heat balance is iterative.

Each atomic species is also balanced by the program. The finite difference program provides the mass (by chemical species) evolved into the combustion space from the bed. The remaining mass inputs to the bed are from air injection and burners. These masses must leave with the flue gases. Again, since flue gas mass depends on the air injection and burner firing, the mass balance is iterative. The mass and heat balance are coupled based on the heat of combustion from bed off-gases and auxiliary fuel (if any).

THE TUNED MODEL

Having developed the computer software needed to model the DRI process for the PSH, the next step was to tune the model to data collected at the Genoa test facility. The test case consisted of an 8-layer pellet bed, using pellets made up of 16.5% coal and 83.5% ore. Table 1 lists the composition of the pellets:

The test conditions showed a 60-minute heating/reduction processing time while firing predominantly at 1500 °C (2732 °F). At the conclusion of this time, the pellets achieved a metallization of at least 95% on all but the bottom layer. The bottom layer achieved a 70% metallization, largely due to the cooling effects caused by the water-cooled supports just beneath the bed.

Figure 3 shows the temperature transient for the test case. Here, it is seen how each successive layer lags behind the heating of the layer above it, as the heat is passed through the bed. Also, the hearth temperature pattern shows a cyclical nature. This was intentionally done by the Genoa experimenters so that the hearth temperature pattern would approximate the pattern that would exist in a PSH facility. It was accomplished by preheating the hearth prior to charging of the green pellets.

Figure 4 shows the metallization transient for each layer during this same heating transient. Corresponding directly with the temperature patterns, the metallization of each successive layer lags behind the layer above it, as again, the heat needed for the reactions is passed through the bed.

THE PSH MODEL

The tuned model detailed above served as the basis for the modeling of a PSH facility. However, several key changes had to be made. First, the hearth refractories had to be changed from the fiber construction used in the test facility to a more durable, composite design. The new refractory composition consisted of various layers that could withstand the heat of the process, as well as maintain its integrity during operation. The design comes from Bricmont's design experience on DRI rotary hearth furnaces. It consists of the following:

150 mm (6 in) 70% Alumina High-Strength Castable
150 mm (6 in) 50% Alumina Castable
75 mm (3 in) 1100°C (2000°F) Insulating Castable
75 mm (3 in) 900°C (1600°F) Insulating Castable

The second change to the model was the need to iterate on hearth temperatures. That is, with the closed -loop process, the hearth temperatures at the start of a heating cycle must equal the hearth temperatures at the end of a heating cycle (plus the cooling that takes place during DRI discharge and transfer between furnaces).

Once these model changes were made, the 8 -layer pellet bed case was revisited to serve as the base case. It was found that, when firing with a zone temperature of 1500 °C (2732 °F), the 60 -minute heating time was about 10 minutes short of providing the desired 95% metallization for all 8 layers. This was a result of the heat transfer interactions between the hearth and the pellet bed. Therefore, the required processing time for an 8-layer pellet bed was determined to be 70 minutes. However, to account for the space required for charging equipment, a plow to level the pellet bed, and discharging equipment, an additional 15 minutes of processing time was deemed necessary for the design case . Figures 5 and 6 show the transient heating and metallization curves for this case. In the figures, it is clearly seen that the first 10 minutes of residence time are in a low -temperature zone, which corresponds to the area under the charge equipment and plow. Figure 6 also shows that the metallization, in fact, is complete at around 73 minutes of the 80 -minute transient. For conservatism, the furnace will be designed to perform for an 80 -minute process, accounting for the unknown. However, should the shorter time predicted by the model prove true, the furnace will be able to move material at a faster pace so that the time at which metallization is completed occurs simultaneously with the time at which DRI pellets are discharged.

In addition to the 8-layer case, Bricmont examined other quantities of layers in hopes of optimizing the process to provide the smallest necessary furnace area. What was learned was that the process is radiation limited. That is, it does not proceed unless there is sufficient heat to drive the reactions. Because the lower layers of the pellet bed are not directly exposed to the furnace chamber, the heat must sequentially pass from the top layer, to and through each successive layer, before finally heating the bottommost layer. Based solely on heat transfer as the limiting factor, it is logically concluded that the fewer the number of layers, the faster the whole bed reduction can occur. However, a key advantage of the PSH process is that the deeper bed better protects the top layer of pellets from re-oxidation. For that reason, it is recommended that the number of layers for the design basis be no fewer than eight. Modeling of process heat transfer with more than eight layers showed no advantage.

In order to provide flexibility in testing, the furnace is designed to accommodate more or less layers. This way, experimental trials can improve the confidence in the system optimization.

THE PSH DESIGN CONCEPT

Protected Metals Initiative Data

This Protected Metals Initiative Data was produced under a Cooperative Agreement identified as DE-FC36-97ID13554 under a DOE Metals Initiative Project and may not be published, disseminated or disclosed to others until five (5) years from February 1, 2006 unless written authorization is obtained from the American Iron and Steel Institute, Vice President of Manufacturing and Technology. Upon expiration of the period of protection set forth in this legend, the Government shall have unlimited rights in this data.

DESIGN COMPONENTS

Protected Metals Initiative Data

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ENERGY CONSUMPTION

Having developed the concept for the furnace system, it then became possible to determine the energy consumption rate. The system heat balance is developed using an analysis tool that is direct -coupled with the transient heating/metallization analysis. The energy balance tracks the flow of energy in the form of heat entering and exiting the furnace system. Included in the inflows are energy in the natural gas and coal, as well as the energy returned to the system in the form of preheated air. Outflows are energy that resulted in the reduced DRI, heat to refractory and water losses, and unrecovered heat that carries out the stack with the hot waste gases. The relative energy flows are shown in a System Heat Balance Diagram in Figure 11. This figure shows energy flows on a per -furnace basis. It shows that each furnace requires 2.40 MMkcal/hr (9.50 MMBtu/hr) of natural gas. So, the actual total natural gas energy required for the whole system is twice that, or 4.80 MMkcal/hr (19.00 MMBtu/hr). In addition, the energy balances for each zone can be found in Table 4.

A good measuring stick for the efficiency of the system is the Fuel Rate, which divides the natural gas requirement by the production rate. The natural gas usage rate per furnace is 2.40 MMkcal/hr (9.50 MMBtu/hr), for a production rate of 2.49 metric tph (2.75 tph). Therefore, it is predicted that the pilot system will produce DRI at a fuel rate (cost) of 0.96 MM kcal/metric ton (3.45 MMBtu/ton). While this is a moderately high number for a full -scale production facility, it is not unreasonable for a small -scale pilot facility. There exists room for improvement , specifically in terms of scale of operation and component design. With a higher production rate through a larger system, the incremental cost of losses will be smaller than the relative increase in production. This will make the full -scale system more efficient. The other area for improvement is in the Water Losses category of the Heat Balance. Though the magnitude of this item seems small, it has a great impact on the overall heat balance. This is because energy that is spent on such losses needs to be supplied by natural gas. This gas-derived energy is highly inefficient, as much of its potential energy is carried out the stack. Finally, full -scale production will benefit from optimization tests on this pilot furnace to perhaps determine optimized equipment design and better operating practices.

EMISSIONS CONTROL

The furnace system is designed to control the emissions of criteria pollutants. These pollutants are Nitrogen Oxides (NO_x), Carbon Monoxide (CO), Sulfur Oxides (SO_x), and Particulates.

Nitrogen Oxides

Nitrogen Oxides (NO_x) are a pollutant formed by the reaction of nitrogen and oxygen at high temperatures. The temperatures needed to form NO_x are commonly found in combustion applications that use air as the oxidizing agent. In the Paired Straight Hearth Furnaces, the roof-mounted burners draw waste gases back into the flame zone to help reduce the temperatures in the flame zone, and therefore, reduce the formation of NO_x. The expected NO_x emission rate is about 0.56 kg NO_x/MMkcal (0.31 lb NO_x/MMBtu). At a total natural gas usage rate of 4.80 MMkcal/hr (19.00 MMBtu/hr), the NO_x emitted from the stack is expected to be 2.69 kg/hr (5.89 lb/hr).

Carbon Monoxide

Carbon monoxide (CO) is another pollutant that requires attention in the PSH process. Usually, carbon monoxide is formed due to the incomplete combustion of hydrocarbon-based fuels. While that is still the case in burning natural gas in the Paired Straight Hearth Furnaces, CO is also generated by the iron reduction reactions described in the Analysis section of this report.

The furnaces are designed to consume much of the CO that is generated by the iron reduction reactions. This is the result of locating the flues at the discharge ends of the furnaces. In addition to reducing emissions, this also serves to make the furnaces more fuel-efficient by using the CO as another fuel.

However, in the event that some of the carbon monoxide does escape the furnace without being oxidized to carbon dioxide, the afterburner will complete the task. By injecting extra air into the afterburner in the presence of a pilot flame, carbon monoxide emissions will not be an issue.

Sulfur Oxides

Sulfur oxides (SO_x) are formed when sulfur reacts with oxygen. This is common in applications that utilize fuels that contain sulfur. Such is the case with coal, which is used in the charged pellets. Bricmont's

experience with DRI furnaces has shown that 67 percent of the sulfur contained in the charge pellets stays in the pellets that are discharged as product. The remaining 33 percent escape the furnaces with the flue gas.

The Sulfur content in the charge pellets is 0.07%. The charge rate of pellets is 3.93 metric tph (4.33 tph) per furnace. Therefore, the total flow of sulfur into the system is 5.50 kg/hr (12.12 lb/hr). If 33% of the sulfur leaves the furnace as SO₂, the total emission rate of SO_x will be 3.63 kg/hr (8.00 lb/hr). When emitted with the stack gas, the SO_x concentration becomes 117 mg-SO_x/Nm³-flue gas.

Particulates

The particulates are all of the solid dust particles that leave the furnaces. It is expected that there will be a significant dust loading due to the handling of pellets that are comprised of ground ore and coal. As the pellets are layered on the pallets, some dust will be generated due to the rubbing between the pellets or the rubbing between the pellets and the refractory pallets. Also, particulates are generated when pellets break apart. This can be due to thermal shock upon entering the furnace chamber or due to stresses caused by volatilization and iron reduction reactions that produce gases that want to escape the solid pellets. Finally, dust can be generated during the DRI discharging process, where pellets are swept by a rake and drop through the discharge chutes.

In expectation of the release of particulates from the furnace (and due to Bricmont experience in such systems), the flue gas system is equipped with a settling chamber. The settling chamber contains large cross-section ducts and a collection box. Because of the large size, the flue gas velocity is slowed to a level where solid particles tend to drop out of the gas stream, and benignly settle in the collection box. The flue gas then leaves the settling chamber with a greatly reduced particulate loading.

The dust that is collected in the settling chamber can be removed on an as-needed basis when the system is out of operation. The settling chamber is equipped with doors through which a Bobcat can be driven in to scoop out the dust. From there, a determination can be made as to what to do with the dust. It is expected that the dust will largely consist of waste oxides. One possibility is that the dust can be sent back to the pelletizing area and re-charged into the furnace. This will depend on the specific constituents of the dust. Another option would be to deliver it to INMETCO's recycling operation for recovery of the metal content. As a last resort, the dust can be landfilled, though this clearly is not the preferred alternative due to the environmental and financial impacts.

COST ESTIMATE

The cost for engineering, project management, materials, and installation for the Paired Straight Hearth Facility described above is estimated to be \$16,729,000. A breakdown of the major units is shown in Table 5. While this has been titled a “pilot” facility, it is intended for continuous production for many years. Bricmont’s estimate is based on requirements for a production facility. A “bare -bones” test facility could save up to \$1,000,000 from this estimate. Also, changes to the pellet screening and drying processes of the pelletizing system could reduce the total by an additional \$1,000,000.

The labor hours estimated for the furnace, exhaust gas system, and foundations total 57,727 hours. The installation costs are based on a composite average pay rate of \$55 per hour. This includes laborers, specialists, and supervisors. This assumes non -union labor in Western Pennsylvania.

The capital costs do not include such items as area lighting, communications systems, and personal facilities.

Utility and raw material costs for operation of the equipment are set forth in Table 6. Based on the data shown in the table, the hourly operating costs for utilities and raw materials are about \$1068.17/hr. Therefore, with a total DRI production rate of 5.00 metric tph (5.51 tph), the operating cost is estimated to be \$213.63/metric ton (\$193.86/ton).

It should be noted that the operating production costs are based on quoted prices for utilities, raw materials, and delivery, which are all highly variable. For instance, the natural gas cost was based on a price of \$29.85/MMkcal (\$7.50/MMBtu), which translates into a production cost of \$28.66/metric ton (\$25.86/ton). Transportation costs also depend on fuel cost, but also on facility location. With INMETCO in Ellwood City, PA as the basis for this analysis, ore delivery was quoted at a cost of \$82.67/metric ton (\$75/ton). A different location could possibly reduce this delivery charge in half.

In addition, there is an estimated maximum water usage rate of 805 m³/hr (3545 gpm). This includes 237 m³/hr (1045 gpm) for water -cooled members inside of the furnaces and the quench sprays, and an additional 568 m³/hr (2500 gpm) for pelletizing.

CONCLUSIONS

Having taken the steps outlined in this report, the main conclusion is that the Paired Straight Hearth (PSH) concept is indeed feasible. Modeling results and experimental results are in agreement about the performance of the tall bed reduction process in a batch mode, within the expected range of operation. Conversion to a continuous operation required a slight increase in processing time, mostly due to the thermal inertia of the refractories that are needed to withstand the high furnace temperatures.

A practical design concept has been developed for a pilot -scale production facility. The facility requires a floor space of 16.8 m (55 ft) by 85.4 m (280 ft). This includes the raw material storage and pelletizing equipment, the furnaces, and the waste gas treatment system.

The basis of the system design includes hydraulic -actuated pusher mechanisms to advance discrete pallets through the furnaces and from one furnace to the other. Processed DRI pellets are raked from the pallets using a hydraulic-actuated rake that drops the pellets through a discharge chute and into an insulated, nitrogen-injected daybin.

The combustion system utilizes roof -mounted burners whose impact on the protective gas layer over the pellets is minimal. Waste gases are diverted between furnaces, through interconnecting flues, to optimize the fuel efficiency. They are then flued out of the discharge end to maximize combustion heat release inside of the furnace chamber. Downstream of the furnace are an afterburner to consume volatiles that may be carried over and a spray water quench to drop the waste gas temperature to a more manageable level. Then, the gases go through a settling chamber to collect particulates before entering a recuperator that is used to preheat the combustion air. Finally, the gases are vented through an induced draft fan and a stack.

The fuel rate of the system is projected to be 0.96 MM kcal/metric ton (3.45 MMBtu/ton).

It is expected that this value can be improved upon as the scale of the operation is increased and through lessons learned about system design and operating procedures during testing. Criteria pollutants such as NO_x, SO_x, CO, and particulates are controlled by the system design.

It is estimated that the total cost for engineering, project management, materials, and installation for the facility is \$16,729,000. Operating costs are projected to run at about \$213.63/metric ton (\$193.86/ton).

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TABLES



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Table 1. Modeled Pellet Composition

Fe ₂ O ₃	8.11%
Fe ₃ O ₄	69.91%
FeO	0.03%
Fe(m)	0.00%
Al ₂ O ₃	0.77%
H ₂ O	0.00%
C-fixed	10.23%
C-volatile	2.60%
H-volatile	0.81%
O-volatile	1.67%
N-volatile	0.31%
S-volatile	0.07%
ZnO	0.00%
CaO	0.31%
SiO ₂	4.69%
MnO ₂	0.12%
MgO	0.35%

Table 2. Pallet Cycle Timing Analysis

Action	Duration (min:sec)	Time (min:sec)
Start Pellet Charge	0:20	0:00
End Pellet Charge / Start Push to Plow Position (#2)	0:20	0:20
Arrive at Plow Position (#2)	4:40	0:40
Start Push to Final Low Roof Position (#3)	0:20	5:20
Arrive at Final Low Roof Position (#3)	4:40	5:40
Start Push to Zone 1 (#4) Position	0:20	10:20
Arrive at Zone 1 (#4) Position	4:40	10:40
Start Push to Zone 1 (#5) Position	0:20	15:20
Arrive at Zone 1 (#5) Position	4:40	15:40
Start Push to Zone 1 (#6) Position	0:20	20:20
Arrive at Zone 1 (#6) Position	4:40	20:40
Start Push to Zone 1 (#7) Position	0:20	25:20
Arrive at Zone 1 (#7) Position	4:40	25:40
Start Push to Zone 2 (#8) Position	0:20	30:20
Arrive at Zone 2 (#8) Position	4:40	30:40
Start Push to Zone 2 (#9) Position	0:20	35:20
Arrive at Zone 2 (#9) Position	4:40	35:40
Start Push to Zone 2 (#10) Position	0:20	40:20
Arrive at Zone 2 (#10) Position	4:40	40:40
Start Push to Baffle Wall Position (#11)	0:20	45:20
Arrive at Baffle Wall Position (#11)	4:40	45:40
Start Push to Zone 3 (#12) Position	0:20	50:20
Arrive at Zone 3 (#12) Position	4:40	50:40
Start Push to Zone 3 (#13) Position	0:20	55:20
Arrive at Zone 3 (#13) Position	4:40	55:40
Start Push to Zone 3 (#14) Position	0:20	60:20
Arrive at Zone 3 (#14) Position	4:40	60:40
Start Push to Zone 3 (#15) Position	0:20	65:20
Arrive at Zone 3 (#15) Position	4:40	65:40
Start Push to Zone 4 (#16) Position	0:20	70:20
Arrive at Zone 4 (#16) Position	4:40	70:40
Start Push to Zone 4 (#17) Position	0:20	75:20
Arrive at Zone 4 (#17) Position	4:40	75:40
Start Zone 4 (#18) Position	0:20	80:20
Arrive at Zone 4 (#18) Position	4:40	80:40
Start Push to Discharge Zone (#19) Position	0:20	85:20
Arrive at Discharge Zone (#19) Position	4:40	85:40
Start Push to Discharge Position (#20)	0:20	90:20
Arrive at Discharge Position (#20) / Start Sliding Hearth	0:20	90:40
End Sliding Hearth / Start Rake Insertion	0:20	91:00
End Rake Insertion / Start Rake Lowering	0:20	91:20
End Rake Lowering / Start Rake Retraction	0:20	91:40
End Rake Retraction / Start Transverse Push / Start Rake Lifting	0:20	92:00
End Transverse Push / Start Transverse Retraction / Start Abutting Pusher to Pallet	0:20	92:20
End Transverse Retraction / End Abutting Pusher to Pallet / Wait for Next Cycle	2:20	92:40
Start Next Cycle		95:00



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Table 3. Connected Burner Input

	Zone 1	Zone 2	Zone 3	Zone 4
Input per Burner MMkcal/hr (MMBtu/hr)	0.13 (0.50)	1.20 (4.78)	0.28 (0.63)	0.44 (1.74)
Number of Burners	2	2	2	2
Connected Input MMkcal/hr (MMBtu/hr)	0.26 (1.00)	2.40 (9.56)	0.32 (1.26)	0.88 (3.48)

Table 4. Zone Energy Balances

	Zone 1	Zone 2	Zone 3	Zone 4	Total Furnace
Heat From:					
Fuel (Gross)	0.00 (0.0)	1.61 (6.4)	0.20 (0.8)	0.58 (2.3)	2.39 (9.5)
Fuel Air	0.00 (0.0)	0.25 (1.0)	0.03 (0.1)	0.08 (0.3)	0.35 (1.4)
Wicket Air	0.03 (0.1)	0.03 (0.1)	0.10 (0.4)	0.03 (0.1)	0.18 (0.7)
Inlet	1.28 (5.1)	0.00 (0.0)	1.76 (7.0)	2.47 (9.8)	0.00 (0.0)
Pellet Gas	0.15 (0.6)	0.08 (0.3)	0.08 (0.3)	0.00 (0.0)	0.30 (1.2)
Volatile RX	0.43 (1.7)	0.13 (0.5)	0.83 (3.3)	0.33 (1.3)	1.71 (6.8)
Interzonal Radiation	0.43 (1.7)	-0.43 (-1.7)	0.03 (0.1)	-0.03 (-0.1)	0.00 (0.0)
TOTAL	2.32 (9.2)	1.67 (6.6)	3.03 (12.0)	3.46 (13.7)	4.93 (19.6)
Heat To:					
Pellets	0.91 (3.6)	0.53 (2.1)	0.40 (1.6)	0.25 (1.0)	2.09 (8.3)
Refractory	0.08 (0.3)	0.05 (0.2)	0.05 (0.2)	0.05 (0.2)	0.23 (0.9)
Water	0.15 (0.6)	0.10 (0.4)	0.10 (0.4)	0.10 (0.4)	0.45 (1.8)
Outlet	1.18 (4.7)	0.99 (3.9)	2.47 (9.8)	3.05 (12.1)	2.17 (8.6)
TOTAL	2.32 (9.2)	1.67 (6.6)	3.02 (12.0)	3.45 (13.7)	4.94 (19.6)

NOTE: Energy Values in MMkcal/hr (MMBtu/hr).

Table 5. Capital Cost Estimates

	Materials	Installation	Total
Pelletizing Equipment	\$2,123,000	\$393,000	\$2,516,000
Furnace	\$5,488,000	\$3,147,000	\$8,635,000
Exhaust Gas System	\$1,225,000	\$980,000	\$2,205,000
Foundations	\$440,000	\$252,000	\$692,000
Freight			\$215,000
Engineering			\$1,329,000
Contingency			\$1,137,000
Total			\$16,729,000

The following are not included in these estimates:

- Building
- Personnel facilities
- Communication system
- Area lighting
- Aviation lighting
- Fencing
- Roadwork/sidewalks
- Sewage system modifications
- Fire alarms / Fire protection systems
- Public address system
- Overhead cranes
- Loading docks
- Front end loaders
- Dump trucks
- Forklifts
- Direction signs
- Security office
- Aesthetic landscaping
- Flood protection
- Parking lots
- Site preparation/cleanup

Table 6. Operating Cost Estimates

Utility/Material	Usage	Assumed Unit Price	Total Cost
Electricity	450 kW	\$0.042/kWh	\$18.90/hr
Furnace Natural Gas	4.80 MMkcal/hr (19.00 MMBtu/hr)	\$29.85/MMkcal (\$7.50/MMBtu)	\$142.50/hr
Iron Ore	7.13 metric ton/hr (7.86 ton/hr)	\$26.10/metric ton (\$23.68/ton)	\$186.12/hr
Iron Ore Delivery	7.13 metric ton/hr (7.86 ton/hr)	\$82.67/metric ton (\$75.00/ton)	\$589.50/hr
Coal	1.41 metric ton/hr (1.55 ton/hr)	\$62.83/metric ton (\$57.00/ton)	\$88.35/hr
Coal Delivery	1.41 metric ton/hr (1.55 ton/hr)	\$7.72/metric ton (\$7.00/ton)	\$10.85/hr
Bentonite	0.08 metric ton/hr (0.09 ton/hr)	308.65/metric ton (\$280.00/ton)	\$25.20/hr
Bentonite Delivery	0.08 metric ton/hr (0.09 ton/hr)	\$82.67/metric ton (\$75.00/ton)	\$6.75/hr
Total			\$1068.17/hr

NOTES:

Electricity (price from INMETCO, January, 2005)

Usage based on serving Induced Draft Fan, Combustion Air Fan, and Hydraulic Pumps

Natural Gas (price from INMETCO, January, 2005)

Iron Ore (price from 2004 Metal Bulletin)

(67% contained iron in ore) * (\$0.389 / metric ton contained iron) = \$26.10 / metric ton ore

Coal (price from Coal News and Markets, February 13, 2005)

Bentonite (price from Rennecker, Ltd., February 22, 2005)

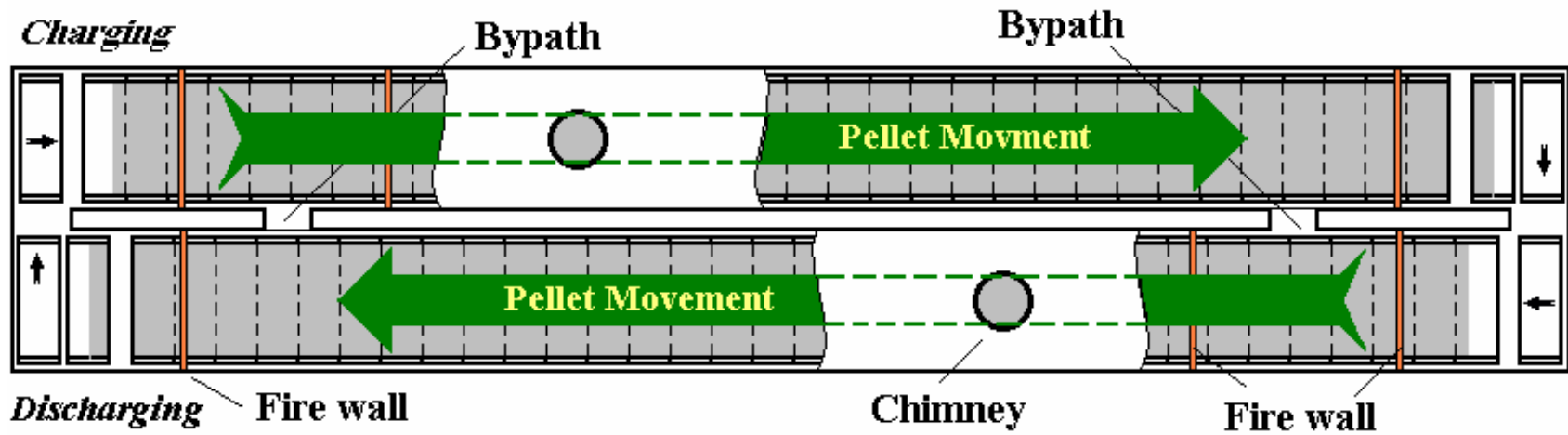
Bulk Prices do not include delivery charges.

FIGURES



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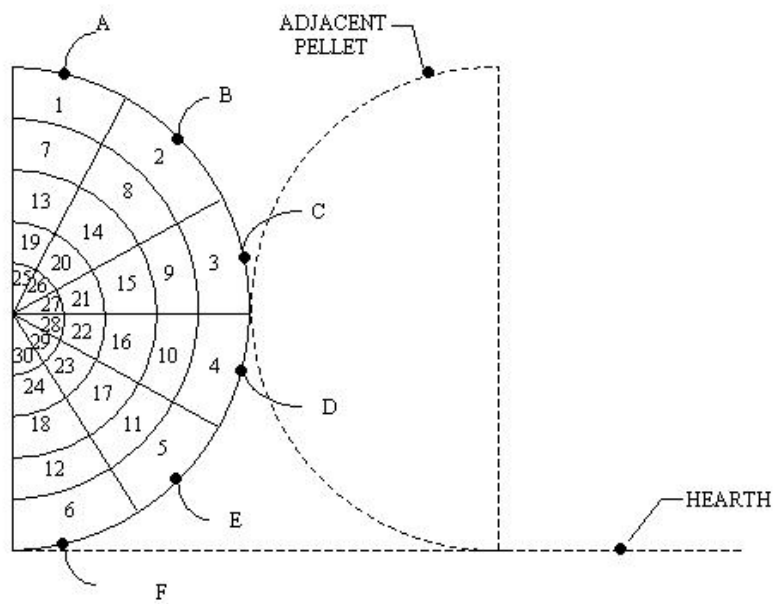
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(Figure copied from Reference 1)

Figure 1. The Top View of a PSH Furnace and the Movement of Pellets

MODEL NODALIZATION



30 TRUE NODES / PELLETT
6 SURFACE NODES / PELLETT

Figure 2. Model Geometry

DRI Pellet Average Temperatures

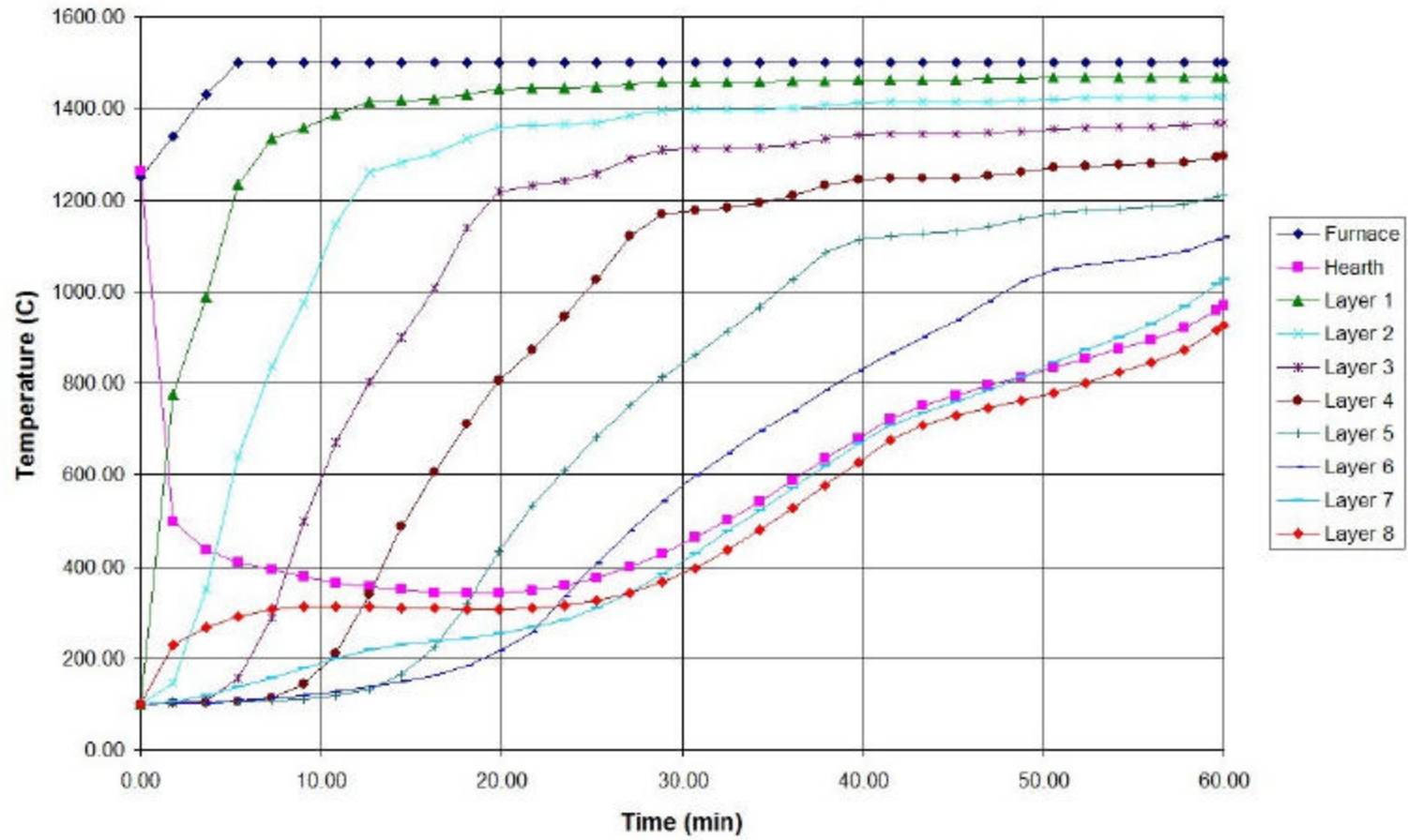


Figure 3. Test Case Temperature Transient

DRI Pellet Metallization

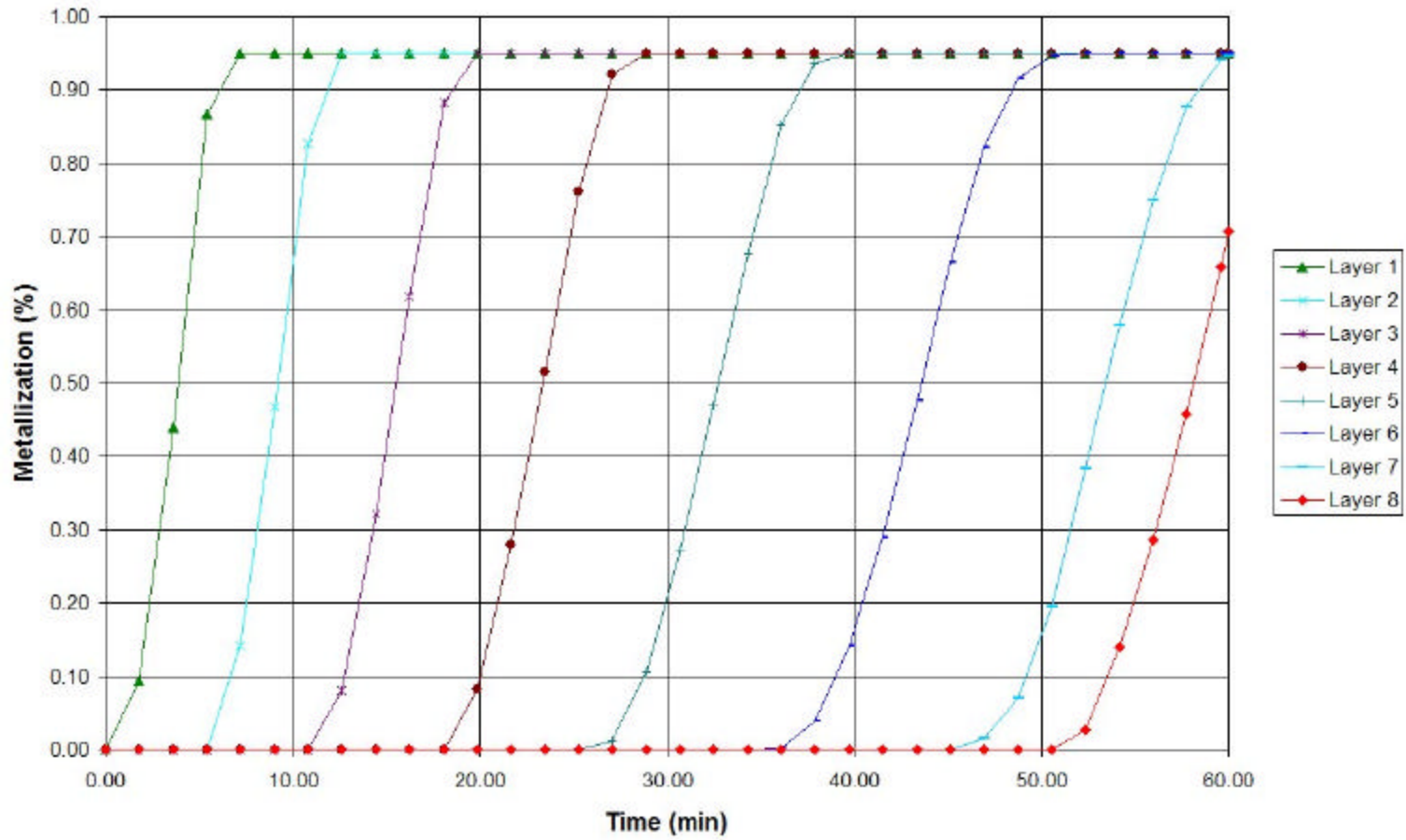


Figure 4. Test Case Metallization Transient

DRI Pellet Average Temperatures

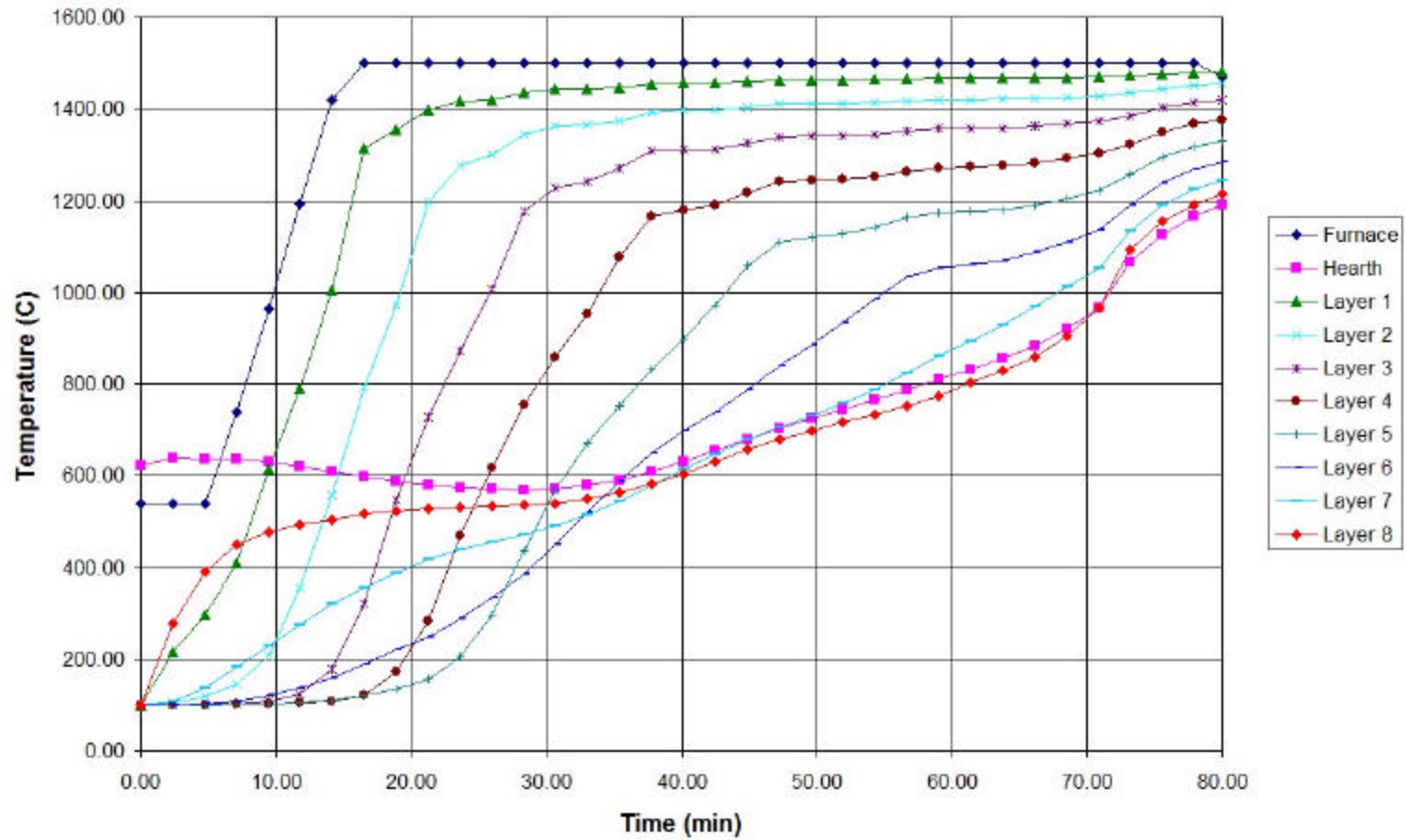


Figure 5. PSH Case Temperature Transient

DRI Pellet Metallization

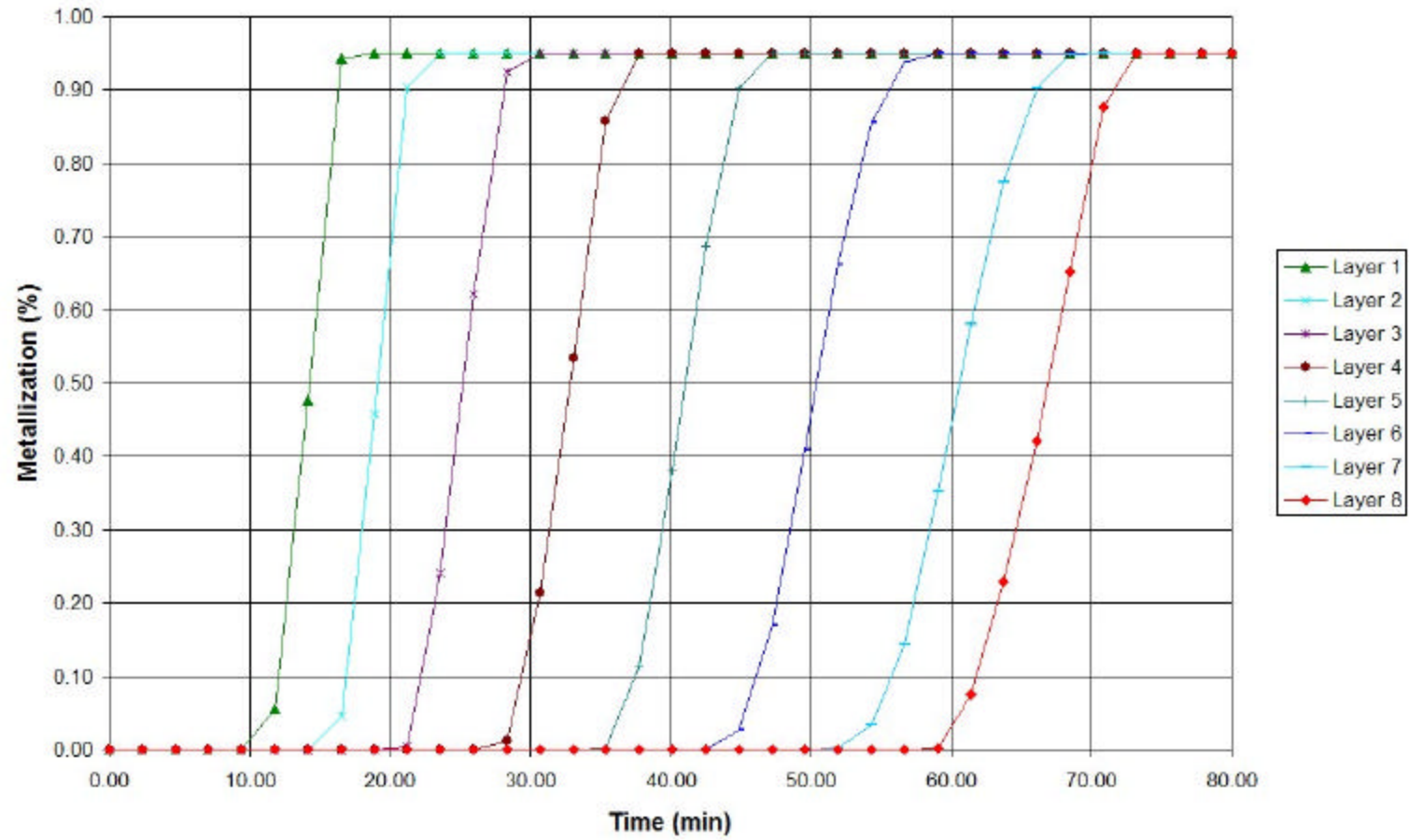


Figure 6. PSH Case Metallization Transient

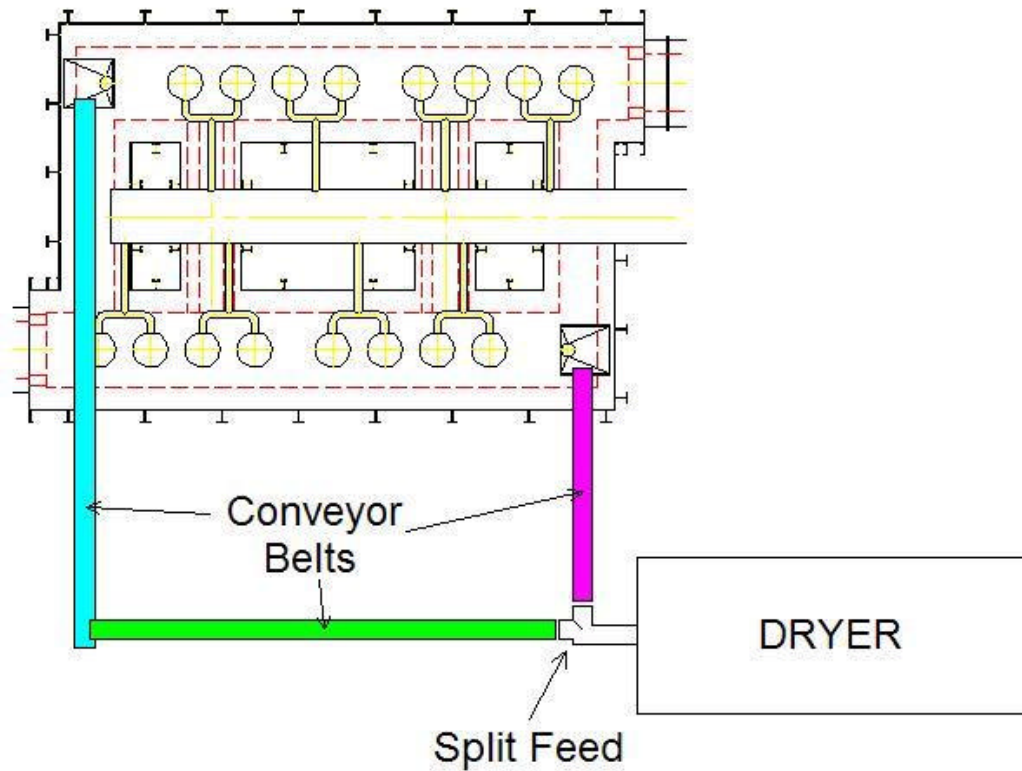


Figure 7. Split Stream Direct Pellet Charging to Furnaces

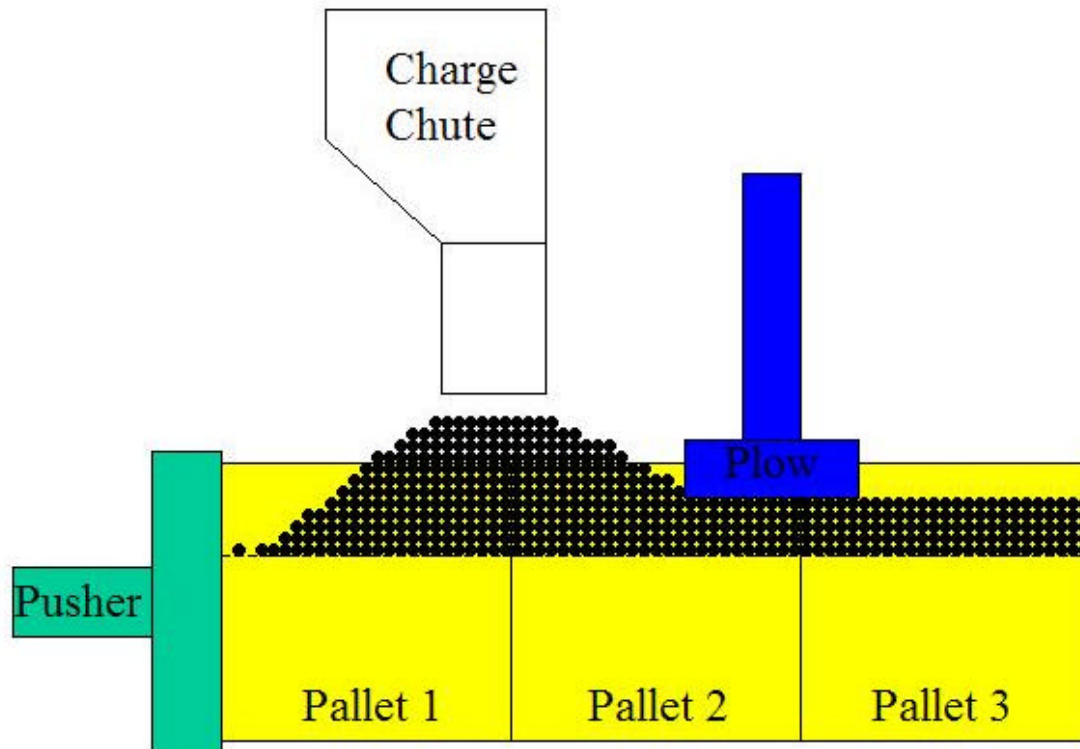


Figure 8. Sketch of Pellet-Charging Practice

Combustible Pellet Gas Generation During Metallization Process

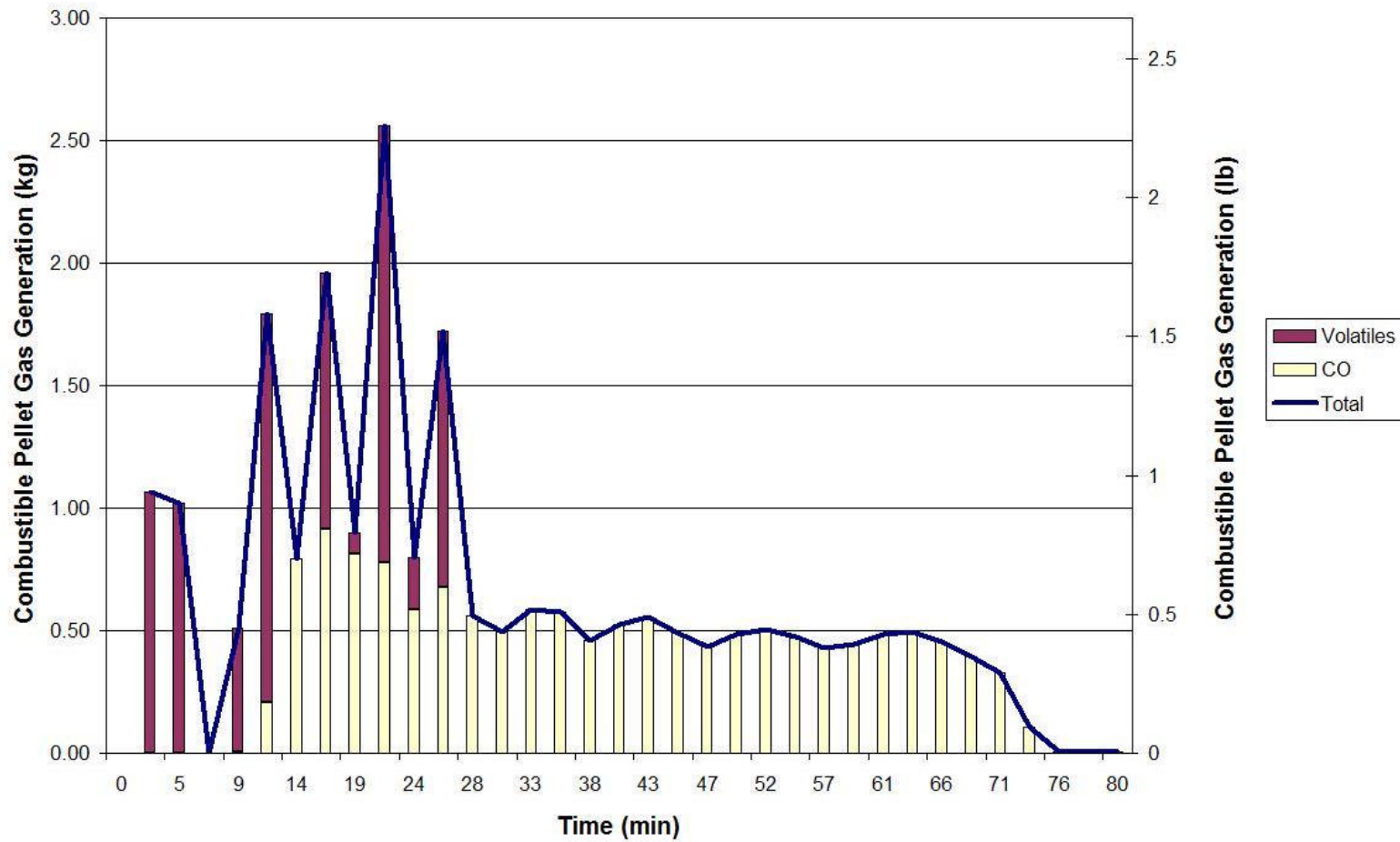


Figure 9. Combustible Pellet Gas Generation

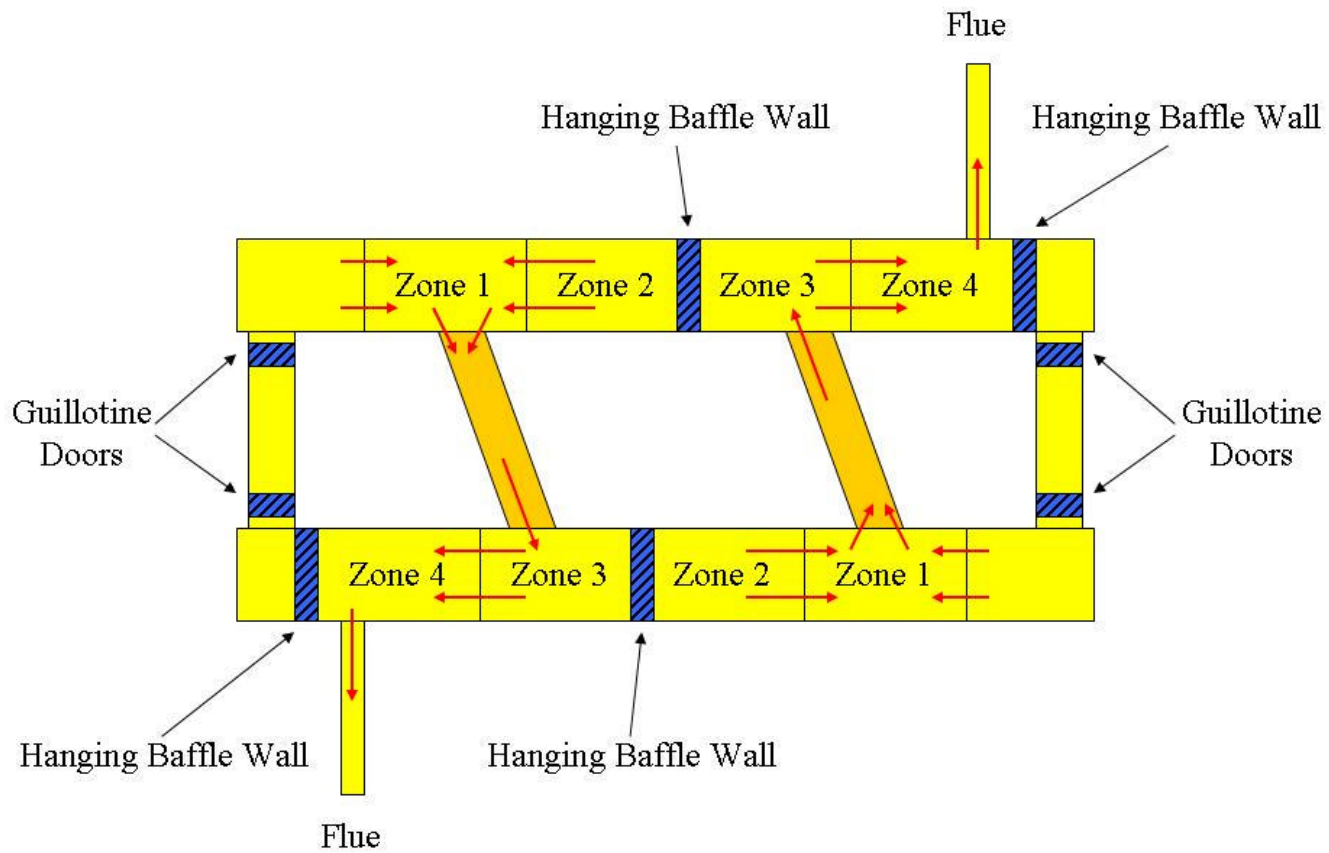
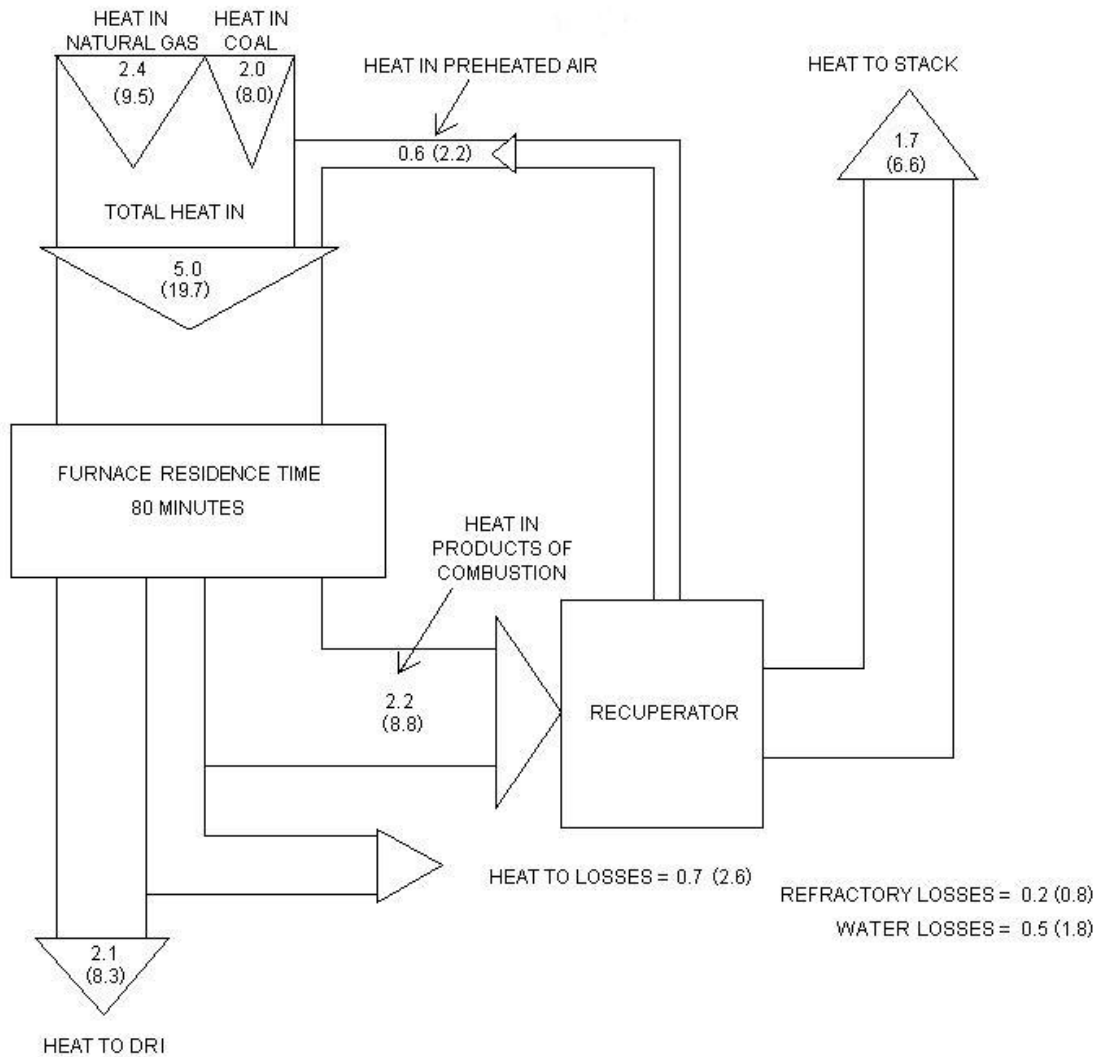


Figure 10. Optimized Furnace Gas Flow Pattern



NOTES:

- 1) HEAT FLOWS FOR SINGLE FURNACE
- 2) 8-LAYER PELLET BED
- 3) EXCESS AIR = 5 %
- 4) FUEL = NATURAL GAS
- 5) ALL HEAT VALUES SHOWN IN MMKCAL/HR (MMBTU/HR)

$$6) \text{ FUEL RATE} = \frac{240 \text{ MM KCAL/HR}}{2.49 \text{ METRIC TONS/HR}} = \frac{(9.50) \text{ MMBTU/HR}}{(2.75) \text{ TONS/HR}}$$

$$= \frac{0.96 \text{ MM KCAL}}{\text{METRIC TON}} = \frac{(3.45) \text{ MMBTU}}{\text{TON}}$$

Figure 11. System Heat Balance Diagram

DRAWINGS

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