NOVEL FLASH IRONMAKING TECHNOLOGY WITH GREATLY REDUCED ENERGY CONSUMPTION AND CO_2 EMISSIONS[1]

H. Y. Sohn[2]
M. E. Choi[2]
M. Olivas-Martinez[2]

Abstract

A new transformational technology for alternate ironmaking is being developed under the financial support of American Iron and Steel Institute. This technology is based on the direct gaseous reduction of iron oxide concentrate in a flash reduction process. The novel Flash Ironmaking Technology has the potential to reduce energy consumption by 32-57% and lower carbon dioxide emissions by 61-96% compared with the average current blast furnace operation. The process uses gaseous reducing agents such as natural gas, hydrogen, syngas or a combination thereof. It is to be applied to the production of iron as a feed to the steelmaking process or a part of a continuous direct steelmaking process. Justified by experimental data obtained during the previous phase of the project, scale-up development work is currently on-going at the University of Utah. Testing in a laboratory flash furnace has resulted in the establishment of a kinetics database over wide ranges of operating conditions and a complete design of a more advanced bench reactor. With an objective to develop an industrially viable Flash Ironmaking Technology, a comprehensive bench-scale testing campaign is planned. The deliverables from this phase of the project are expected to be the determination of the scalability of the process, substantive process simulation results and fundamental engineering data leading to the design and construction of an industrial pilot plant.

Keywords: Alternate ironmaking technology; Carbon dioxide emission; Flash smelting; Iron oxide concentrate.

---

[1] *6th International Congress on the Science and Technology of Ironmaking – ICSTI, 42nd International Meeting on Ironmaking and 13th International Symposium on Iron Ore, October 14th to 18th, 2012, Rio de Janeiro, RJ, Brazil.*

[2] *Professor, Department of Metallurgical Engineering, University of Utah, Salt Lake City, Utah 84112*

INTRODUCTION

According to the World Steel Association, world crude steel production has already recovered from the global economic crisis. The upturn came earlier and stronger than expected so that the steel production of 2010 (1,414 million metric tons) even exceeded the record production levels in 2007 (1,347 million metric tons). To sustain the needed levels of steel production, it will be necessary to ensure an adequate supply of iron. Further, as the industry progresses into higher grade steels to enhance product durability and performance, the need for low residual metallics raw materials for the steelmaking operation will become increasingly important. The blast furnace has been the major source of low residual iron to facilitate the production of high quality steels. High quality steel scrap is another crucial source of iron units. However, recovered scrap in general is expected to decline, particularly due to longer product retention as a result of the improved durability of products like automobiles. Consequently, diminishing scrap supply and price volatility will result in a greater demand for scrap substitutes.

It is clear that a viable commercial alternative process for producing iron that addresses the concerns and limitations associated with the blast furnace technology and other available direct reduced iron processes must be developed It is envisioned that the Flash Ironmaking Process described in this paper could meet the demand of integrated steel producers that depend on a reliable source of iron.

TECHNOLOGY DESCRIPTION

The Flash Ironmaking Technology is based on the direct gaseous reduction of iron oxide concentrates. The technology will have considerable energy and environmental benefits, arising largely from the elimination of cokemaking and pelletization/sintering steps in the predominant ironmaking technology (BF furnace). The energy savings will be up to 57% of the average blast furnace operation. The use of coke in the BF generates more than 1.1 ton of CO_2 per ton of iron as well as other pollutants, which will be greatly reduced by the new technology [1, 2].

An important factor in the development of the Flash Ironmaking Process is that the U.S. already produces large quantities of iron oxide concentrates that are well suited for flash reduction. These concentrates have to undergo pelletization or sintering process to be utilized as a feed to the blast furnace. Up to 60% of the U.S. iron production [3] is based on taconite concentrates (50-55 million tons/year). On a world-wide basis, good quality lump ore is at a premium. Ores from newer reserves also need to be ground to finer sizes in order to beneficiate them and make them acceptable for ironmaking.

The Flash Ironmaking Process is to be operated using natural gas as a fuel and reducing agent. Natural gas is an abundant readily available resource in the U.S. According to the 2011 Annual Energy Outlook [4], the estimation on the U.S. production rate of natural gas predicts a steady increase. Further, there is a big push to increase natural gas production in the U.S. from its considerable reserves. The recently discovered reserves in Marcellus Shale [5] represent a good example of this trend. For an annual production of 20 million tons of iron, which would represent about 40% of the current U.S. production rate, the Flash Ironmaking Process would require 0.33 TCF/year (trillion cubic feet per year) of natural gas. This represents less than 1.5% of the total U.S. consumption rate (22.7 TCF/year) [6]. As a comparison, this is similar to the 1.5% of the total U.S. energy consumption used by the U.S. steel industry. When natural gas is used as a reducing agent, the proposed process will produce iron with varying carbon contents such as the iron produced by HYL's ZR self-reforming process [7]. In the latter process, carbon levels can be up to 5.5 %.

The Flash Ironmaking Process can also be designed to be operated with pure hydrogen to take advantage of the development of a hydrogen economy. The product will be low-carbon iron with a possibility for direct steelmaking. The product could also be collected as a solid, to be fed into an EAF for steelmaking, in which case carbon could be added in the briquetting step. Alternatively, the EAF could be modified by adding a lance for gas injection to promote optimum slag foaming, rather than relying on CO produced from dissolved carbon to enhance the refining and steelmaking reactions. Further, the reduced iron material could be melted in a coal-based melter or an electric melter to produce a molten metal feed of different characteristics.

The Flash Ironmaking Process will remove many of the limitations associated with other alternative processes. Specifically, (a) direct use of iron oxide concentrates without the need for pelletization or sintering; (b) no cokemaking required (If coal is used to generate the hot reducing gas, pulverized coal of wide variety can be used.); (c) high temperature can be used because there will be no particle sticking or fusion problems (and thus, the process can be intensive); (d) possibility to produce either solid or molten iron; and (e) low refractory problems, ease of feeding the raw materials, and the possibility of direct steelmaking in a single unit.

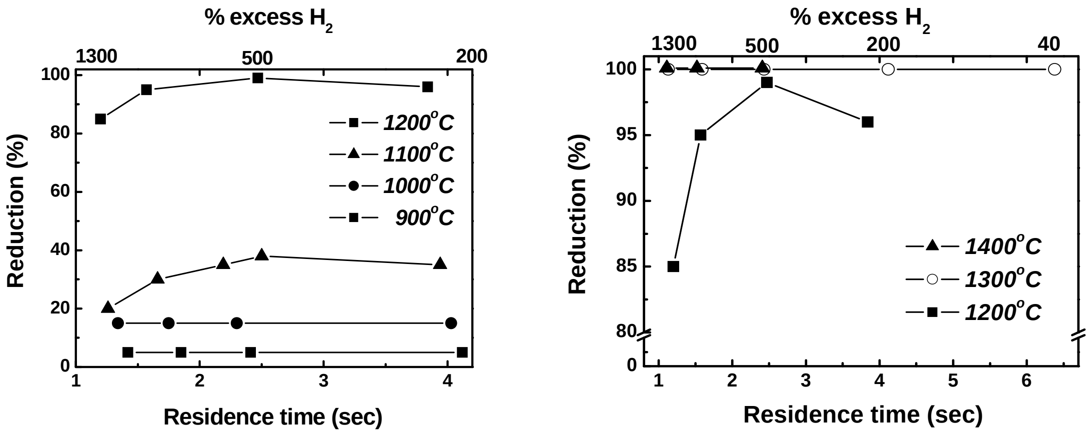
KINETIC FEASIBILITY TESTS

Based on the above discussion, a flash reduction process presents the best alternative for a high-intensity process. The fineness of the concentrate particles allows a very rapid reaction rate, thus requiring residence time measured in seconds compared with the minutes and hours it takes to reduce pellets and even fines.

Historically, processes based on iron ore *fines* have been less than successful. One must recognize, however, that *concentrate particles* are much finer, by more than one or two orders of magnitude, than the typical iron ore 'fines' used in a typical fluidized bed, and the flash process is meant to take advantage of this fact. The fluid bed processes use particles in the range of +0.1 mm to -10 mm (Iron Carbide, Circored and FIOR) compared with 0.02 – 0.06 mm particles in the concentrates. The rate of reduction increases in proportion to the reciprocal of the particle size or its square, depending on temperature. Thus, compared with concentrate particles, even ore 'fines' take much longer time to reduce than the time available in a flash reduction process.

Experimental data from our previous work [7] have conclusively proven that concentrate particles are sufficiently small to permit the use of a flash reduction process with its short residence time. In a drop-tube reactor, over 90% reduction was attained in 1.6 seconds and the particles were almost completely reduced in 2.5 seconds at 1200^{o}C in large excess hydrogen, as shown in Figure 1-(a). Above 1300^{o}C complete reduction was accomplished in less than 1.1 seconds, as shown in Figure 1-(b), and even when excess hydrogen was lowered to 40%, complete reduction was reached in less than 6.5 seconds. These results confirm that the rate is sufficiently fast for the reduction of currently available concentrate to be carried out in the flash reduction process above 1200^{o}C. Therefore, the kinetic feasibility for the flash ironmaking process was sufficiently established for the development and testing of a technically sound process concept that takes advantage of the rapid reduction of iron concentrates in a large scale.

High temperature gas-solid suspension contact processes, such as the flash, flame reaction or cyclone smelting, are well established in industry and can readily provide a residence time of up to about 10 seconds. The success enjoyed by the flash smelting processes in nonferrous industries, which use concentrate particles of similar sizes, further supports the expectation of the success of the technology being developed.



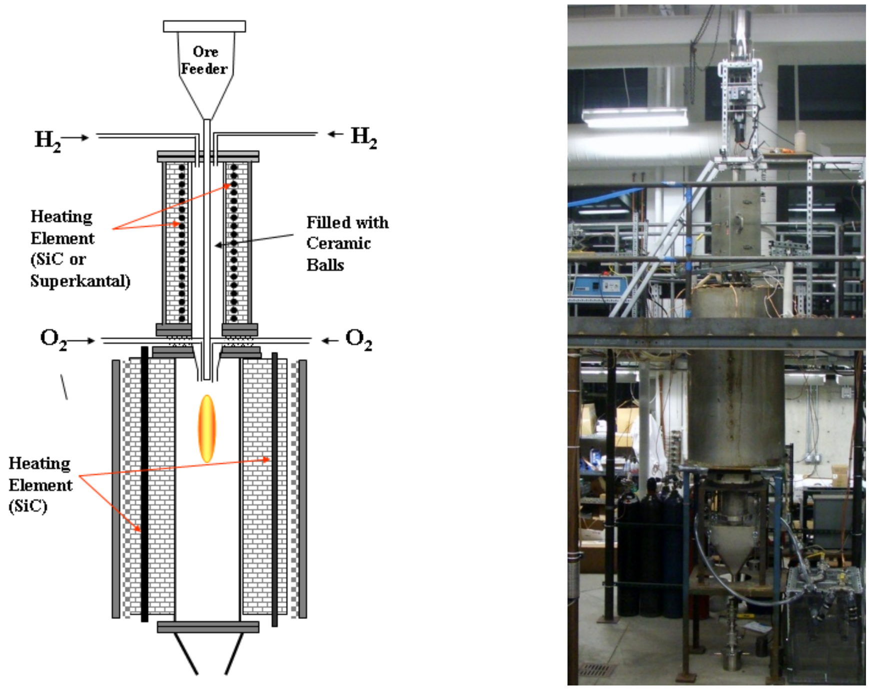
(a)

900 ~ 1200°C (b) 1200 ~ 1400 °C

Figure 1. Hydrogen reduction rate of iron oxide concentrate vs. residence time and % excess H_2 at 900 - 1400°C. (particle size: 25 - 32 µm)

BENCH-SCALE TESTING

Encouraged by the promising results from the kinetic feasibility work, scale-up tests have been conducted using an existing laboratory flash reactor at Utah. The flash reactor system consists of a powder feeding unit, a process gas preheater, a non-premixed burner, a reaction shaft, a powder collecting system, an off-gas scrubbing system, and various instrumentation devices. Figure 2 shows the apparatus consisting of two electrically heated parts; the upper part (0.064 m ID, 1 m long) is a hydrogen preheater and the lower part is the reactor (0.194 m ID, 1.93 m long) in which iron ore concentrate particles are reduced. They are connected by a nozzle through which hydrogen and oxygen are injected to form a H_2/O_2 flame. Hydrogen fed to the reactor is preheated to 800°C. Inside the top part of the reactor, part of the preheated hydrogen is combusted with oxygen that is supplied at room temperature. The energy released from the H_2/O_2 diffusion flame heats the hydrogen-rich reducing gas stream as well as the concentrate particles injected downward through the preheater. This hot reducing gas stream reduces the iron oxide fed at a rate of 0.1 to 1 kg/hr. Heating elements around the main reactor supplies additional energy provides partial compensation for heat loss, and also keeps the H_2/O_2 diffusion flame more stable by maintaining the reactor above the auto-ignition temperature (about 570°C for a stoichiometric mixture at normal atmospheric pressure). The off-gas stream consisting of particles and gas passes through a dust collecting chamber in which its velocity decreases, thus allowing the particles to be separated from the main gaseous stream. The reduced particles fall into the receptacle.



(a) (b)

Figure 2. Utah Laboratory flash reactor: (a) schematic diagram; (b) photograph.

The concentrate used for the experiments was provided by ArcelorMittal (East Chicago, USA) and had the composition presented in Table I. The reduced concentrate was sampled for chemical analysis at three different locations: the powder collecting chamber, the bottom flange of the reactor, and the elbow connections. The samples were then characterized by various analytical techniques and the degree of reduction is determined.

Table I. Chemical composition of the iron ore concentrates from ArcelorMittal.

Component	Total Iron	FeO	SiO_2	CaO	MgO	Al_2O_3	TiO_2	MnO	Na_2O	K_2O	P	S
wt%	68.22	28.24	4.30	0.19	0.29	0.061	0.021	0.021	0.011	0.044	0.014	0.0005

Table II presents the most representative product samples collected at different parts of the reactor from different experimental runs. Also, the powder feeding method used in the corresponding experiment is indicated. In case of the gravity feeding, the powder was supplied using a disc-type micro-feeder. The feeding port was located at the center of the burner. As a result, the concentrate powder went through the flame. On the other hand, the pneumatic feeding was carried out through an auxiliary feeding port located between the hydrogen flame and the inner wall of the reactor.

Table II. Three Representative Cases

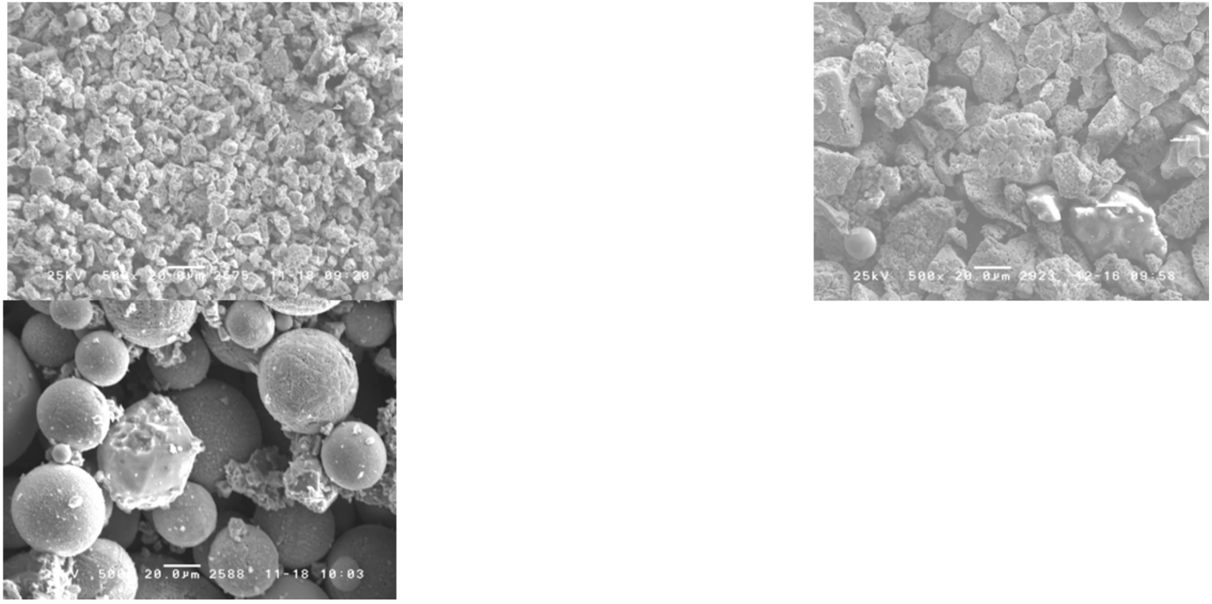
Sample	RD, %	Powder Feeding Method	Sampling Location
1	100	Pneumatic[1]	Off-gas passage
2	72	Pneumatic[1]	Bottom reactor flange
3	35	Gravity[2]	Collecting chamber

[1] H_2 used as a carrier gas.
[2] Disc-type micro-feeder. Powder fed through the burner.

Sample 1 represents the fine particles that are entrained in the flow of the process gas and exit the system as dust. They were collected from the elbow connections used in the off-gas system. SEM micrographs, Figure 3-(a), indicated that the largest particles have sizes smaller than 20 μm. XRD results, Figure 4-(a), indicated that the predominant phase is metallic iron.

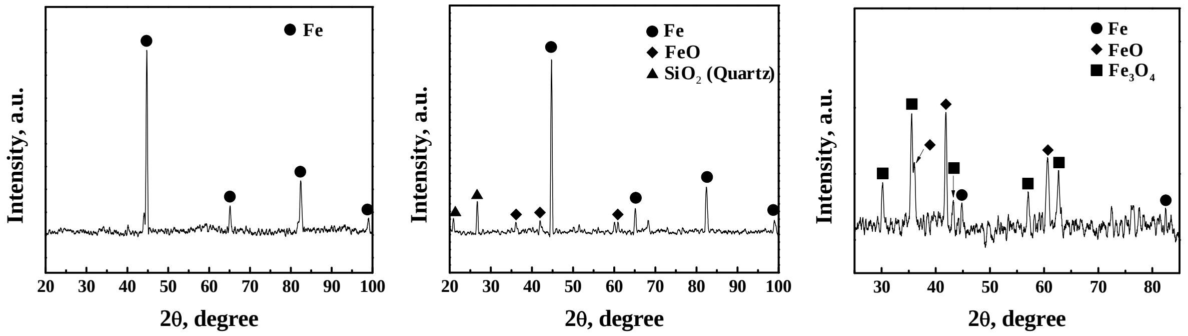
Sample 2 was collected from the reactor bottom flange. SEM micrographs, Figure 3-(b), show that the particles almost kept the original shape of the concentrate but they lost the sharp edges and developed porosity. XRD results, Figure 4-(b), suggest that the metallic iron is the most abundant phase. The chemical analysis by titration indicated that the reduction degree of this sample was 72%.

In the last case (Sample 3), the iron concentrate was fed using a disc-type micro-feeder. SEM micrographs, Figure 3-(c), showed spherical porous particles with sizes larger than the average size of the concentrate powder. This is explained by the fact the particles melted upon contacting the flame before undergoing reduction. XRD results, Figure 4-(c), showed that metallic iron, wustite and magnetite phases are present in the collected powder. This result is consistent with the chemical analysis that indicates a reduction degree of 35%. EDS results indicated that the particle surface is mostly composed of metallic iron.



(a) (b) (c)

Figure 3. SEM micrographs of Samples 1~3 with reduction degrees of (a) 100%; (b) 72%; (c) 35%.



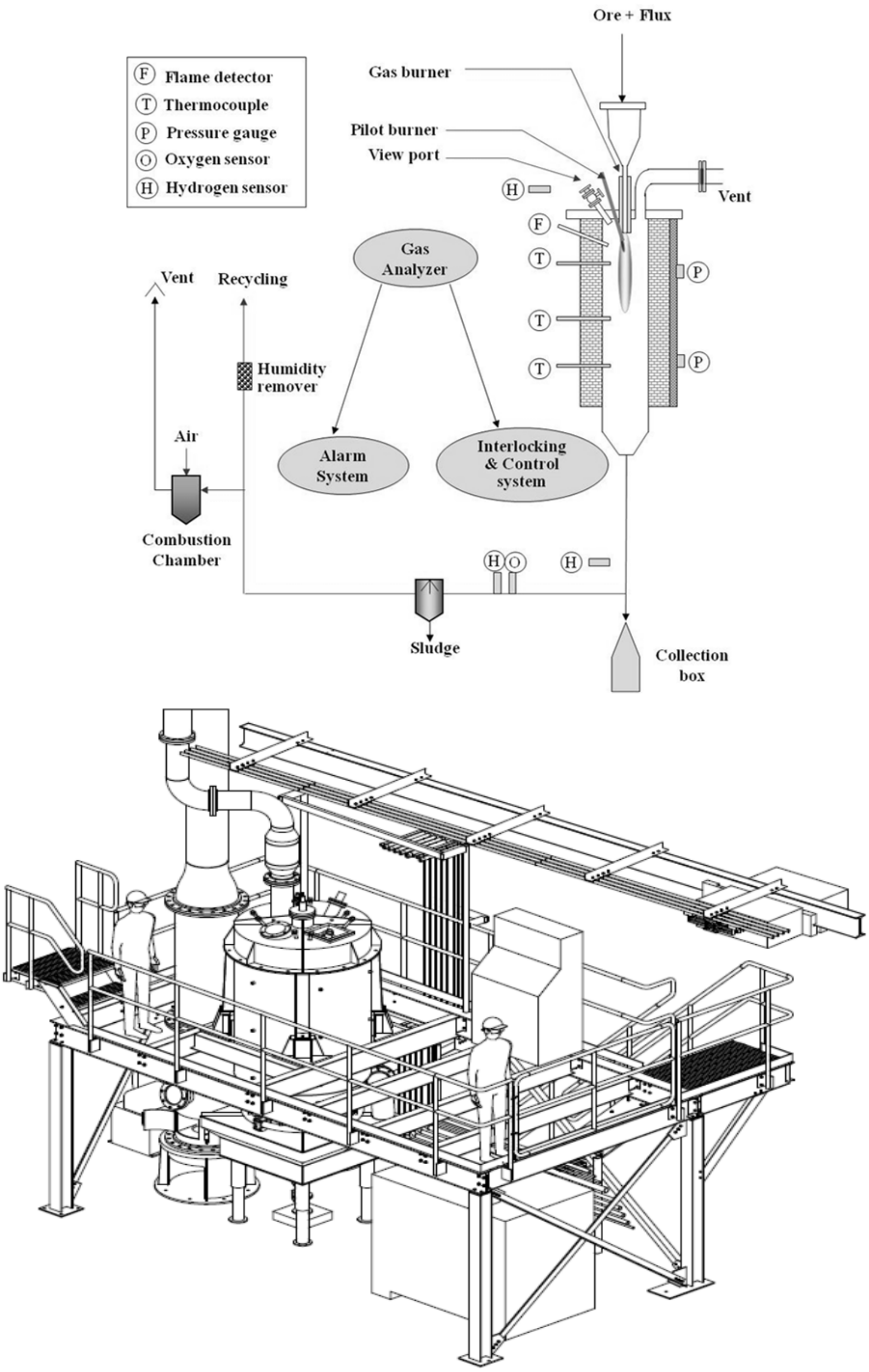
(a) (b) (c)

Figure 4. XRD patterns of Sample 1~3 with reduction degrees of (a) 100%; (b) 72%; (c) 35%.

Due to the limitations inherent in its design and reactor body material, testing in the existing laboratory flash reactor is not able to provide all the necessary information to assess the Flash Ironmaking process as an industrially viable technology: the major limitation in the current laboratory flash reactor is to provide a sufficient amount of heating. Thus, a large-scale bench reactor test program is in progress. In identifying the specific design and functional features necessary for the bench facility, the method of supplying heat has been the keydriver. The bench reactor will produce iron using hydrogen or natural gas as the fuel as well as the reductant in a cylindrical reactor. The energy for the sensible heat of solid and gas feed materials and for the reduction reaction of iron oxide will be supplied by a single burner installed on top of the reduction chamber in combination with a plasma torch as a supplementary heat source.

Figure 5 shows the conceptual diagram and preliminary facility layout of the large bench-scale test facility comprising several subsystems such as a hydrogen burner, a pneumatic powder feeder, gas delivery lines, safety measures and interlocking system, a quenching chamber, a powder collection bin, and a flare stack to burn the hydrogen remaining in the off-gas. (In an industrial plant, the off-gas will be recycled after removing water vapor contained in it.) A gas burner will generate a flame inside the top part of the reaction chamber (0.81 m ID, 1.52 m high). The design feed rate of iron ore concentrate in this scale is 5 kg/h. Concentrate particles will be supplied through the burner or in the vicinity of the hydrogen/oxygen flame. The flame will also be the main energy source for the sensible heat for the process. The average temperature of the reaction shaft will be 1400~1600°C. The entire system will be monitored by several safety measures and controlled by proper emergency shut-off procedures.

It is noted that the large bench reactor has many features of an eventual industrial reactor. They include a burner as the main heat source and a refractory-lined vessel. Upon completing this project phase, engineering data necessary for industrial pilot-plant operations will have been generated, such as heat loss, product collection, raw materials feeding, process control strategy, burner design, and off-gas treatment.



(a) (b)

Figure 5. Large-scale bench reactor: (a) conceptual diagram; (b) preliminary facility layout

CONCLUSIONS

A novel flash ironmaking technology is under development for producing iron directly from fine iron ore concentrates by a gas-solid suspension reduction process. The technology will significantly reduce energy consumption by 32-57% and lower carbon dioxide emissions by 61-96%, depending on the type of the fuel/reductant used, compared with the average blast furnace ironmaking route. These benefits come largely from the elimination of cokemaking and sintering/pelletization.

The project team is developing a large bench-scale reactor. The design of the bench reactor has been completed and the major components fabricated. The bench-scale testing results will be used to determine the scalability toward larger industrial-scale trials and generate the necessary information and data needed to design an industrial pilot-scale plant.

While the new bench-scale test facility is under construction, tests have been performed with an existing laboratory flash reactor (at Utah) to identify technical hurdles and develop design parameters for construction of the large bench reactor. Test results so far yielded successful operation of a H_2/O_2 burner as the main heat source and satisfactory degrees of reduction.

ACKNOWLEDGMENTS

This work was supported by the American Iron and Steel Institute (AISI) under AISI's CO_2 Breakthrough Program. Special thanks are extended to Mr. H.R. Kokal and Dr. P.C. Chaubal of ArcelorMittal and Ing. R. Viramontes B. of Ternium HYLSA for providing the iron oxide concentrates used in this work and technical discussion. Technical comments and helpful inputs provided by Dr. M. Atkinson of ArcelorMittal are gratefully acknowledged.

REFERENCES

1 Pinegar, H. K.; Moats, M. S.; Sohn, H. Y., Flow Sheet Development, Process Simulation and Economic Feasibility Analysis for a Novel Suspension Ironmaking Technology Based on Natural Gas: Part I. Flow Sheet and Simulation for Ironmaking with Reformerless Natural Gas; Part II. Flow Sheets and Simulation for Ironmaking Combined with Steam-Methane Reforming; Part III: Economic Feasibility Analysis, *Ironmaking Steelmaking*, accepted.
2 Pinegar, H. K.; Moats, M. S.; Sohn, H. Y., Process Simulation and Economic Feasibility Analysis for a Hydrogen-Based Novel Suspension Ironmaking Technology, *Steel Res. Int'l.*, accepted.
3 USGS, Minerals Yearbook - Iron Ore, 2005, http://minerals.er.usgs.gov/minerals/pubs/commodity/iron_ore/
4 U.S. Energy Information Administration – Annual Energy Outlook 2011 http://www.eia.gov/forecasts/aeo/index.cfm
5 Pittsburgh Post-Gazette, Penn State forecasts boom for Marcellus Shale,
6 http://www.post-gazette.com/pg/11202/1161933-503.stm; see also
7 http://www.eia.gov/analysis/studies/usshalegas/
8 Duarte, P. E.; Becerra, J.; Lizcano, C.; Martinis, A., Energiron Direct Reduction Ironmaking – Economical, Flexible, Environmentally Friendly. *Steel Times International*, 2010, p. 25.
9 Moo Eob Choi; H. Y. Sohn, Development of a Green Suspension Ironmaking Technology Based on Hydrogen Reduction of Iron Oxide Concentrate: Rate Measurements, *Ironmaking Steelmaking*, 37, 81-88 (2010).