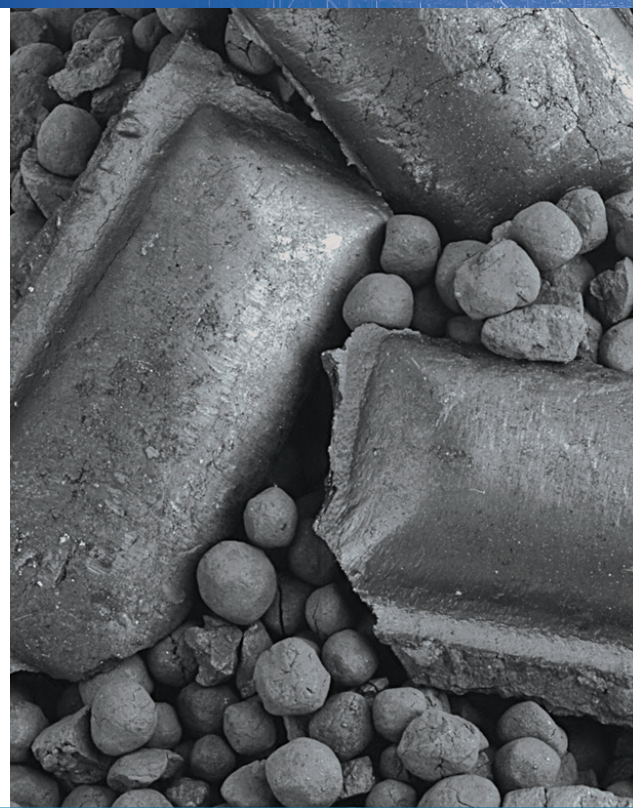


DIRECT FROM MIDREX

3RD QUARTER 2017



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COMMENTARY

BUILDING ON CORE TECHNOLOGY- CREATING FLEXIBILITY AND VALUE



By Christopher Ravenscroft
Manager - Global Marketing &
Communications

Midrex at its core is a technology company. It has built its business on the concept of renewable technology – a self-sustaining cycle that builds on itself blending, science, engineering and real world experiences to renew and improve existing processes, systems and equipment. At its center is the idea of finding practical, technically-sound means to increase operational flexibility to produce value.

In this issue of *Direct From Midrex*, we feature two examples of technological innovations to the MIDREX® Direct Reduction Process flowsheet. One is a technology that is now available to both existing and new plants and the other represents the near future - a technology anticipating a coming change within the industry.

The MIDREX Adjustable Carbon Technology (ACT™) is available now and can increase the production flexibility of new or existing MIDREX® Plants by providing an independent means of increasing the carbon levels of the DRI products without lowering temperature. This is an important advancement, as there is no universal answer to what is the optimum carbon level for a steelmaker to have. The level of carbon needed can be very much situational.

For steelmakers using hot transport and/or high percentages of DRI product within an EAF, high carbon levels in the DRI can be counterproductive; however, steelmakers using lower percentages of DRI as charge materials can benefit from DRI carbon over 3%.

The MIDREX ACT™ gives operators the freedom to choose the desired carbon level. More importantly, it allows operators to vary that level whenever they want. Think of the ACT™ as a multi-tool. The ACT™ further increases operational flexibility to benefit overall steelmaking operations.

The other technology profiled in this issue looks towards a future where steelmakers may choose to supplement or replace hydrocarbon-based ironmaking with “green” hydrogen-fueled DRI production. The reforming of natural gas into a hydrogen/CO-rich reducing gas is a key element of the MIDREX® Process. It

has been demonstrated that hydrogen (H₂) can be substituted for up to 1/3 of the required natural gas in a MIDREX® Plant, and Midrex is working on a flowsheet that uses 100% H₂ and requires no MIDREX® Reformer.

This future technology, MIDREX H₂™, is similar to the standard MIDREX® Process except that the H₂ input gas is generated external to the process. In practice, the reducing gas H₂ content is about 90%, with the balance being CO, CO₂, H₂O and CH₄, which result from the addition of natural gas for temperature control and carbon addition. Further, with MIDREX H₂™, CO₂ emissions could be reduced up to 80% vs. the BF/BOF steelmaking route.

MIDREX ACT™ and MIDREX H₂™ illustrate our continuing efforts to create options and operational flexibility for DRI producers and steelmakers. Geared to be practical for an ever-evolving industry, our technology innovations are engineered to help solve problems steelmakers face today while anticipating and preparing for future challenges. That is the value of improving technology and that is the goal we strive to meet. ■





INCREASING CARBON FLEXIBILITY IN MIDREX® DRI PRODUCTS



**Adjustable to 4.5%,
Excellent Temperature Retention
with MIDREX ACT™**

By Michael D. Arandas, Vincent F. Chevrier and Christopher M. Ravenscroft of *Midrex Technologies, Inc.*

INTRODUCTION

Worldwide, there are approximately 70 MIDREX® Plants producing Direct Reduced Iron (DRI) products: cold direct reduced iron (CDRI), hot direct reduced iron (HDRI) and hot briquetted iron (HBI), or a combination of these forms of DRI (Figure 1). Over the nearly five decades the MIDREX® Direct Reduction Process has been in operation, product carbon levels have varied based on plant location and product use. In 2016, MIDREX® Plants produced more than 47 million tons of DRI products with carbon levels of approximately 0.5% to 3%, controllable to meet the requirements of individual plant operators.

Recently, Midrex Technologies, Inc. has created a new flexible technology that can increase the carbon content of DRI produced in a MIDREX Plant up to 4.5% while maintaining the discharge temperature. This patent pending innovative technology is called ACT™, which stands for Adjustable Carbon Technology. MIDREX ACT™ allows MIDREX® Plants to produce the widest range

DRI PRODUCTS	CDRI	HBI	HDRI
			
Product Form	Pellet & lump	Briquettes* (density ≥ 5.0 grams per cubic centimeter (g/cc))	Pellet & lump
Product Temperature	Ambient	Ambient	550° C or Higher
Where used	EAF & BOF	EAF, BOF & BF	EAF
Charging Method	Continuous & Batch	Continuous & Batch	Continuous & Batch

FIGURE 1. DRI Product Forms

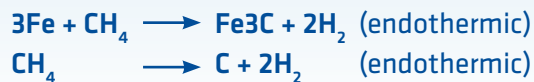


of carbon in DRI products and can be easily adjusted during operation. The technology can be retrofitted to existing plants or integrated in the design of a new plants to provide Midrex customers the flexibility to produce a higher carbon DRI and HBI.

MAKING CARBON THE MIDREX WAY

In the MIDREX[®] Shaft Furnace, carbon is added to DRI in three places:

- **The reduction zone** - In the MIDREX[®] Process, the main purpose of the reduction zone is to metallize the iron to the desired product metallization using reductants CO and H₂ produced by the MIDREX[®] Reformer. However, some carbon is added in the reduction zone derived from CH₄ and CO. Carbon from CH₄ is endothermic (i.e., consume heat), while carbon from CO is exothermic (i.e., liberates heat).
- **The transition zone** - A controlled flow of transition zone natural gas is added, which is the main method of adding and controlling the amount of carbon in MIDREX[®] DRI Products. The natural gas feedstock to MIDREX[®] Plants contains hydrocarbons, mostly methane, and using methane as an example, the carbon comes by:



These carbon-forming reactions are endothermic and cool the DRI, this is desirable for plants producing CDRI but not necessarily so for plants producing HDRI or HBI.

- **The cooling zone** - MIDREX[®] Plants that have a cold discharge furnace use cooling gas to cool the DRI. The cooling gas contains hydrocarbons and carbon is added in a similar manner as in the transition zone.

DEVELOPMENT OF MIDREX ACT[™]

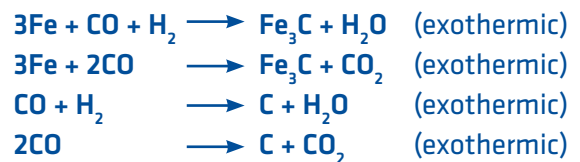
To meet market demands for a more flexible DRI product, Midrex Research and Technology Development was challenged to develop a new technology to add carbon without cooling the DRI. The technology had to be flexible (carbon easily adjustable during plant operation) and capable of being added to the MIDREX[®] Process to permit the retrofitting of existing plants,

as well as to be offered in the design of new plants. Midrex R&D came up with the conceptual idea, theoretical calculations, and computer modeling (thermodynamic and kinetic) and conducted laboratory testing to prove the concept (*Figure 2*).

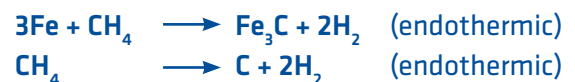


FIGURE 2. Test stand at Midrex R&D Center used to verify the ACT[™] concept and to perform experiments that provided the data needed to develop the commercial design.

With the MIDREX ACT[™], carbon monoxide (CO), made in the MIDREX Reformer, is added to the transition zone in the form of a CO-rich gas stream. The CO contacts the DRI bed and the resulting exothermic reactions provide extra energy:



Transition zone natural gas is added along with the CO-rich stream, using the CO-generated energy to provide the energy to produce additional carbon without sacrificing temperature:





By adjusting the amount of CO added to the transition zone, the plant operator can adjust the amount of energy added to DRI products. Adjusting the natural gas addition will control the carbon content of the DRI. Using these simple principles, this technology allows for independent control of the temperature increase and the amount of carbon added.

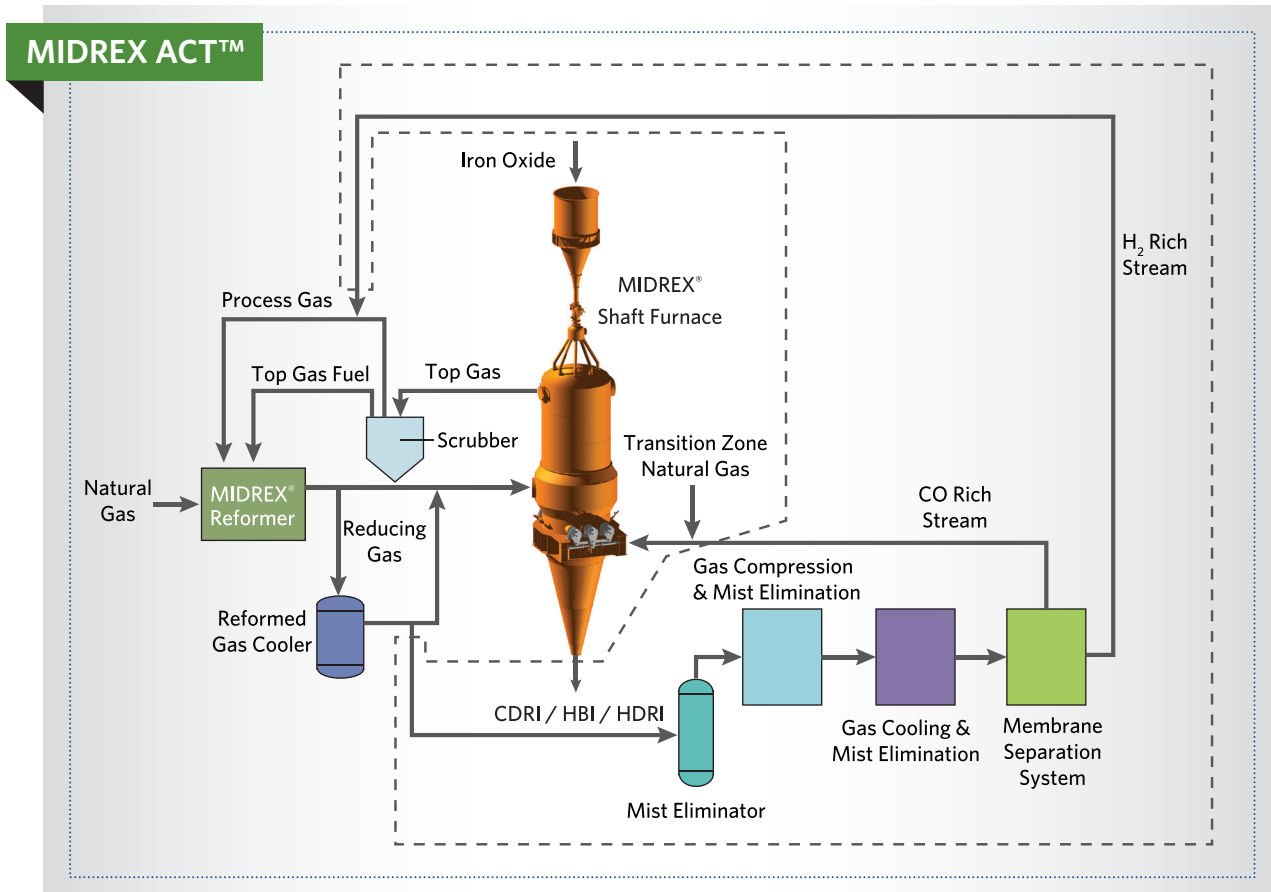


FIGURE 3. Simplified MIDREX ACT™ Flowsheet

MIDREX ACT™ AT A GLANCE

- Can be used in every type of MIDREX® Plant (CDRI, HDRI, HBI or a combination)
- Allows amount of carbon in DRI to be adjusted up or down
- Carbon can be added without cooling the DRI
- 85-90% of the carbon in MIDREX® DRI Products will be in the form of iron carbide (Fe₃C)
- Can be retrofitted into existing MIDREX® Plants, as well as included in new MIDREX® Plants
- Can be turned on and off to suit the desired carbon level without disrupting plant operation (i.e., MIDREX® Process can operate with or without it).

MIDREX ACT™ DESIGN FEATURES

The MIDREX ACT™ starts by diverting a portion of the reformed gas, which is rich in H₂ and CO to the reformed gas cooler. All equipment used is well-proven and reliable. A simplified flow-sheet is shown in *Figure 3*.

Reformed Gas Cooler

All new MIDREX® Plants (and most existing ones) have a reformed gas cooler, which is used to control bustle gas temperature during plant start-up and occasionally during normal operation. There, a relatively small stream (typically about 10% of the reformed gas flow) of cooled reformed gas is diverted to the MIDREX ACT™.

Mist Elimination

The cooled reformed gas is then sent to a mist eliminator, which



is similar in design to ones already used in MIDREX® Plants, to remove excessive water and protect subsequent equipment.

Gas Compression

The gas is then compressed to approximately 14 barg. This pressure is needed for the downstream membrane unit.

Gas Cooling

The gas from the compressor is hotter than needed for the downstream membrane unit, so it is cooled by a syngas aftercooler and the mist is removed by a mist eliminator. This equipment is similar in design to that which Midrex supplies in current new plants.

Membrane Separation

The gas, having been suitably compressed and cooled, enters the membrane unit. This technology, which is used in gas separation industries, employs a pressure difference to selectively allow some of the gas components in the feed stream to permeate across a membrane, separating the feed into two product streams. In this case, a CO-rich stream and a H₂-rich stream are produced. The CO-rich stream is sent to the transition zone, where the exothermic reactions generate heat (and some carbon deposition) and the endothermic reactions deposit carbon. The H₂-rich stream (i.e., the low-pressure stream from the membrane unit) is recycled to the discharge of the process gas compressors. The gas entering the membranes is cleaned and suitably conditioned within the membrane system, the features of which have been tailored for the MIDREX® Process.

Controls and Logic

The amount of carbon added to the MIDREX® DRI Products is adjusted by the flowrate of gas to the membrane unit (affecting mostly temperature) and the flowrate of transition zone natural gas (affecting mostly carburization), which provides operators an independent control loop for carbon and temperature.

The necessary engineering was performed for piping, controls, instrumentation, gas composition measurements, isolation and control logic for normal operation, start-up, shut-down and isolation of the MIDREX ACT™.

Utilities

The MIDREX ACT™ has the following utilities requirements:

- **ELECTRICITY** – Electrical consumption for the MIDREX® Plant will increase approximately 20 kWh/ton of DRI due mainly to the compressor and the electric heater in the membrane unit.
- **COOLING WATER** – Machinery cooling water is needed for compressor cooling and the syngas aftercooler.
- **NITROGEN** – A small amount of nitrogen is needed intermittently for system purging.
- **INSTRUMENT AIR** – A small amount of instrument air is needed for control valves.

CONCLUSIONS

The MIDREX ACT™ increases the product flexibility of existing or new MIDREX® Plants by providing an independent means to increase the carbon level of the DRI products or to increase the discharge temperature at a given carbon level. For applications where higher carbon is desired, the amount of carbon added is controllable and the DRI discharge temperature is maintained; with this technology, MIDREX® Plants will have a wide range of carbon amounts available to them – from 0.5% up to 4.5%.

With the MIDREX ACT™, a MIDREX® Plant will have the ability to:

- Produce CDRI with higher carbon content.
- Produce HDRI with either higher carbon or at higher temperature or both.
- Produce HBI with higher carbon content without detrimental loss of temperature at the briquetting machine or increasing briquetting temperature at a given carbon content.
- Merchant plants (CDRI and HBI) can tailor their product chemistry and produce a value-added product to the specifications of their end users.
- Chose to operate with MIDREX ACT™ when higher carbon levels are desired or to operate without MIDREX ACT™ when lower carbon levels are desired.

MIDREX ACT™ is designed for retrofitting into existing plants, and the equipment used in the technology is well proven in actual operation. The design is of the same robust nature as all MIDREX® Technology solutions. There will be some additional OPEX, mainly due to increased electrical consumption. ■

(This article is based on the presentation, "New Technologies for Maximizing Operational Flexibility of MIDREX® DRI Plants ACT™ – Adjustable Carbon Technology", made at AISTech 2017 in Nashville, TN, USA.



MIDREX H₂™: Ultimate Low CO₂ Ironmaking and its place in the new Hydrogen Economy



By Jayson Ripke, PhD, Manager – R&D,
and John Kopfle, Director – Corporate Development,
Midrex Technologies, Inc.

EDITOR'S NOTE: This article is based "Future of Direct Reduction in Europe – Medium and Long-Term Perspectives," co-authored by Primetals and Midrex and presented at the ESTAD Conference in June 2017.

INTRODUCTION – THE VALUE OF DRI

Over the past few decades there has been increasing interest and work to explore and mitigate CO₂ emissions in the iron and steel industry. The natural gas-based MIDREX® Direct Reduction Process paired with an electric arc furnace (EAF) has the lowest CO₂ emissions of any commercially proven steelmaking route; yet, there is even more room for lower emissions through use of hydrogen as a fuel and chemical reactant. The best possibility for drastically reducing the steel industry's CO₂ footprint is the use of pure hydrogen as the energy source and reductant for direct reduced iron (DRI) production in a MIDREX® Shaft Furnace. This concept, known as MIDREX H₂™, holds great promise to be developed and realized in either new or existing DRI Plants. A major obstacle to implementing hydrogen direct reduction ironmaking is the difficulty of producing pure hydrogen without a large CO₂ footprint. Still, this idea may be closer than many realize as the idea of the "Hydrogen Economy" evolves. This article will look at the new Hydrogen Economy and how it will influence next-generation iron and steelmaking, specifically by examining the MIDREX H₂™ concept of using the proven MIDREX® Process with an H₂ energy source.

MOVING FROM A HYDROCARBON ECONOMY TO A HYDROGEN ECONOMY

Most energy today comes from one of three hydrocarbon sources: petroleum, coal or natural gas. This is called the Hydrocarbon Economy when talking about energy and its relationship to global markets. The Hydrogen Economy is a proposed system of delivering energy using hydrogen. It has been put forth as a way to solve some of the negative effects of using hydrocarbon fuels, which release carbon to the atmosphere as carbon dioxide, carbon monoxide, unburnt hydrocarbons, and so on.

Proponents of a world-scale Hydrogen Economy argue that hydrogen can be an environmentally cleaner source of energy to end-users without the release of pollutants, such as particulate matter or carbon dioxide at the point of end use. However, there are many issues to overcome for hydrogen to become a major economic factor. For instance, hydrogen has a high energy density by weight, but a low energy density by volume when not compressed or liquefied, thus the high cost of a hydrogen fuel cell has been a major obstacle in its development. Other related issues, such as storage, distribution infrastructure and hydrogen purity and concerns for safety will have to be overcome for



the Hydrogen Economy to take off.

Also, there is the classic “chicken and egg” syndrome. Potential producers are eagerly awaiting consumers to come forward so they can demonstrate the use of hydrogen at scale, while consumers appear ready once sufficient amounts of hydrogen can be produced at a competitive cost. Full realization of the Hydrogen Economy will require the cooperation of industry, academia, government and the consumer.

Getting to Know Hydrogen

There are two major uses for hydrogen today. About half is used to produce ammonia (NH₃) for use in fertilizer. The other half is used to convert heavy petroleum sources into lighter fractions suitable for use as fuels, which is known as hydrocracking. Because this can effectively enhance poorer source materials, such as tar sands and oil shale, hydrocracking is seen as a growth area.

In 2016, 96% of global hydrogen production was from fossil fuels: 48% from natural gas, 30% from oil and 18% from coal; water electrolysis accounted for 4%. Linking the centralized production of hydrogen to a fleet of light-duty fuel cell vehicles would require the siting and construction of a costly distribution infrastructure. Further, the technological challenge of providing safe, energy-dense storage of hydrogen on board the vehicle must be overcome to provide sufficient range between fill-ups. Therefore, of the four methods for obtaining hydrogen, partial combustion of natural gas in a natural gas combined cycle (NGCC) power plant appears to offer the most efficient chemical pathway and the greatest off-take of usable heat energy.

Most hydrogen is produced in a steam methane reformer (SMR) using natural gas as the feedstock. This is similar technology to a MIDREX® Reformer. The reformer produces a gas containing H₂ and CO, then the CO is removed. While large-scale hydrogen production utilizing steam reformers is a reality today, it does not provide a solution for greatly reducing

CO₂ emissions because it is made from natural gas; therefore, an SMR has significant CO₂ emissions.

Another technology for H₂ production is electrolysis, which uses electricity to split water into hydrogen and oxygen. This is done today, but there are two problems for its use in the Hydrogen Economy: 1) in most countries, electricity is generated primarily with fossil fuels so there remains a large CO₂ footprint, and 2) the cost of hydrogen is too high for many applications at prevailing electricity prices (about twice the cost of hydrogen from steam reforming). There are 1.0 MW electrolyzers available today, but the total world installed capacity is only about 50 MW.

In 2016, the US Department of Energy (DOE) identified “H₂@Scale” as an underemphasized major opportunity, which they term a “Big Idea.” DOE is focusing on it in a combined effort with 14 of their 17 national labs. Rather than generating H₂ by electrolysis using electricity produced during times of peak demand, DOE envisions the use of lower cost off-peak power, storing the H₂ produced, then transporting it to users when required. **Figure 1** shows its vision of the economics. Using \$0.01/kWh electricity, the cost of hydrogen is about the same as from a steam reformer (see second bar from left in **Figure 1**). Further R&D advances could result in an even lower cost for electrolytic hydrogen. The volumes that could be produced at this cost

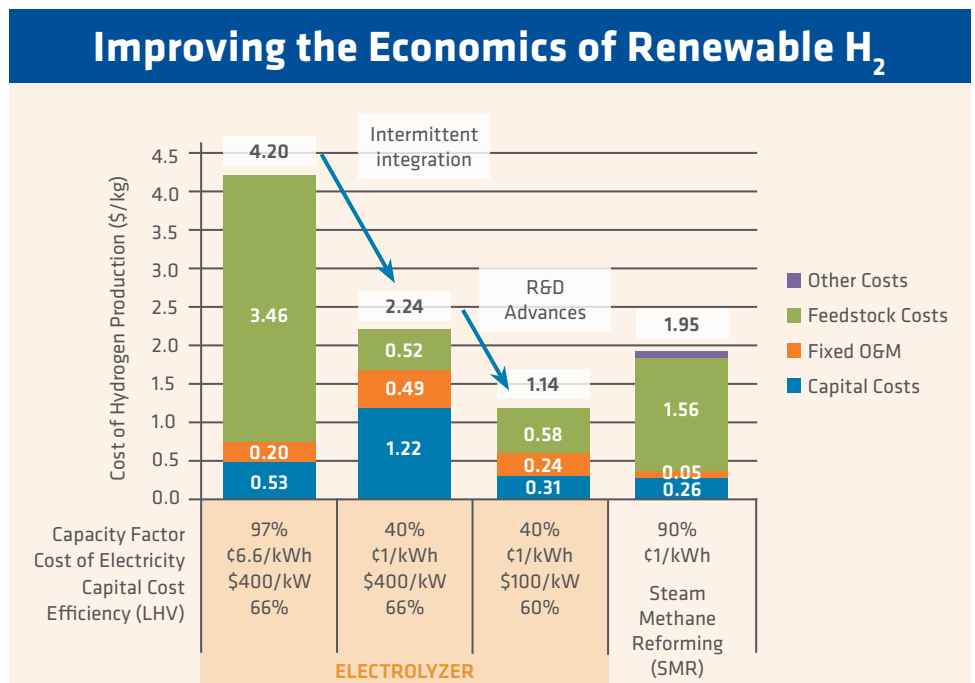


FIGURE 1. Improving the Economics of Renewable H₂; Department Of Energy H₂ @ Scale FCTO Webinar - July 28, 2016



leads us to the very real possibility of using H₂ for the purpose of iron and steelmaking.

Using Hydrogen for Ironmaking

There is tremendous interest and work underway worldwide to reduce CO₂ emissions. A very promising solution is use of hydrogen as a fuel and chemical reactant rather than fossil fuels.

The steel industry accounts for as much as 5% of total world greenhouse gas emissions because of its significant use of coal. About 75% of the world's steel is made using blast furnace (BF) iron processed in a basic oxygen furnace (BOF). The BF uses coke (refined coal) as the energy source and reductant. This process route generates about two tons of CO₂ for every ton of steel produced.

The natural gas-based MIDREX® Direct Reduction (DR) Process, paired with an electric arc furnace (EAF), has the lowest CO₂ emissions of any commercially proven steelmaking route. This occurs because natural gas contains much more hydrogen than does coal. The process gas of a typical MIDREX® Plant contains about 55% hydrogen and 36% carbon monoxide (CO), whereas BF gas is nearly all CO. As a result, the MIDREX/EAF combination produces about half the CO₂ emissions per ton of steel as a BF/BOF.

By adding CO₂ scrubbers, Midrex can lower CO₂ emissions even more by removing CO₂ in the flue gas. If the CO₂ can be used and/or sequestered, emissions are reduced by half again versus the BF/BOF.

Despite the benefits of natural gas-based DR/EAF steelmaking, there is interest in an even lower emissions process route to dramatically reduce the steel industry's CO₂ footprint. Major initiatives underway worldwide to use hydrogen to make iron are described in the Appendix to this article. This is not a new concept. Cleveland-Cliffs, Lurgi and LTV Steel built a 400,000 ton/year Circored direct reduction plant in Trinidad that used hydrogen from a steam reformer as its reductant and energy source. The plant was started up in 1999, but the fluidized bed reactor had numerous problems and it produced only about 150,000 tons by the time it was shut down in 2001.

The ultimate low CO₂ ironmaking solution would be to produce pure hydrogen using a low carbon energy source such as solar, wind, hydro, or nuclear, and use the hydrogen in a shaft furnace to make DRI. Midrex is now developing MIDREX H₂™ to do just that.

An Iron Reduction Primer

Before going into the details of ironmaking with hydrogen, let's review some basics. Pyrometallurgical (high temperature) ironmaking uses CO and H₂ to accomplish reduction, which is the removal of oxygen from ore (opposite of oxidation). There are many reactions occurring in a direct reduction reactor or a blast furnace, but the primary ones are shown in *Figure 2*. Iron is represented by Fe and methane (primary component of natural gas) is represented by CH₄.

Reduction (removal of oxygen from iron ore)

1. $\text{Fe}_2\text{O}_3 + 3\text{H}_2 \longrightarrow 2\text{Fe} + 3\text{H}_2\text{O}$ (endothermic)
2. $\text{Fe}_2\text{O}_3 + 3\text{CO} \longrightarrow 2\text{Fe} + 3\text{CO}_2$ (exothermic)

Carburization (addition of carbon to iron)

3. $3\text{Fe} + \text{CO} + \text{H}_2 \longrightarrow \text{Fe}_3\text{C} + \text{H}_2\text{O}$
4. $3\text{Fe} + \text{CH}_4 \longrightarrow \text{Fe}_3\text{C} + 2\text{H}_2$
5. $3\text{Fe} + 2\text{CO} \longrightarrow \text{Fe}_3\text{C} + \text{CO}_2$

Reforming (conversion of CH₄ to CO and H₂)

6. $\text{CH}_4 + \text{CO}_2 \longrightarrow 2\text{CO} + 2\text{H}_2$
7. $\text{CH}_4 + \text{H}_2\text{O} \longrightarrow \text{CO} + 3\text{H}_2$

FIGURE 2. Ironmaking Reactions

In a blast furnace, almost all reduction is done using CO (reaction 2), which is generated from coke. In direct reduction, reduction is accomplished with CO and H₂. In the case of the standard MIDREX® Process using natural gas, 60% (ratio of H₂ to CO) of that is done with hydrogen. Since reduction occurs in a BF at about 1300°C and in a DR furnace at about 900°C, temperature control is a very important consideration. Reaction 1 is endothermic (requires heat) while reaction 2 is exothermic (gives off heat). The MIDREX® Process, using the typical gas content of 55 percent H₂ and 36 percent CO is easy to control because the temperature in the furnace stays relatively constant.

The carburization reactions occur automatically in the BF because of all the carbon present; in a direct reduction process, they occur if the reducing gas contains CH₄ and CO. The reforming reactions occur when methane is present either in a BF or a DR furnace. Many BFs now inject methane (natural gas) into the furnace to reduce coke consumption.



Hydrogen Use in MIDREX® Plants

As noted in the paper, “Future of Direct Reduction in Europe – Medium and Long-Term Perspectives,” co-authored by Midrex and Primetals and presented at the ESTAD Conference in June 2017, hydrogen can be used in two ways in a DR plant. Some H₂ can be introduced in a natural gas-based plant as a substitute for part of the natural gas or the DR plant can be based on 100% H₂. In the case of H₂ addition to a MIDREX® Plant, one-third of the required natural gas can be substituted. For example, 60,000 Nm³/h of H₂ can be substituted for approximately 20,000 Nm³/h of natural gas in a 2.0 Mtpy plant, which represents approximately 30% of the total natural gas consumption. The flowsheet for this approach is shown in *Figure 3*. This can be done with an existing or new plant.

MIDREX H₂ refers to the use of 100% hydrogen as the feed gas. Midrex has vast experience using hydrogen to make iron in a shaft furnace. Since 1969, MIDREX® Plants have produced more than 955 million tons of DRI made with over 50% hydrogen. MIDREX® Plants utilize three different ratios of H₂ and CO. Most use natural gas and a standard MIDREX® Reformer that produces a reducing gas with 55% H₂ and 36% CO (H₂/CO of 1.5). The FMO MIDREX® Plant in Venezuela uses a steam reformer,

and H₂/CO has varied from 3.3 to 3.8. There are six MIDREX® Modules that utilize gas made from coal, and these have hydrogen to CO ratios from 0.37 to 0.56. Thus, the MIDREX® Process has successfully produced DRI at H₂/CO ratios from 0.37 to 3.8.

Based on initial modeling and laboratory experiments, it is possible to use almost pure hydrogen to make DRI in a MIDREX® Shaft Furnace. The flowsheet is shown in *Figure 4*. It is similar to the standard MIDREX® Process except that the H₂ input gas is generated external to the process. Thus, there is no reformer and a gas heater is employed to heat the gas to the required temperature. In practice, the reducing gas H₂ content is about 90 %, with the balance CO, CO₂, H₂O and CH₄. These constituents result from addition of natural gas for temperature control and carbon addition, as described in the following section.

Because H₂ is converted to H₂O and condensed in the top gas scrubber, no CO₂ removal system is necessary. Hydrogen consumption is approximately 550 Nm³/t DRI. Additionally, up to 250 Nm³/t DRI of H₂ or other environmental friendly heat sources such as waste heat, electricity, and/or natural gas is required as fuel for the reduction gas heater. With this process, CO₂ emissions could be reduced up to 80% vs. the BF/BOF steel-making route.

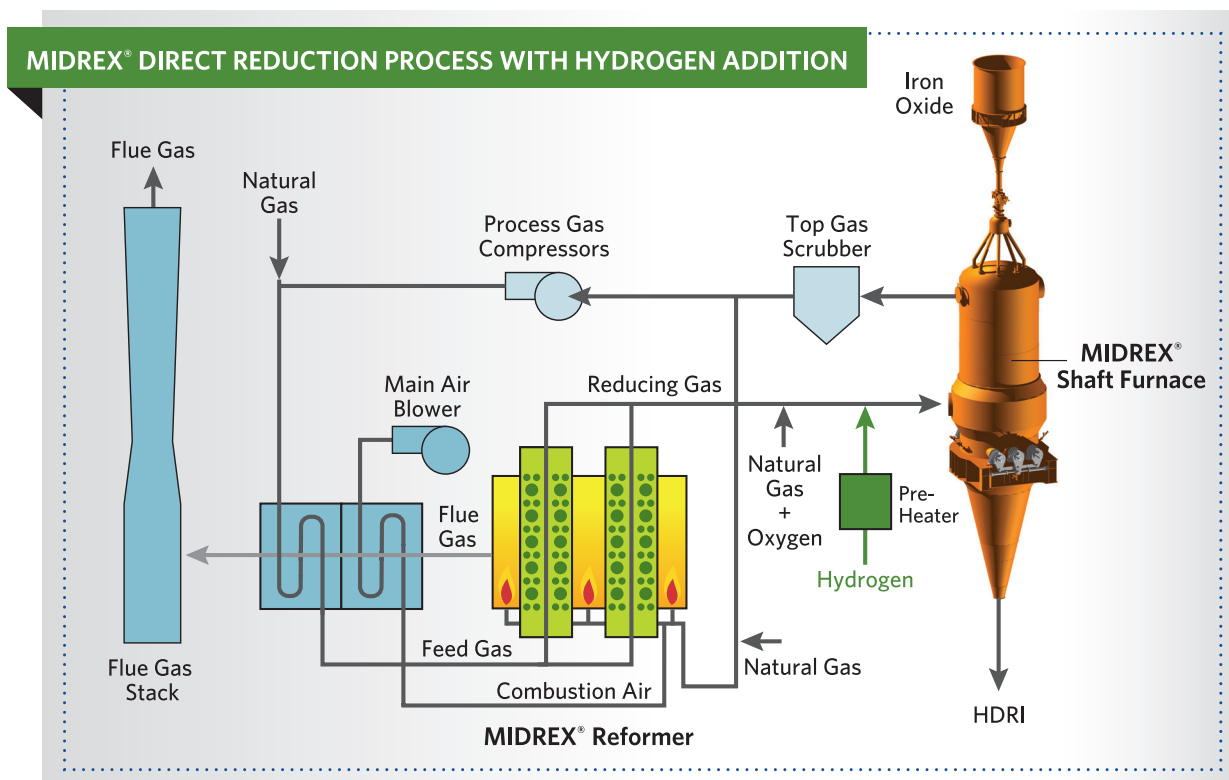


FIGURE 3. MIDREX Process with Hydrogen Addition

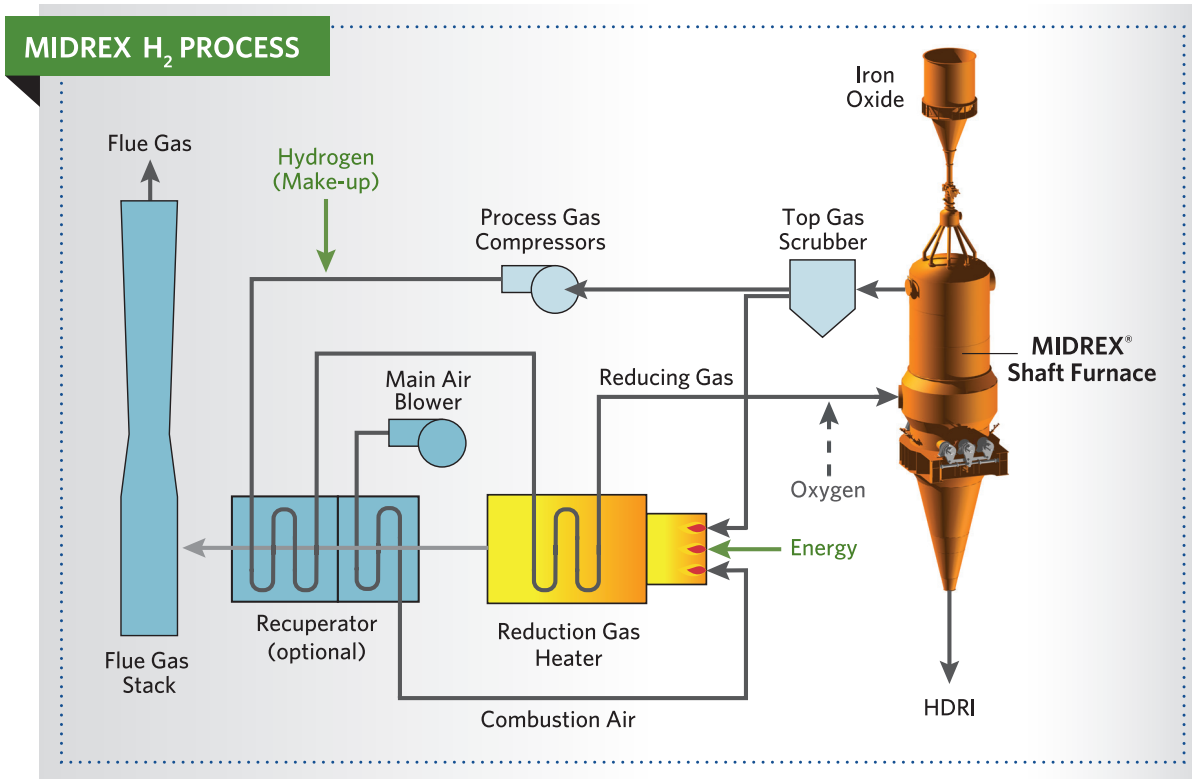


FIGURE 4. MIDREX H₂™ Process

There are a number of considerations for the MIDREX H₂™ Process, first of which is temperature. With so much hydrogen, the DRI cools off as the reducing gas enters the shaft furnace because of ironmaking reaction 1 (see Figure 2). Thus, it is necessary to add natural gas to maintain the desired reduction temperature. According to Midrex modeling, the addition of natural gas at a rate of 50 Nm³/t DRI should accomplish this.

The second issue is DRI carbon content. The vast majority of DRI is used in EAFs. EAF steelmaking practice today generally employs carbon added either in metallic charge materials such as DRI, HBI and pig iron or as pure carbon. Burning this carbon with injected oxygen creates significant heat which reduces electricity consumption and enables faster melting. Since pig iron is made from BF hot metal that is saturated with carbon, it contains 4-4.5 percent carbon. DRI can have 1-4.5 percent carbon depending on the process, reducing gas used and the way the DR plant is operated. Most EAF steelmakers prefer to use DRI with 1.5-3 percent carbon, but the optimum carbon level varies based on metallic charge mix and the steel grade produced.

With high amounts of hydrogen in the reducing gas, it will be necessary to add hydrocarbons at some place in the process

to achieve the desired carbon level. DRI carburizing options include addition of hydrocarbon to the cooling zone or in the furnace lower cone. Addition of 50 Nm³/t of natural gas for temperature control results in DRI carbon of about 1.4 percent. The next evolution in steelmaking will be to melt iron without using carbon, but this will be very energy intensive since the melting point of steel increases as carbon content decreases.

CONCLUSION

Today, the best possibility for drastically reducing the steel industry's CO₂ footprint is the use of pure hydrogen as the energy source and reductant for iron ore. There are many efforts underway worldwide to achieve this goal. The use of hydrogen in a MIDREX® Shaft Furnace, known as the MIDREX H₂™, holds great promise to be developed and realized in either new or existing DRI Plants. The main obstacle to implementing hydrogen direct reduction ironmaking is in the difficulty of producing pure hydrogen without a large CO₂ footprint. Despite this hurdle, governments and industry are looking at ways to make a Hydrogen Economy a reality in the near future and with it a cleaner way to make iron and steel.



APPENDIX: HYDROGEN IRONMAKING RESEARCH PROGRAMS

USA

American Iron & Steel Institute (AISI) – CO₂ Breakthrough Program

AISI has been working with leading universities and the Department of Energy on projects aimed at developing revolutionary new ways of making steel while emitting little or no CO₂ through research called the CO₂ Breakthrough Program. Two potential “breakthrough technologies” are currently being tested. The first is Molten Oxide Electrolysis, a program conducted at the Massachusetts Institute of Technology (MIT) that seeks to produce iron by molten oxide electrolysis, which generates near-zero CO₂ emissions. The second program involves “Flash Smelting” technology, which is adapted from mining processes and includes advances in furnace technology utilizing hydrogen. This work is being done at the University of Utah.

US Department of Energy

H₂@Scale is a concept that describes the potential of wide-scale renewable hydrogen production to dramatically reduce U.S. greenhouse gas emissions. The DOE will facilitate the development of the Hydrogen Economy by supporting research and engaging stakeholders such as utilities and regulators, industrial gas suppliers, major oil companies, metals and ammonia producers and the investment community. Research areas include low and high temperature H₂ production, storage and distribution and end use.

EUROPE

Salzgitter

Salzgitter has formed a project named “GrInHy” (Green Industrial Hydrogen) via reversible high-temperature electrolysis together with various international partners including Salzgitter Mannesmann Forschung. The project’s core will be a high-performance high-temperature electrolyser (HTE) at the Salzgitter Flachstahl strip mill. The unit will be able to convert steam into hydrogen, as well as oxygen by means of electrolysis and produce power by means of fuel cells. Its start of operation is planned for summer 2017. The hydrogen produced by the HTE could partially substitute for carbon as a reduction agent in the blast furnace or be used in annealing processes.

SSAB/LKAB/Vattenfall (Sweden)

Swedish steelmaker SSAB, iron ore producer LKAB and power company Vattenfall have launched a joint initiative called Hybrit to develop carbon dioxide-free steelmaking and have received SEK 6.7 million from the Swedish Energy Agency. The project, called Hybrit (hydrogen breakthrough ironmaking technology), is performing a pre-feasibility study. If successful, this will be followed by a full feasibility study with trial operation of a pilot plant during the period 2018-24. The project calls for this to be followed by construction of a demonstration plant to undertake trials in 2025-2035.

voestalpine Stahl

voestalpine Stahl is working to gradually decarbonize steel production. The company built the world’s first direct reduction plant for largely environmental reasons. The facility, a MIDREX® Plant near Corpus Christi, Texas, is producing HBI for use in their blast furnaces in Austria. This will enable voestalpine to better manage its CO₂ footprint. In addition, voestalpine is also building a pilot facility at its site in Linz, Austria, which will use electrolysis to produce hydrogen to reduce iron. Siemens is providing a proton exchange membrane electrolyzer for H₂ generation, and the Austrian utility Verbund will provide hydro and solar electricity. Hydrogen generated at the test facility will be fed directly into voestalpine’s gas network for testing in various process stages of steel production. Two-thirds of the project’s funding will come from the EU, and the pilot will run for 4½ years. Voestalpine CEO Wolfgang Eder has said, “Our researchers and technicians are optimistic that hydrogen-based steel production will be feasible in the 2030s.”

ASIA

Posco

In 2009, Posco announced plans to eventually halt carbon emissions by switching to a hydrogen-based steelmaking process from 2021. ■



MIDREX News & Views

CLIFFS ANNOUNCES PLANS FOR GREAT LAKES HBI PLANT



Cleveland-Cliffs Inc. has selected Midrex Technologies Inc. to design, engineer and procure equipment for a new 1.6 million ton/year hot briquetted iron (HBI) plant to be located in Toledo, Ohio.

The brownfield site at the Port of Toledo is considered a prime location due to its proximity to several future customers, as well as its logistics advantages including affordable gas availability and access by multiple rail carriers. Cliffs anticipates breaking ground for construction of the HBI production plant in early 2018, with production of commercial tonnage beginning in mid-2020.

Founded in 1847, Cleveland-Cliffs Inc. is a leading mining company and is recognized as the largest and oldest independent iron ore mining company in the United States. The Company is a major supplier of iron ore pellets to the North American steel industry from its mines and pellet plants located in Michigan and Minnesota. Cliffs also operates an iron ore mining complex in Western Australia.

Lourenco Goncalves, Cliffs Chairman, President and Chief Executive Officer, said, "Today's announcement marks a very important strategic milestone for Cliffs as we begin to implement our plans to be the sole producer of high-quality HBI for the EAF steel market in the Great Lakes region."



Conceptual rendering of new MIDREX® HBI plant in Toledo, Ohio



MIDREX News & Views

METALLOINVEST LAUNCHES RUSSIA'S LARGEST HOT BRIQUETTED IRON PRODUCTION FACILITY

- **MIDREX® HBI Plant will produce 1.8 million metric tons of hot briquetted iron (HBI) per year**
- **7-day Performance Guarantee Test (PGT) completed with 100% achievement of performance guarantee parameters**

Metalloinvest has launched its third hot briquetted iron production facility (HBI-3 Plant) at Lebedinsky GOK in Gubkin, Belgorod region. It is the largest HBI production facility in Russia and one of the biggest in the world.

The new 1.8 million metric ton per year MIDREX® HBI plant at LGOK was supplied to Metalloinvest by a consortium of Midrex Technologies, Inc. and Primetals Technologies. Midrex HBI-3 began commissioning in early 2017 with the official launch ceremony occurring on July 14, 2017.

Participants in the official launch ceremony for HBI-3 Plant included: Vladimir Putin, President of the Russian Federation; Denis Manturov, Minister of Industry and Trade of the Russian Federation; Alexander Beglov, Plenipotentiary Representative of the President of the Russian Federation in the Central Federal District; Evgeny Savchenko, Governor of the Belgorod region; Alisher Usmanov, founder of USM Holdings; Ivan Streshinsky, Chairman of the Board of Directors of Management Company Metalloinvest; Andrey Varichev, CEO of Management Company Metalloinvest; and Oleg Mikhailov, Managing Director of Lebedinsky GOK.



Ivan Streshinsky commented: “HBI-3 Plant will increase Metalloinvest’s efficiency and strengthen the Company’s position in the global raw materials market. The launch of the plant is the key investment project in Metalloinvest’s strategy, which envisions increasing the Company’s output of products with high added value.”

Investment in HBI-3 Plant has amounted to approximately USD 660 million and over 400 highly-skilled jobs have been created at the plant.

Andrey Varichev noted: “HBI has proven itself as an effective addition to scrap metal for the production of high-quality steel grades. We are confident that demand for HBI will continue to grow not only in Russia but also abroad, and we are ready to meet global demand for this premium raw material. An important competitive advantage of HBI-3 Plant is its minimal environmental impact. The use of new technological solutions is enabling the Company to minimise the plant’s pollutant emissions.”

HBI-3 Plant has a design capacity of 1.8 million tonnes of HBI per year, which will increase Metalloinvest’s HBI annual production capabilities to 4.5 million tonnes. The plant will reinforce Metalloinvest’s leading position in the global merchant HBI market, of which the Company currently has a share of over 40%.

In order to increase the quality and quantity of raw materials required by HBI-3 Plant, the Company conducted a large-scale modernisation of the relevant production facilities (the pelletisation plant and beneficiation plant), which will ensure the increased production of higher-quality concentrate and pellets.

The process of direct reduction of iron used in HBI production is the most environmentally-friendly method of extracting



iron from iron ore. It does not create the emissions associated with the production of coke, sintering ore and pellets, or solid waste in the form of slag.

By decree of the government of the Russian Federation, the construction of HBI-3 Plant was included in the list of initiatives for the Year of the Environment, as a project making use of the best available technologies.

HBI-3, the newest MIDREX® HBI plant at Lebedinsky Mining and Processing Integrated Works (LGOK), has announced the completion of the 7-day Performance Guarantee Test (PGT). It is LGOK's second HBI plant supplied by a consortium of Primetals Technologies and Midrex Technologies, Inc.

HBI-3 began commissioning in early 2017, and first product was made on March 11, 2017. Preliminary acceptance was received on March 15, 2017, and the PGT was successfully completed on the first attempt on May 13. The plant received its Performance Test Certificate on June 13, 2017. Test parameters included HBI production, HBI physical and chemical characteristics, the plant's key natural gas and electricity consumption and environmental/emissions impacts.

Midrex and Primetals were responsible for engineering and supply of mechanical and electrical equipment, steel structure, piping, ductwork, as well as training and advisory services. Metalloinvest also utilized the expanded project financing capabilities (export credit financing) of Primetals and Midrex through Midrex UK, Ltd.

The first HBI module at LGOK using the MIDREX® Direct Reduction Process also was supplied by the Primetals/Midrex consortium in 2005 and began operation in 2007. For the first two years of operation, MIDREX HBI-2 produced approximately 90 percent of its design capacity. In each of the last 5 years, the plant has operated over its 1.4 million metric tons/year design capacity, and on April 26, 2015, produced its ten millionth ton of HBI.

ABOUT METALLOINVEST

Metalloinvest is a global player in the production of beneficiated iron ore products, converting the majority of its primary iron ore concentrate production into value-added products such as high grade iron ore concentrate, iron ore pellets, HBI/DRI and finished steel products.

The company's Lebedinsky Mining and Processing Integrated Works (LGOK) is the leading producer of merchant HBI globally, accounting for over 40% of DRI/HBI shipments in 2016 and is the largest HBI/DRI producer in Europe. Currently, LGOK operates three HBI plants having a combined capacity of 4.2 million tons/year. Feed for the new HBI plant consist of 100% pellets produced from Lebedinsky GOK iron ore.

Metalloinvest also owns Oskol Electrometallurgical Works (OEMK) in Stary Oskol, a mini-mill in the same region of Russia, which operates four MIDREX® Plants that produce DRI for onsite EAF steel production. ■

Christopher M. Ravenscroft: Editor

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CONTACTING MIDREX

General E-mail:
info@midrex.com

Phone: (704) 373-1600
2725 Water Ridge Parkway
Charlotte, NC 28217 USA

General Press/Media Inquiries
Christopher M. Ravenscroft
cravenscroft@midrex.com
Phone: (704) 378-3380