The recent slowdown in the global steel industry may have overshadowed current projects and capacity expansion; however, there is no doubt that the Direct Reduction Ironmaking industry will continue to expand capacity dramatically over the next few decades. Interests in DRI products and their use continue to grow as new applications outside of the EAF industry are explored. The world’s annual DRI production has surpassed 70 million tons per year and DRI upward growth is an important part of encouraging steel industry sustainability.

To this point, two new MIDREX® Plants are currently in construction with two additional plants that have recently begun, representing nearly nine million tons of new capacity with almost half of that production devoted specifically to production of hot briquetted iron (HBI). Product flexibility continues to be a key to the success of modern DRI plants. In addition, this next generation of DRI plants will focus on overall efficiency, including better utilization of resources through improvements to process and equipment, as well as reduction of emissions.

This paper examines some of the new technologies in practice and takes a look at current DRI production milestones. We will also review the most recently commissioned MIDREX® projects throughout the world.

**Keywords:** Direct Reduction Ironmaking, DRI, HBI, HDRI, MIDREX®, MXCOL®, HBI, Hot briquetted iron HBI, hot transport, DRilpax™, ACT™, Adjustable Carbon Technology

*Manager Global Marketing Communications, Bachelors of Science in Public Relations and Journalism-Syracuse University, Masters of Business Administration - McColl School of Business – Queens University, Midrex Technologies, Inc., Charlotte, USA*
Introduction

The Direct Reduction Ironmaking industry is in a state of continued growth and will continue to expand capacity dramatically over the next few decades. This growth continues to be due to increasing interest in direct reduced iron (DRI) products as their use expands with new applications outside of the EAF industry being explored. DRI products represent a fraction of the world’s total iron production. Three years ago total world output set a new record in 2014 at 75 million tons of DRI produced, which sounds massive until you realize blast furnaces produce over 1 billion tons each year.

The 2016 world DRI production is currently estimated at about 72 million metric tons. This is down from record production in 2014; however, this “drop” in production is not a sign of declining interest, but rather of production shifting in terms of technologies and regions.

Direct Reduction Ironmaking (DRI) and DRI products

The modern DRI industry is young …relatively speaking. Although the modern industry is more than a half century old, much has changed in how the product can be produced as well as the evolution of DRI in product forms.

For the beginner, Direct Reduced Iron – is a premium quality, ore-based metallic raw material made by removing chemically-bound oxygen from iron oxide pellets or lump ores without melting. For most of its history DRI had essentially one product form, but through decades of development and use in the industry, DRI is now better defined as three specific products.

<table>
<thead>
<tr>
<th>DRI PRODUCTS</th>
<th>CDRI</th>
<th>HBI</th>
<th>HDRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Form</td>
<td>Pellet &amp; lump</td>
<td>Briquettes* (density ≥ 5.0 grams per cubic centimeter (g/cc))</td>
<td>Pellet &amp; lump</td>
</tr>
<tr>
<td>Product Temperature</td>
<td>Ambient</td>
<td>Ambient</td>
<td>550°C or Higher</td>
</tr>
<tr>
<td>Where used</td>
<td>EAF &amp; BOF</td>
<td>EAF, BOF &amp; BF</td>
<td>EAF</td>
</tr>
<tr>
<td>Charging Method</td>
<td>Continuous &amp; Batch</td>
<td>Continuous &amp; Batch</td>
<td>Continuous &amp; Batch</td>
</tr>
<tr>
<td>Description:</td>
<td>CDR (Cold DRI) is a high quality metallic ideal for use in a nearby EAF. It can also be transported via rail to another site when proper precautions are made. It is not recommended for ocean transport.</td>
<td>HBI (Hot Briquetted iron) is a premium form of DRI and is the industry and regulatory preferred method of preparing DRI for long term storage and transport. HBI is commonly used in EAFs and can also be added to the Blast Furnace and BOF.</td>
<td>HDR (Hot DRI) is discharged hot from the shaft furnace and transported to an EAF for melting and provides the optimum way for DRI users to increase productivity and reduce cost.</td>
</tr>
<tr>
<td>IMO Restrictions for transport</td>
<td>Inerting (N₂) or passivation REQUIRED for cargo during the transport</td>
<td>No Special Precautions</td>
<td>N/A</td>
</tr>
<tr>
<td>Number of MIDREX® Plants currently in operation</td>
<td>50</td>
<td>12</td>
<td>7</td>
</tr>
</tbody>
</table>

* The MIDREX® Process requires less oxide coatings than competing DR technologies, which allows for easier briquetting of DRI and stronger physical HBI characteristics.

Figure 1.
Forms of direct reduced iron (DRI)

These are: Cold DRI pellet and lump (CDRI), which is cooled before handling and use; Hot DRI (HDRI), direct reduced iron discharged from the shaft furnace without cooling and charged into a melter; and Hot Briquetted Iron (HBI), direct reduced iron discharged from the shaft furnace at ≥ 650°C and compacted to...
a density ≥ 5gm/cc. (Figure 1). Each product form has special qualities that make them suited for different applications and purposes. Throughout its history, DRI has been linked with the EAF industry as a means to efficiently produce steel in areas with a shortage of scrap, and to produce higher quality steel than when using scrap alone. Extremely low levels of metallic residuals, such as copper, and high iron content DRI make DRI a highly effective diluent for other furnace charge materials and an efficient way to manage nitrogen content in liquid steel.

Today all grades of steel can be produced in an EAF when DRI is included in the charge mix. DRI became a globally traded product with the introduction of hot briquetted iron (HBI) and made available the benefits of DRI use to EAFs worldwide and to integrated steelmakers, who had previously considered DRI not suitable for use in the blast furnace. Today an increasing number of blast furnace operators are considering HBI for use in their blast furnaces on a regular basis to increase hot metal output when needed and to help limit CO₂ emissions. Figure 2 shows the flow of DRI products in iron and steelmaking today.

**Direct Reduction Ironmaking Technology**

Most naturally occurring iron oxide has the composition of hematite (Fe₂O₃) and contains about 30% oxygen. As previously stated, DRI is produced by the reduction (removal of oxygen) of iron oxide at temperatures below the melting point of iron. The direct reduction process removes most of this oxygen by exposing the iron oxide pellets to a reducing gas comprised of hydrogen (H₂) and carbon monoxide (CO).
produced from natural gas or coal. The $H_2$ and CO reduces $Fe_2O_3$ into metallic iron (Fe) and the byproducts of this reaction are $CO_2$ and $H_2O$. Figure 3 shows the basic flow of DRI production independent of specific technology.

![Diagram showing the flow of DRI production](image)

**Figure 3 – Commercial ways to make DRI**

*Source: IIMA http://metallics.org.uk/dri/

Beginning in the mid-20th century, the very first DRI plants produced relatively meager tonnages in the hundreds of thousands of tons per year. By the end of the 20th century DRI facilities got bigger, with the average capacity surpassing 1.0 million tons as more and more steelmakers began to use and make DRI products.

![Available Processes diagram](image)

**Figure 4 – Technologies used to make DRI**

*Source: IIMA http://metallics.org.uk/dri/*
Figure 4 shows the varying technologies that can be employed to produce DRI. The majority of annual production is achieved through natural gas-based shaft furnace technology, of which more than 80% of DRI production is by plants using MIDREX®-based DRI technology.

The MIDREX® Direct Reduction Process - brief history and description

In 1966, Midland-Ross Corporation discussed and began the pursuit of developing a DRI process for producing highly metallized direct reduced iron (DRI) pellets for use in steelmaking. This was the genesis of what today is known as the MIDREX® Direct Reduction Process. MIDREX® was not the first DRI technology process, but it was the first to use a continuously fed shaft vessel for making DRI

- Iron Oxide pellets and/or lump are fed to top of furnace and flow downward
- Iron Oxide is heated and converted to DRI by a high temperature reducing gas
- Products can be discharged hot or cold in combinations that include CDRI, HBI or HDRI

<table>
<thead>
<tr>
<th>REACTION</th>
<th>HEAT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3\text{Fe}_2\text{O}_3 + \text{CO} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO}_2)</td>
<td>Exothermic</td>
<td>Reduction by CO</td>
</tr>
<tr>
<td>(3\text{Fe}_2\text{O}_3 + \text{H}_2 \rightarrow 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O})</td>
<td>Exothermic</td>
<td>Reduction by H₂</td>
</tr>
<tr>
<td>(\text{Fe}_3\text{O}_4 + \text{CO} \rightarrow 3\text{FeO} + \text{CO}_2)</td>
<td>Endothermic</td>
<td>Reduction by CO</td>
</tr>
<tr>
<td>(\text{Fe}_3\text{O}_4 + \text{H}_2 \rightarrow 3\text{FeO} + \text{H}_2\text{O})</td>
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<td>(\text{FeO} + \text{CO} \rightarrow \text{Fe} + \text{CO}_2)</td>
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<td>Endothermic</td>
<td>Reduction by H₂</td>
</tr>
<tr>
<td>(3\text{Fe} + \text{CH}_4 \rightarrow \text{Fe}_3\text{C} + 2\text{H}_2)</td>
<td>Endothermic</td>
<td>Carburizing Reaction</td>
</tr>
<tr>
<td>(3\text{Fe} + 2\text{CO} \rightarrow \text{Fe}_3\text{C} + \text{CO}_2)</td>
<td>Exothermic</td>
<td>Carburizing Reaction</td>
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<tr>
<td>(3\text{Fe} + \text{CO} + \text{H}_2 \rightarrow \text{Fe}_3\text{C} + \text{H}_2\text{O})</td>
<td>Exothermic</td>
<td>Carburizing Reaction</td>
</tr>
</tbody>
</table>

**Figure 5 – MIDREX® Shaft Furnace Overview**

Each year since 1987, over 60 percent of the world’s direct reduced iron has been produced in MIDREX® Direct Reduction Plants. The heart of the MIDREX® DRI/HBI/HDRI Process is the MIDREX® Shaft Furnace,
which provides immense operational flexibility for DRI production, where iron oxide in pellet or lump form is fed to the top of the furnace and flows downward (figure 5).

The MIDREX® Shaft Furnace can use natural gas or a syngas from coal or coke oven gas as its reductant and has been proven in using the widest variety of oxide pellets or lump ores to produce CDRI, HDRI and/or HBI.

Over its history, the MIDREX® Direct Reduction Process has evolved into two main plant configurations: MIDREX NG™ (using natural gas) and MXCOL® (using coal). In both flowsheets, reduction occurs in the MIDREX® Shaft Furnace.

**Evolution of Technology Advancements: Operational & Product Flexibility**

As mentioned at the beginning, DRI is first and foremost a metallic iron raw material for making steel. Simply stated, it is a means for achieving the goals and objectives of the steelmaker using it. To that extent DRI has evolved into various forms over the last 50 years and technology has adapted and progress to provide steelmakers with greater operational flexibility.

All three DRI product forms are versatile ore-based metallics (OBMs) that have distinctive characteristics that benefit steelmakers. The most effective and efficient use of DRI products will depend on the financial and operational objectives of the user. Much like operation of a meltshop, the use and preference of metallic materials will vary with the complexity of the steelmaking practice and the market in which the steel producer operates.

The first modern direct reduction plants were built adjacent to the steel mills and produced only a cold metallic product (CDRI). Typically these plants were built to feed EAFs in areas where scrap supplies were limited. DRI was stored and bucket charged along with locally available scrap to make long products, such as reinforcing bar (rebar) and billets. As the iron and steel industry became more aware of DRI and steelmaking technology continued to evolve, EAF operators began to realize that DRI could help them penetrate a market formerly reserved for traditional integrated steelmakers – flat products.

As this demand for DRI increased, a product with excellent handling and shipping characteristics was needed for the merchant market, which resulted in development of hot briquetted iron (HBI) in the 1980s. Over time EAF steelmakers with captive DRI plants (i.e., plants adjacent to or nearby the meltshop) wanted a way to take advantage of the heat contained in DRI immediately following reduction. This led to the development of transporting and charging hot DRI (HDRI) in the late 1990s-early 2000s (figure 6).

The MIDREX® Process has provided a solid foundation for continuous improvement of the technology. Further, Midrex realizes that innovation needs to address and be born of practical concerns, thus the company has worked on methods to produce DRI using different fuels as well as finding ways to optimize production to increase profitability.
Natural gas continues to be the most ideal reducing gas source for the production of DRI; however, some areas of the world do not have access to low-cost natural gas in the volumes needed for steady DRI production. Because of the flexibility of the MIDREX® Process, the MIDREX® Furnace has the capability of utilizing many types of syngas for DRI production. In fact, bio gases are possible to be used in the furnace, but ultimately are not feasible as the sole source of fuel and reductant based on the volumes necessary to operate a typical DRI plant.

Midrex commercially offers technology utilizing syngas derived from natural gas and coal sources. Coal-based technologies include: MXCOL®, COREX®/MXCOL® and the new MIDREX® Thermal Reactor System™ (TRS®).

The first commercial application of MIDREX® Technology using syngas from coal was commissioned in 1999 at ArcelorMittal Steel South Africa. Here the export gas from a COREX® Plant is used in a MIDREX® Shaft Furnace to supply DRI to the meltshop in addition to the hot metal from the COREX Plant. In 2009, Midrex and Jindal Steel and Power Limited signed a contract to build a 1.8 mtpy MXCOL Plant at their Angul location using a syngas produced by a Lurgi fixed bed coal gasification plant (figure 8). This plant is in commercial operation and is an essential part of the site’s steelmaking operation.
Further development has continued and Midrex now has an alliance with Synthesis Energy Systems Group to further develop the MXCOL® Plant plus coal gasification arrangement to optimize energy consumption, cost and productivity.

**Increasing size and reliability of plants: tons & hours**

With each decade, there has been greater demand for DRI production as well as larger individual plants to keep in step with advancements to EAF technology. From the earliest modules at Portland, Oregon- USA in 1969, designed for 150,000 tpy, to the latest Algerian plants at 2,500,000 tpy capacities, Midrex has approached increasing the size of DRI plants in a very deliberate, responsible and successful manner.

Midrex has taken a very conservative approach to scalability to minimize risk to the client. Sizing of a furnace alone does not guarantee production. DRI plants have a yearly rated capacity based on tons per hour multiplied by a base number of 8000 hours per year (HBI plants are based on 7800 hours). Therefore for example, a CDRI/HDRI plant with 200 tons per hour production has a rated capacity of 1.6 mtpy.

Maintaining or surpassing that number of operating hours is yet another way these MIDREX® Plants have increased their production. MIDREX® Plants are known for their reliability and hours of continuous operation and many facilities have surpassed 8000 hours per year on a regular basis. The synergy of the MIDREX® Shaft Furnace and MIDREX® Reformer optimization while increasing plant utilization and reliability has led to remarkable feats.

As of 1Q 2015, the world’s largest producing single DRI module is the MIDREX® Hadeed Mod E in Saudi Arabia (figure 9). Although there are other plants worldwide in operation with larger name plate capacities, the Hadeed 1.76 mtpy plant is the only DRI plant to date that has produced more than 2 mt in a single calendar year (2013).
Plant and Process Optimization: DRIpax™

The goal of plant process optimization is to provide smooth and stable operation plus high performance. One of the challenges is to cope with the delay of several hours between when a process change is made and the resulting actual product analysis is available from the laboratory.

DRIpax™ is the trade name for an integrated process optimization system designed for MIDREX® Direct Reduction Plants. The technology was designed by Primetals Technologies (formerly Siemens VAI) and Midrex Technologies, Inc. to aid in plant state evaluation as well as prediction of product carbon content, metallization, and furnace discharge temperature. DRIpax™ is structured into three modular system layers: the Process Information & Data Management System, the DRI Plant Process Models, and the DRI Plant Expert System.

Over the past four decades Midrex has collected information from various plants, creating immense complex data sets of assorted variables. To interpret this Big Data, Midrex developed the MIDREX® Superdata program/model. The MIDREX® Superdata program has been used to process the big data accumulated from various MIDREX® Plants over decades of operation in a variety of situations and locations. It runs cyclically and performs mass and energy calculations using online-measurements, feed materials and product analyses. Calculations are carried out to provide further useful information to the operators, especially data concerning the quality of the different gas streams and operation of the MIDREX® Shaft Furnace and MIDREX® Reformer. It can be used to monitor and assess reduction furnace utilization, bustle gas quality and flows, DRI production rate, reformer performance, combustion air requirements, flue gas flows and analyses, and heat recovery performance. The Superdata Model is fully integrated into DRIpax™, enabling DRIpax™ to provide:

- Scheduling of the model calculations
- Collection and preparation of the model input data
- Display of model result data integrated in the HMI
In contrast to a standalone installation of the MIDREX® Superdata Model, the benefits of this full integration include time savings to operating personnel and avoidance of common errors, since no manual input is required to execute the calculations.

The DRIpax™ hardware/software package is configured to be easily integrated into an existing or new basic automation system of a MIDREX® Plant. The system is configured using state-of-the-art technology with regard to both hardware and software platforms, as well as advanced process modeling technology.

The system consists of a Server-Client Architecture with a link to an arbitrary process control system via the worldwide standardized communication interface. This ability allows the plant complete control to provide access to the system in other areas of the facility for remote viewing.

The ability to predict the metallization and carbon levels enables better control of DRI consistency. This is achieved through the ability of DRIpax™ to take into account the MIDREX® Superdata (plant operating data analysis) results and inputs from the lab to predict what the met and carbon will be based on the current operation of the plant. DRIpax’s predictive ability can help plant operators avoid off-spec DRI by enabling them to diagnose any potential problems early.

The DRIpax™ system is currently featured in a few MIDREX® DRI Plants including Qatar Steel along with an advanced system in operation at the newly commissioned voestalpine Texas, LLC HBI plant located in Portland, Texas. The system can be utilized in new or existing MIDREX® Plants and its flexibility enables it to be easily adjusted to various plant configurations.

Meltshops will also benefit from DRIpax™. Having a tighter tolerance and more consistent DRI feed, an EAF should expect to see reduced electricity and refractory consumptions, reduced tap-to-tap time and an increase in yield and productivity. The MIDREX® Superdata Model and the Quality Prediction Models evaluate the state of the process and the expected product quality. In case of undesired process conditions or product quality, it is the operator’s duty to perform corrective actions.

The next step in the development of DRIpax™ is the implementation of an Expert System for MIDREX® plants for the shaft furnace and the reformer areas. This is part of the installation is in operation at the recently commissioned voestalpine Texas HBI Plant in Portland, Texas.

Midrex is contributing the process and operation know-how and Primetals is creating the knowledge base for the existing Expert System shell. The DRIpax™ Expert System will provide closed-loop and semi-automatic operation mode; in semi-automatic mode, suggestions made by the Expert System will be executed automatically after acceptance by the operator. In closed-loop mode, operator acceptance is not required for the execution of corrective actions; however, he can still reject corrective actions, keeping the human factor in the plant. Figure 10 shows the system configuration.

The knowledge base of the DRIpax™ Expert System is principally defined by Midrex specialists. Nevertheless, special operational rules and control philosophy of the individual customers will also be included in the knowledge base. In this sense, each customer will get a tailored expert system perfectly fitting to his needs.
With the introduction of the DRIpax™ Expert System, a first powerful step will be taken in the direction of fully automated quality control and equipment protection. The application of an expert system helps to foster uniform operator decisions over all shifts and early detection of undesired process conditions resulting in small corrective actions that have a positive impact on the overall plant performance and efficiency.

**ACT - Adjustable Carbon Technology**

Recently, Midrex created a new flexible technology that can easily be added to MIDREX® DRI Plants that can increase the carbon content of DRI up to 4.5% carbon. The name of this patent pending innovative technology is ACT™ (Adjustable Carbon Technology). With ACT, the amount of carbon added is controllable and the DRI discharge temperature is maintained. With this technology, MIDREX Plants will have the widest range of carbon available to them, from 0.5% up to 4.5%. Benefits of this technology include:

- Producing CDRI with higher carbon content
- Producing HDRI with either higher carbon, higher temperature or both
- Producing HBI with higher carbon content without detrimental loss of temperature at the briquetter, insuring both HBI strength and high yield.

The technology can easily be retrofitted to existing plants and is ready for deployment to MIDREX® customers that desire the flexibility to produce a higher carbon DRI/HBI. The basic flowsheet is shown in Figure 11 and additional papers on the system are now available/presented at the 2017 AISTech event in Nashville, TN USA, May 7-11 and at the 2017 SEAISI conference held in Singapore, May 21-15

**Midrex ACT™ Features**

- Can be used in every type of MIDREX® Plant; CDRI, HDRI, HBI or a combo plant
- Allows amount of carbon in DRI to be adjusted up or down.
- Added carbon comes without cooling off the DRI.
- Approximately 90-92% of the carbon in MIDREX DRI Products will be in the form of iron carbide, Fe\textsubscript{3}C.
- This technology is a “bolt on” type design.
- ACT™ can be integrated into existing MIDREX® Plants and used for new MIDREX® Plants.
- The technology can be turned on and off to suit the desired carbon level; the MIDREX® Process can operate without it.

![Simplified ACT™ Flowsheet](image)

**Figure 11. Simplified ACT™ Flowsheet**

**New MIDREX® Production**

Throughout the world two new MIDREX® DRI plants are under construction with an additional two that have been recently commissioned. These new DRI plants employ many of cutting-edge technologies described in this paper for better operational and product flexibility; this flexibility continues to be a key to the success of modern DRI plants and DRI/EAF steelmaking. Last year saw a major first for North American DRI production. In the United States the voestalpine Texas MIDREX® Plant, the first hot briquetted iron (HBI)
plant in the United States, owned and operated by voestalpine Texas LLC, commenced operation on September 27, 2016, and within little more than 24 hours, it was in stable operation at around 160 tons per hour producing on-grade briquettes (Figure 12). The plant is currently making HBI for voestalpine’s blast furnaces in Austria as well as for three North American EAF customers.

![Figure 12 – voestalpine Texas – a 2.0 tpy HBI plant in Portland, Texas, USA currently the largest single module HBI unit in the world](image)

In Russia, the LebGOK III MIDREX® HBI Plant at Gubkin in Belgorod started up in 2016 and is currently ramping up production. The plant has been designed to supply 1.80 million tons per year of HBI to LebGOK’s customers worldwide.

The newest MIDREX® Plants are being built in Algeria and both are 2.5 million ton per year HDRI/CDRI MIDREX® DRI Combo Plants.

In 2015 Tosyali Holding awarded Midrex and its partner Paul Wurth S.A., the project to build the world’s largest multiple product direct reduced iron plants for Tosyali Algeria located in Bethioua (Oran). The new MIDREX NG™ Direct Reduction Combo Plant will be designed to produce 2.5 million tons of DRI and have the capability to vary its production to produce hot direct reduced iron (HDRI) and/or cold direct reduced iron (CDRI) simultaneously without stoppage of production. HDRI will be fed via an Aumund hot transport conveyor to a new EAF meltpshop located adjacent to the MIDREX® DRI Plant allowing for greater EAF productivity and energy savings; CDRI can also be produced for additional onsite use (figure 13).
The second plant, shown in Figure 14, is being constructed for Algerian Qatari Steel (AQS). The new natural gas-based MIDREX NG™ DRI plant will be located in Bellara, Algeria, 375 km east of Algiers. AQS is a joint venture between Sider Co. and National Investment Fund (51%) and Qatar Steel International (49%) The MIDREX® Plant will be part of the overall steel complex that will produce 2.0 million tons of rebar and wire rod finished products.
Conclusion - Challenges for today and the future

The Direct Reduction Ironmaking industry is gaining momentum and will continue to expand capacity over the next few decades. The industry has gained greater acceptability as it has become more flexible, provide greater options to the market place. The flexibility has materialized in terms of emerging product forms and specifications. Technology suppliers are expected to develop new and improved products that keep pace with the quicker, more demanding pace of an evolving global marketplace. Staying on the leading edge of technology requires a seamless blending of research and operational experience that never loses sight of the goal - to provide customers the performance, flexibility and reliability needed to be successful. For DRI technology, that means providing operational flexibility to the client and the end steelmaker. The MIDREX® Process was the world’s first continuous DRI process and new technologies such as DRIPax™ and ACT™ from Midrex are aimed to give producers more control over their production, allowing customization of products and production to meet the specific needs of the site and/or operation. Innovations and continuous improvements along with the company’s commitment to advancing the process, have kept the MIDREX® DRI technologies at the forefront of the industry. This innovation not only benefits new plants, but helps older ones stay on the cutting edge of DRI technology.

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3. International Iron Metallics Association (website), http://metallics.org.uk/dri