MIDREX Technology Development: A FIRM FOUNDATION + CONTINUOUS IMPROVEMENT

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> *"Nothing is permanent but change"*
> *Heraclitus*

A FIRM FOUNDATION

Since 1969, Midrex and its partners have built (or are constructing) 63 MIDREX® Modules (shaft furnaces plus reformers and associated systems) in 21 countries. To date, these facilities have produced over 500 million tons (Mt) of DRI and HBI, with a market value exceeding $70 billion. This record of plant sales, successful start-ups, and continued outstanding performance has resulted in a market share for MIDREX® Technology of 60 percent or more each year since 1987.

Donald Beggs

The success of the MIDREX® Direct Reduction Process is based on the firm foundation of the work done by Donald Beggs and his colleagues in the Surface Combustion Division of the Midland-Ross Corporation in the 1960s. Beggs' concept of pairing a stoichiometric CO_2 reformer with a shaft furnace to reduce iron oxide was brilliant, a once-in-a-lifetime achievement. The MIDREX Process concept has stood the test of time due to this solid foundation with continual technology development and now produces over 36 million tons of iron per year, trailing only the blast furnace.

What are the features of the basic process that enabled this success to occur? Here are three:

Simplicity – the MIDREX Process is inherently simple to operate, involving only three major unit operations: gas preheating, natural gas reforming, and iron ore reduction. Over the years, many other direct reduction process concepts have been devised with theoretically lower energy or iron ore consumptions and reduced operating and capital costs, but they proved too complex or expensive in practice, or just did not work. The simplicity of the MIDREX Process is possible because it uses natural gas, a very clean fuel, and agglomerated iron ore, which makes the processing relatively easy.

Efficiency – a packed bed reactor with counter-current reactant flows is generally the most efficient means to process materials. There are three primary reasons: 1) since the reactor (shaft furnace) is filled completely with iron oxide, the volumetric productivity is very high, 2) a moving packed bed ensures that each particle of iron oxide experiences the same temperature profile, gas composition, and residence time as every other particle, and 3) counter-current flow provides the largest "driving force" for reaction and fast reaction times. It is no surprise that the other major means of producing iron, the blast furnace, is also a shaft with counter-current solids and gas flows.

Flexibility – MIDREX Plants have proven flexibility regarding iron ores and reducing gas sources. A number of unique design features, including the MIDREX® Reformer, burdenfeeders and easy flow devices, provide for excellent gas-solids contact and

Figure 1 - Midrex Technical Center

the successful use of high percentages of lump ores. The MIDREX Process can utilize almost any ratio of hydrogen to carbon monoxide. Plants are operating successfully with H_2/CO ratios from 0.5 to 3.5.

CONTINUOUS IMPROVEMENT

In addition to the soundness of the basic flowsheet, the other factor that has enabled the MIDREX Process to remain the dominant direct reduction process for almost 30 years has been the process improvements developed and commercialized by Midrex, MIDREX Licensees, and project partners. Since installation of the first commercial-scale plant in Portland, Oregon, USA, Midrex has continued to advance the state-of-the-art in gas-based direct reduction. Improvements have been made in plant capacity, productivity, energy consumption, raw materials and reductant flexibility, and product form.

Perhaps the best evidence of this ongoing technology development is the increased production of our existing plants over time. There are 21 MIDREX Modules that have been in production for more than 20 years. The total rated capacity of these plants when installed was 9.5 Mtpy. These plants produced a total of 13.3 Mt in 2005. This same trend continues with the new generation of MIDREX Plants and the overall capacity utilization for all MIDREX Plants in recent years has been about 130 percent.

Midrex has an active technology development effort and that process expertise is reflected in our 40 plus patents. The company has unique experience in pyro-processing as well as substantial capabilities in high temperature refractory and equipment design, super-alloy selection and application, combustion systems, reforming, waste heat recovery systems, and high temperature furnace applications.

Midrex's technology development program is overseen by a Technology Steering Committee. This committee consists of senior management from all areas of the company, as well as members from Kobe Steel, Midrex's parent company. Midrex's Technology Development Department carries out much of the detailed technical analysis and assessment required.

In the company's business plan, there are several three year goals for technology development. Perhaps the most important is to bring two technological improvements to commercialization each year.

A crucial part of Midrex's technology development activities is the company's state-of-the-art Technical Center, which is the focus of research and development activities. The facility, shown in Figure 1, is located near Charlotte, NC USA, and has been an essential part of our business strategy for more than 30 years.

During the last few years, Midrex has made a significant investment in the Technical Center facilities, including a major upgrade of its mineral processing capabilities. The Tech Center contains the following equipment:

- Sample preparation, including drying, crushing, splitting, and pulverizing
- Wet chemistry laboratory for analyzing iron ores and other iron-bearing materials
- Physical analysis equipment, including size distribution, crush strength, and tumble test
- Numerous analyzers, including gas chromatographs, surface area analyzers, optical spectrometers for elemental analysis, and LECO carbon/sulfur analyzer
- Furnaces for conducting iron ore characterization (Linder and Hot Load)
- Various bench-scale furnaces for characterizing raw materials
- Equipment for pelletizing and briquetting iron ores, coals, and other solids
- A 150 kg/h FASTMET Process Simulator and an Electric Ironmaking Furnace for pilot testing of the FASTMET®, FASTMELT®, and ITmk3® Processes
- A variety of equipment for beneficiating solids

Midrex maintains an ongoing technology transfer program to share knowledge with plant operators and project partners. This effort includes a Technical Services program, frequent travel to plant sites, the annual Operations Seminar, and numerous bulletins regarding new technology developments.

DON'T REST ON YOUR LAURELS

From 1970-2006, DRI output from MIDREX Plants grew to 36 Mtpy, as shown in Figure 2.

Even though the world steel industry experienced two severe multi-year downturns during that period, MIDREX Plant production increased nearly every year. A major factor in this record of outstanding performance was technology development. Improvements were developed and commercialized during that period in the areas of plant capacity, productivity, energy consumption, raw materials and reductant flexibility, and product form.

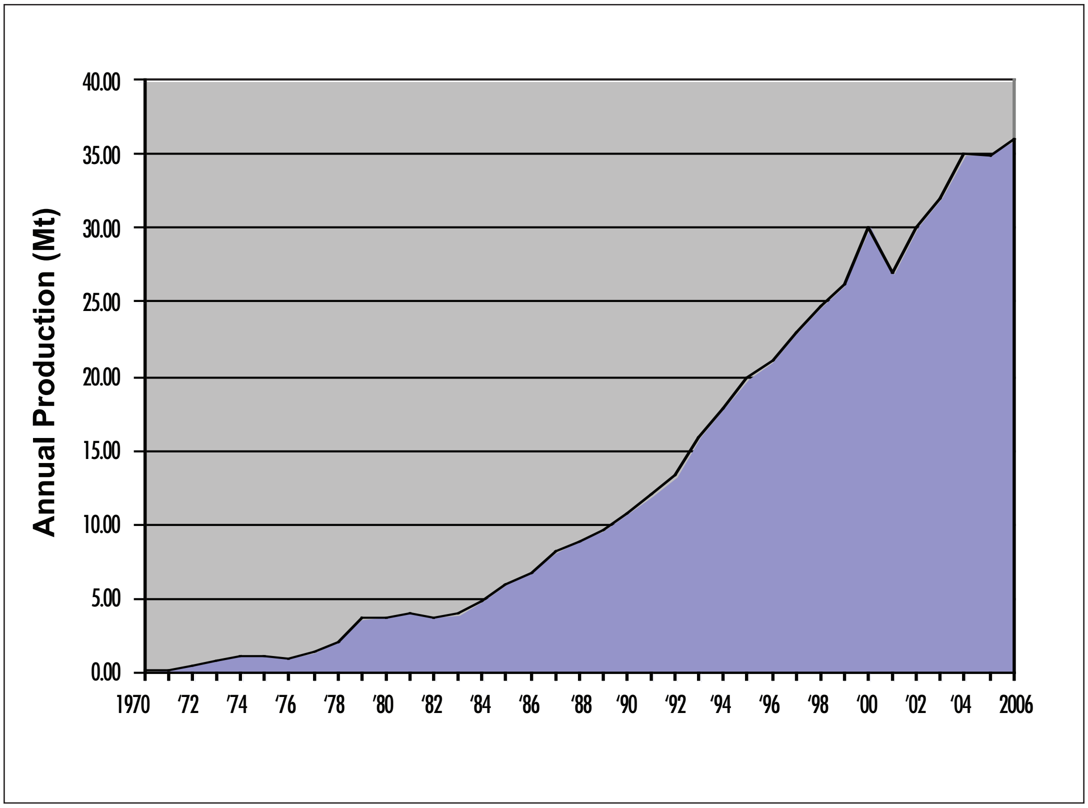

Figure 2 - MIDREX Plant Production

Plant Capacity

The first MIDREX Plant had two shaft furnaces of 3.7 meter diameter, with annual capacity of 150,000 t/y each. Over the years, Midrex built larger and larger modules and the standard MEGAMOD® now has a 6.65 meter diameter furnace and an annual capacity of over 1.5 Mt. Thus, the capacity of a single module (shaft furnace, reformer, and associated equipment) increased by a factor of more than ten. Because of the major economy-of-scale of the technology, these larger plants have significantly enhanced economics.

Productivity

The volumetric productivity of the shaft furnace is a convenient benchmark for relative comparison to other MIDREX Shaft Furnaces and is very important for profitable operation. The shaft furnace specific production rate is expressed in tons per day per cubic meter of reduction volume ($t/d\text{-}m^3$). The specific production rate is most efficiently increased through the use of higher operating temperatures, which increases reaction kinetics, and internal devices, which facilitate good gas-solids contact. Several MIDREX Plants have achieved annual productivities of 14 $t/d\text{-}m^3$, the highest in the direct reduction industry. MIDREX Plants routinely exceed rated capacity, and in recent years the overall capacity utilization has been 120-130 percent. Some MIDREX Plants have achieved as high as 210 percent of capacity on an annual basis using improved operating techniques and equipment modifications.

Energy Consumption

The first MIDREX Plants had a natural gas consumption above 3 Gcal per ton of DRI. Due to more efficient heat recovery systems, modern plants can now achieve levels of under 2.3 Gcal/t. State-of-the-art MIDREX Plants can incorporate up to four stages of heat recovery.

Raw Materials and Reductant Flexibility

Over the years, MIDREX Plants have operated on over 50 iron oxide sources, including pellets and lump ores, from around the world. Several plants have operated on 50 percent or more lump ore for extended periods of time, and plants have been designed for continual use of 70 percent lump ore. Most MIDREX Plants use standard natural gas processed in a MIDREX® Reformer to create a syngas with a hydrogen/carbon monoxide ratio of 1.5/1. The OPCO Plant in Venezuela reforms natural gas using a steam reformer, which generates a syngas with a ratio of 3.5/1. A MIDREX Plant was built at Saldanha Steel in South Africa for the use of COREX® Offgas made from coal, with a ratio of 0.5/1.

Product Form

Until the mid-1980s, all MIDREX Plants produced cold DRI, primarily for use at an adjacent mini-mill. Midrex responded to the market demand for a safe way to ship DRI with the application of hot briquetting expertise from Maschinenfabrik Köppern GmbH & Co KG (Köppern), a world leader in briquetting technology. Köppern and Midrex successfully developed expertise and equipment to hot briquette DRI, separate the briquettes, and cool them. The first MIDREX Plant to employ hot briquetting was Antara Steel (originally called Sabah Gas Industries) in Malaysia in 1984. There are now 10 MIDREX Modules employing hot briquetting, with four under construction. Annual MIDREX HBI production is over five million tons.

Major technology developments commercialized from 1970-2006 are shown in Table I. MIDREX Plant operators contributed greatly to this effort by pioneering and demonstrating several of the enhancements.

SOLUTIONS FOR STEELMAKERS: 2007 AND BEYOND

Midrex is continuing to refine and enhance the MIDREX Process. As always, the first step in technology development should be to determine the needs of the steel industry. Then, a strategy can be formulated to apply the company's expertise and skills to develop new technologies, what we call "Solutions for Steelmakers." What are the requirements for the steel industry of the future? Following are several:

- Fewer unit operations and more continuous processing
- Lower capital cost (CAPEX)
- Higher capacities, to maximize economy-of-scale
- Lower environmental impact
- Higher energy efficiency
- Use of low cost energy sources
- Use of fines, low grade ores, and waste materials

From mid-2006 through 2008, there will be over 14 Mt of new MIDREX Plants or expansions started up, as shown in Table II.

In-situ reforming
Standard/alternate flowsheet configurations
Lump ore use
Larger module sizes
Improved catalysts
Gas preheating
Hot discharge shaft furnace
Hot briquetting
Top gas fuel preheat
Iron oxide coating
Oxygen injection
Alternate reducing gases: steam reforming and coal gasification
Briquette slow cooling
Centrifugal compressors

Table I - Major MIDREX Technology Developments commercialized from 1970-2006

PLANT	Country	Start-Up	Capacity (tpy)	Product
Essar Module V	India	2006	1,500,000	Hot DRI & HBI
Mobarakeh VI	Iran	2006	800,000	Cold DRI
Nu-Iron (Nucor)	Trinidad	2006	1,600,000	Cold DRI
Acindar Expansion	Argentina	2007	250,000	Cold DRI
Al-Tuwairqi	Saudi Arabia	2007	1,000,000	Cold DRI
Hadeed Mod E	Saudi Arabia	2007	1,760,000	Hot & Cold DRI
LGOK Module 2	Russia	2007	1,400,000	HBI
Lion Group	Malaysia	2007	1,540,000	Hot DRI & HBI
QASCO Module 2	Qatar	2007	1,500,000	Cold DRI & HBI
Shadeed	Oman	2008	1,500,000	HOTLINK & HBI
Tuwairqi Steel Mills	Pakistan	2008	1,280,000	Hot & Cold DRI
TOTAL			**14,130,000**	

Table II - New MIDREX Projects

Many of these plants incorporate new developments that address the steel industry needs listed above. These developments and their benefits are shown in Table III.

Midrex has technology development programs in place for 2007 and future years to continue advancing the state-of-the-art in shaft furnace direct reduction. These programs include the use of gasification to provide the reducing gas, process options to reduce CO_2 and other emissions, and use of lower-grade iron ores.

With all these technology development efforts, Midrex has broadened its product offerings both upstream and downstream to include preparing the iron ore for processing and use of the DRI product. Midrex no longer supplies just natural gas-based plants to produce cold DRI using standard iron ores and energy sources. There are options available or under development for various energy sources, alternatives for product form and use of lower grade ores. These provide a wide variety of solutions for steelmakers, as shown in Table IV.

Applications	Integrated steel complex with EAF Merchant sales
Options	Energy source: natural gas or coal (gasification) H_2/CO ratio: 0.5 to 3.5 Module size: 300,000-2,500,000 tpy Product form: cold DRI, hot DRI, HBI Product carbon content: up to 3% Hot transport/charging: HOTLINK, containers, conveyor

Table IV - MIDREX Process Options

Development	Benefits
Hot DRI discharge/transport/charging (containers, conveyor, or HOTLINK®)	EAF productivity increase and electricity savings More continuous steelmaking
External DRI cooler	Product flexibility
"Combo" plants	Capability to produce hot DRI and either cold DRI or HBI
Higher capacity shaft furnaces (7 m diameter furnace for 1.76 Mtpy)	Lower specific CAPEX
Nineteen bay MIDREX® Reformer	Lower specific CAPEX
Centrifugal compressors applied to the process gas loop	Lower specific CAPEX Higher pressure capability
Higher capacity briquette machines (up to 70 tph)	Simpler plant layouts Lower specific CAPEX
HBI slow cooling conveyor	Enhanced product quality
SIMPAX® Expert Control System	Better process control Higher energy efficiency

Table III - New MIDREX Technology Developments and Benefits

CONCLUSION

Since 1969, Midrex and its partners have built (or are constructing) 63 MIDREX® Modules (shaft furnaces plus reformers and associated systems) in 21 countries. The successful operation of MIDREX Plants has resulted in a market share for MIDREX® Technology of 60 percent or more each year since 1987. This success is based on the firm foundation of the work done by Donald Beggs and his colleagues, who conceived the idea of pairing a stoichiometric CO_2 reformer with a shaft furnace to reduce iron oxide. In addition to the soundness of the basic concept, the other factor that has enabled the MIDREX Process to remain the dominant direct reduction process for almost 30 years has been continuous technology development. Improvements have been made in plant capacity, productivity, energy consumption, raw materials and reductant flexibility, and product form. Midrex has an ongoing, extensive technology development program, with much of the work done at the Midrex Technical Center. There is over 14 million tons of new MIDREX Plant capacity in start-up or under construction around the world, and numerous innovations are being commercialized at these facilities. A major focus is hot discharge of product, transport to the meltshop, and hot charging to the EAF. Midrex is continuing to advance the state-of-the-art in gas-based direct reduction.