

DIRECT FROM MIDREX

1ST QUARTER 2016



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COMMENTARY

IN MEMORIAM



DONALD R. LYLES

October 24, 1946 –
March 13, 2016

EDITOR'S NOTE:

Midrex lost one of its own a few weeks ago. If you ever worked on a negotiation for a MIDREX® Plant or even just passed through our Charlotte offices, chances are that you met Don Lyles. He simply was a striking personality and a well-respected man.

It's unfair to try to sum up an individual in just a few words, so I won't. Rather I will say it was a pleasure to work with and beside Don for the past decade and a half. We miss you Don, and we thank you for the time we shared.



Don Lyles was an enigma. To some he was a fearsome presence across the negotiation table. To others he was the one you could turn to for help. He never sought attention or acclaim but often was thrust into situations that required clear vision and a resolute spirit. He was often mistaken as aloof and impassive, but I have never known a person who had the capacity to care as much as Don.

We talk a lot about leadership. Often we mistake displays of ego and bravado for leadership and are disappointed when our expectations are not met. Don was a quiet leader, one who through his intellect, work ethic and personal standards made those around him better at what they did. He would challenge shallow arguments and question “half-baked” ideas so that when it mattered they would be successful.

Don was sent on trips when the stakes were high ... a tough business deal, a face-off with a would-be competitor or establishing the boundaries of a partnership. When others got caught up in the emotion of the moment, he would remain calm and focused.

I remember traveling with Don on several occasions. Knowing he was there gave me the confidence to be bold when it was needed. His timing was impeccable. He knew how and when to interject insightful comments with a surgical touch.

Don was deeply devoted to his family; his wife and children, as well as those of us in his Midrex family. He took his pleasure from seeing all of us flourish, and he understood that sometimes you have to be stern and demanding to bring out the best. But there was never malice or ill will in anything he did or said.

The history of Midrex and the career of Don Lyles cannot be separated. He was among the first to join the fledgling company when it was established in Charlotte. Although he came to Midrex as an honors graduate of North Carolina State University in Chemical Engineering, Don made his mark on the business side of the company and went on to earn an MBA. The contracts and license agreements he crafted are the standards of today.

The memories he leaves behind are the mark of a good man. Everyone who knew Don took something away from the experience that has made him or her a better person ... and he will be greatly missed. ■

Frank N. Griscom
Midrex, 1981-2002



DRI PRODUCTION USING COKE OVEN GAS (COG):

Test Results of Thermal Reactor System™ (TRS®)

By Gary Metius, Process Technology Manager, Midrex Technologies, Inc.

Natural gas continues to be the most ideal reducing gas source for the production of direct reduced iron (DRI). However, some areas of the world do not have access to low-cost natural gas in the volumes required for steady, sustained DRI production. For years companies have considered using coke oven gas (COG) to produce DRI. In theory the concept is simple; however, due to the composition of COG, a simple solution has not been readily available.

In June of 2012, Midrex Technologies, Inc. and Praxair, Inc. signed a strategic alliance agreement to develop and market the Thermal

Reactor System™ (TRS®), which will allow the production of DRI with a variety of fuels including COG. TRS® will use an innovative partial oxidation technology developed by Praxair to convert hydrocarbon fuels into high quality, high temperature syngas suitable for DRI production in the MIDREX® Direct Reduction Furnace.

This article describes the Thermal Reactor System™ (TRS®) and presents the results of the final phase of development testing involving the operation of a TRS® Demonstration Plant at the Midrex Research & Development Technology Center in Pineville, NC, near Charlotte.



Stephen Montague, VP of Sales & Marketing for Midrex, at signing of the strategic alliance agreement in 2012 with Pravin Mathur, Global Market Director - Steel & Combustion for Praxair.

BACKGROUND

Coke oven gas (COG) is a byproduct of the coke-making process consisting of a complex mixture of typically 55% H₂, 7% CO, 25% CH₄ and small amounts of CO₂, H₂O, heavy tars and volatile hydrocarbons. Today, most COG is used for heating applications, as a chemical plant feedstock or is flared, leaving its potential as a reducing gas untapped. Using COG for DRI production has always been of interest, but the challenges have been the conversion of methane to CO and H₂ and cleanup of the tars and volatile hydrocarbons.

Midrex first started looking at methods of using COG for direct reduction in the 1970s. The principal problems involved the presence of unsaturated hydrocarbons, tars and liquids, as well as high levels of methane and sulfur compounds in the raw gas. The earliest studies focused on conditioning the COG to

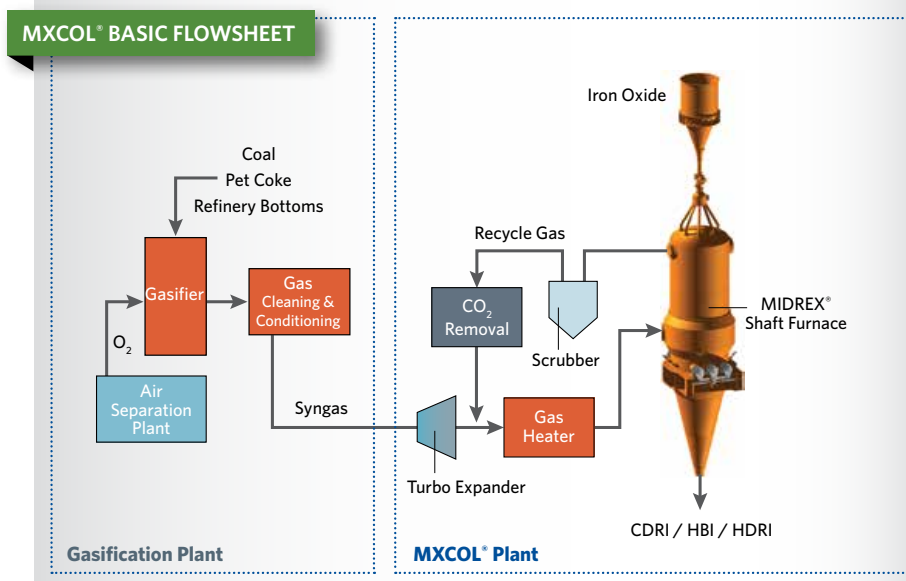


FIGURE 1 MXCOL® FLOWSHEET



use it as a feed gas component for a MIDREX® Reformer. More recently, interest has turned to the possible use of COG in an MXCOL® Plant, which is designed specifically to use coal-derived gases as the reducing gas for the production of DRI products (see Figure 1).

Recent developments in partial oxidation technology led Midrex to investigate the possibility of using it to condition COG as an appropriate reducing gas for an MXCOL® Plant. However, the need to add steam to the reactants to reduce soot formation resulting from the oxygen reactions has been a major concern. As a result, Midrex formed an alliance with Praxair, Inc., a leader in partial oxidation technology, to develop and market a new process technology for the production of DRI from a variety of fuels including COG.

PRAXAIR HOT OXYGEN TECHNOLOGY

In mid-2011, Praxair made a presentation to Midrex that covered a variety of technology developments which they were offering commercially. One of these was the Hot Oxygen Burner (HOB). Its unique features offered the potential to perform partial oxidation of hydrocarbons soot-free without steam injection. When this technology is combined with an extended thermal reaction chamber into which a stream of preheated COG is injected, the product gas leaving the reactor is suitable for use as a reductant source for direct reduction. All together, this equipment grouping including gas compression, preheating and reacting makes up what has become known as the Thermal Reactor System™ or TRS®.

THERMAL REACTOR SYSTEM™ (TRS®)

TRS® employs Praxair's HOB technology for partial oxidation of a variety of fuels including COG. The system produces an in-situ, hot, extreme velocity oxygen jet that rapidly entrains preheated COG, reforms the methane, breaks down heavy hydrocarbons and destroys the tars without the need for any catalyst. Reformed syngas then exits the TRS® and is fed into the MIDREX® Shaft Furnace to produce DRI.

In pilot scale tests with the HOB, over 96% tar destruction was achieved along with optimized methane reforming. In addition, operating conditions have been developed to avoid net soot generation.

Based on the results of the pilot scale tests, the decision was made in 2012 to construct a 1/10-scale demonstration plant at the Midrex Research & Development Technology Center in

Pineville, NC, near Charlotte. In all, the demonstration plant operated for three campaigns covering more than 2000 hours during the 29-month project period. The plant operated on two major blends of COG feedstock, with toluene levels from 0-1.9 mol % and 100% natural gas as feedstock. It also used four different gas combinations for the firing fuel of the HOB. The TRS® Demonstration Plant is shown in Figure 2.



FIGURE 2 TRS® Demonstration Plant

Midrex and Praxair completed the final phase of development testing in 3rd quarter 2014, and the Thermal Reactor System™ (TRS®) is now ready for commercial application. The TRS® will be jointly marketed by Midrex and Praxair.

TRS® DEMONSTRATION PLANT



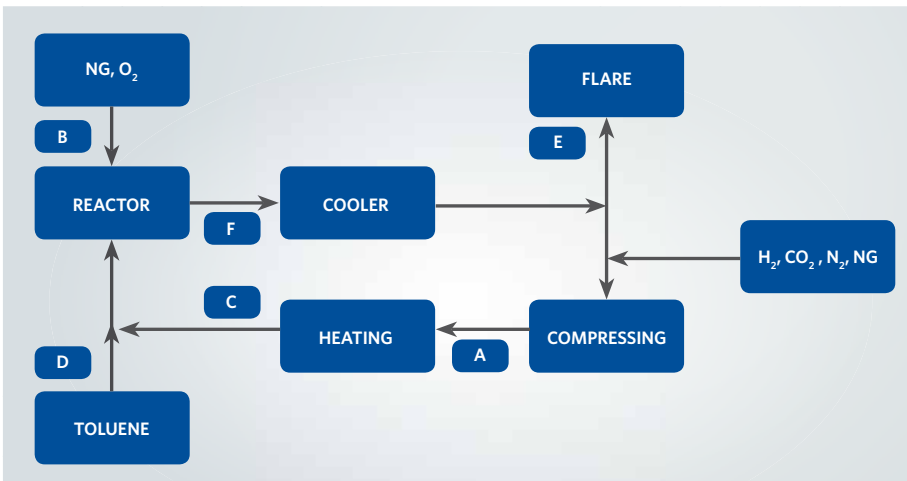


The concept of the demonstration plant was to combine the primary gaseous components of coke oven gas, hydrogen, methane, nitrogen and carbon dioxide from liquid bulk sources and recirculate a portion of the syngas generated to supply the carbon monoxide required. A separate stream of toluene would be added at varying levels to study the BTX component of COG and its effect on system performance and syngas quality.

CAMPAIGN PLANNING

The test plan for 2013 called for campaigns to establish clear parameters for operation of the TRS[®]. Campaign 1 was expected to develop clear operating procedures for the demonstration facility, as well as develop a preliminary understanding of the range of the operating envelope of the facility. Campaign 2 was to establish the critical operating points for commercial operation of the TRS[®] units, as well as turndown and upper limits on system capacity. The nominal design capacities at different points in the demonstration plant are shown in *Figure 3*. The flowsheet for Campaigns 1 & 2 is shown in *Figure 4*.

Following completion of Campaign 2, a test plan for Campaign 3 was developed. It required the use of different fuels in the HOB. To accomplish this, the flowsheet of the demonstration plant needed to be modified for additional gas metering and compression (*see Figure 5*). These modifications and further commissioning corrections were completed by June 2014. The HOB also required some independent testing because its primary fuel had been only natural gas up to this point.



- A. 1250 Nm³/h COG from compression
- B. 350 Nm³/h O₂ from liquid supply
- C. 450°C from feed stock heater
- D. 77 kg/h toluene from bulk tank
- E. 1800 Nm³/h syngas to flare
- F. Reactor pressure: 2 bar-g (low nominal) and 7 bar-g (high nominal)

FIGURE 3 Nominal design capacities at different points in the demonstration plant

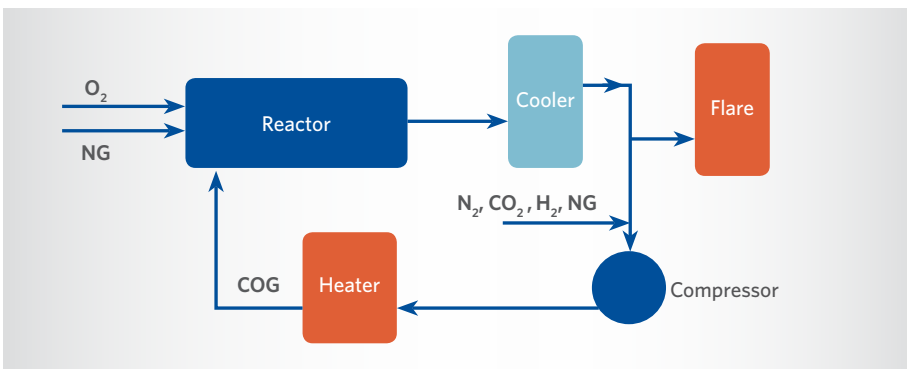


FIGURE 4 TRS[®] Demonstration Plant Flowsheet for Campaigns 1 & 2

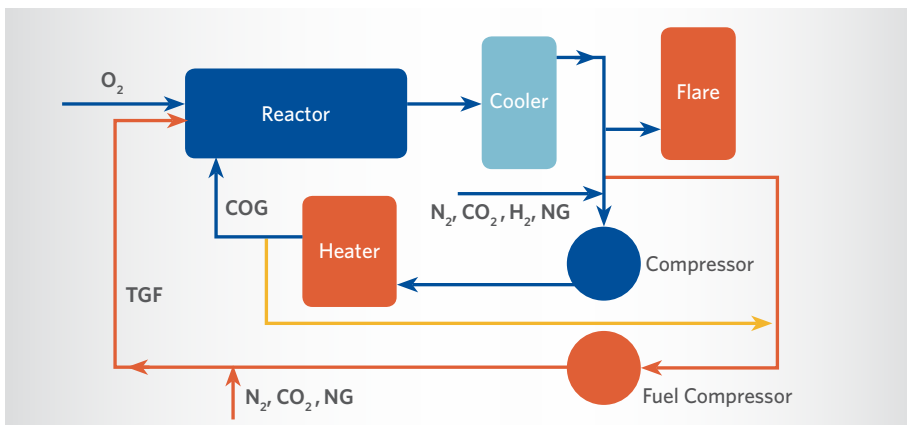


FIGURE 5 TRS[®] Demonstration Plant Flowsheet Modified for Campaign 3



RESULTS OF TEST CAMPAIGNS

Campaign 1

The first campaign was run for 15 days in June 2013 and tested numerous COG feedstock combinations with varying toluene content and varying oxygen rates, expressed as a stoichiometric ratio, or SR. The objectives were to determine the range of operation for this system and to begin to define the soot generation relationship with regard to the reactor temperature and SR.

The system was run at 2.0 bar-g reactor pressure and was fed with the following COG feedstock composition range:

Component	mol %
CO	6.1 - 10.4
CO ₂	2.2 - 2.7
H ₂	54.3 - 59.7
N ₂	1.0 - 4.2
CH ₄	21.2 - 29.7
C ₇ H ₈	0 - 1.9

In Campaign 1, the SR was operated over a wide range, from 0.14 to 0.21. The best raw syngas quality was obtained near the center of the test range. This represented a major improvement over the prior tests in the lab-scale pilot facility, which ran best at an SR over 0.21. The improved SR is likely due to the reduced heat loss of the new reactor, 3.5% versus 40-50% for the prior lab-scale test reactor.

Other developments which were applied in the first campaign included a laser opacity measuring arrangement designed to quantify and trend the soot generated within the reactor and a sub-stoichiometric burner arrangement used to preheat and idle the system at temperatures in excess of the auto-ignition temperature.

After a follow up review, it was clear that one of the major objectives for Campaign 2 would be to reduce the plant operating variations and bring a better understanding of the soot generating conditions.

Campaign 2

In Campaign 2, which ran for 20 days from late July into August, 2013 the operating plan was targeted for a much tighter control of feedstock and reactor conditions. A soot sampling arrangement was established to verify the laser readings and the laser

opacity system also was modified to improve stability, in particular to overcome the system sensitivity to external temperature effects. The operating pressure of the reactor was increased to 3.3 bar-g to match the expected commercial design pressure then under consideration, and the COG feedstock target composition range was adjusted to:

Component	mol %
CO	5.2 ± 1.5
CO ₂	1.75 ± 0.5
H ₂	64.0 ± 3.0
N ₂	3.6 ± 1.0
CH ₄	25.5 ± 3.0
C ₇ H ₈	0.50 ± 1.00

During the second campaign, soot was filtered out of a slip stream of syngas from the reactor during 30-60 minutes sampling periods. The samples provided good spot validation of the laser opacity trends and the data required to determine the critical SR for minimum soot formation. The soot data collected is shown in *Figure 6* and clearly shows the impact of toluene levels on soot generation.

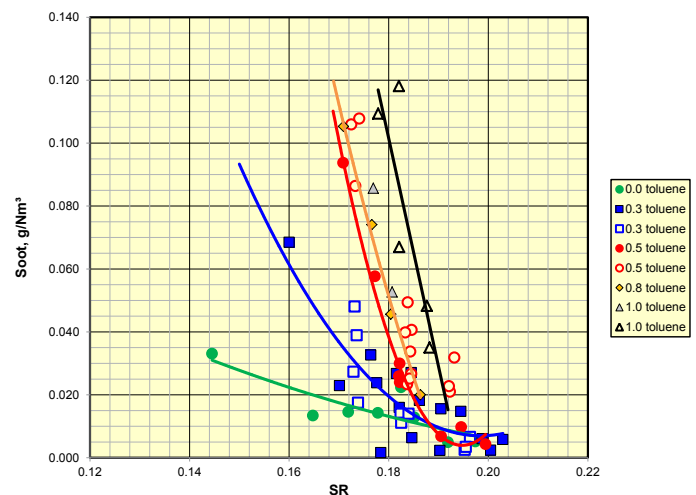


FIGURE 6 TRS® Soot Generation at Various Toluene Levels

Two additional pieces of important data for DRI production from syngas are the temperature of the syngas and the residual methane contained in that syngas. Their inter-relationship is shown in *Figures 7* and *8* (next page).

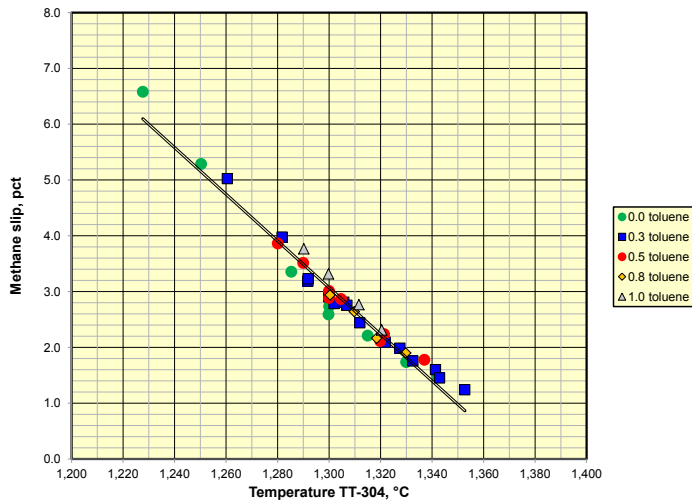


FIGURE 7 Peak Reactor Temperature vs Methane Slip from TRS[®] in Campaign 2

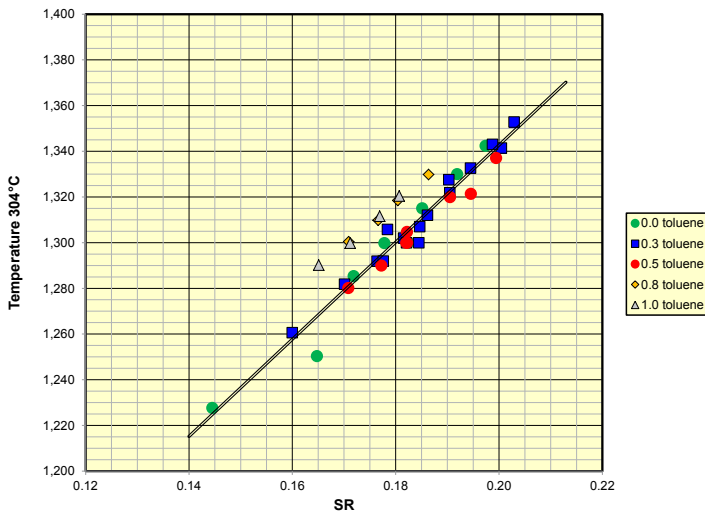


FIGURE 8 Peak Reactor Temperature vs SR in Campaign 2

Based on the operating data from Campaign 2, the raw syngas produced from the TRS[®] reactor that was fed by the COG composition identified earlier would have a typical reductants-to-oxidants ratio $[(H_2+CO)/(H_2O+CO_2)]$ of about 6 for the uncooled raw syngas at 1340°C, as shown in the next column above.

Component	mol %
CO	21.8
CO ₂	1.66
H ₂	56.07
H ₂ O	11.95
CH ₄	1.36
N ₂	7.05
C ₂ H ₆	0.02
C ₃ H ₈	0.003
C ₂ H ₂	0.020
C ₂ H ₄	0.040

Gas Quality 5.72 = $[(H_2+CO)/(H_2O+CO_2)]$

The reductants-to-oxidants ratio increases to about 15 when the raw syngas is quenched to about 40°C to reduce the H₂O content. As a rule of thumb, for every 100 Nm³ of COG the TRS[®] produces 175-180 Nm³ of the raw syngas at approximately 1340°C.

Campaign 3

For Campaign 3, the remaining issue to be demonstrated was the use of the low heating value fuels in the HOB. Two different hot oxygen temperatures also were tested. The fuel compositions run during the test period ranged from top gas fuel (TGF), which was typical of spent reducing gas available in a DRI plant, to COG taken from the feedstock to the TRS[®], as follows:

Component	TGF	COG	NG
	mol %	mol %	mol %
CO	20.5	11.7	-
CO ₂	14.6	3.2	1.35
H ₂	46.1	55.3	-
H ₂ O	0.7	1.2	-
N ₂	13.4	3.9	0.31
CH ₄	4.6	23.6	95.40
C ₂ H ₆	-	0.7	2.34
C ₃ H ₈	-	-	0.60
C ₇ H ₈	-	0.3	-
LHV (kcal/Nm ³)	2201	4032	8649

For Campaign 3, the TRS[®] feedstock analysis target reverted to the target from Campaign 1 and resulted in the following composition (next page):



Component	mol %	Std. Dev.	
		mol %	mol %
CO	0.6	±	1.3
CO ₂	3.4	±	1.1
H ₂	54.3	±	1.3
H ₂ O	0.8	±	0.1
N ₂	3.8	±	0.6
CH ₄	25.6	±	0.2
C ₂ H ₆	0.8	±	0.01
C ₇ H ₈	0.1 - 0.5	±	0.02

The resulting syngas, produced from the above range of HOB gases and TRS® feedstock was as follows:

Component	mol %	mol %	mol %
CO	23.76	23.10	21.81
CO ₂	2.40	1.99	1.66
H ₂	48.07	51.46	56.07
H ₂ O	14.65	12.93	11.95
N ₂	10.22	8.39	7.05
CH ₄	0.85	2.06	1.36
C ₂ H ₆	0.045	0.044	0.024
C ₃ H ₈	0.006	0.005	0.003
Gas Quality	4.21	5.00	5.72
	[[H ₂ +CO)/(H ₂ O+CO ₂]]		

As with the previous campaigns, the major issues focused on the control of the peak gas temperature, the methane slip and the potential for soot generation in the reactor. These are each shown in *Figures 9, 10 and 11*. The use of lower heating value fuels was successful in generating a reducing quality gas with low CO₂ content and free from significant soot generation. As would be expected, the lower the fuel heating value, the higher the oxidant level in the raw gas for the same peak operating temperature. The resulting gas qualities are easily improved with full or partial cooling of the hot syngas streams. The typical resulting H₂O content would be between 9% - 10% for partial quench and 1.5% - 2.0% for a full quench.

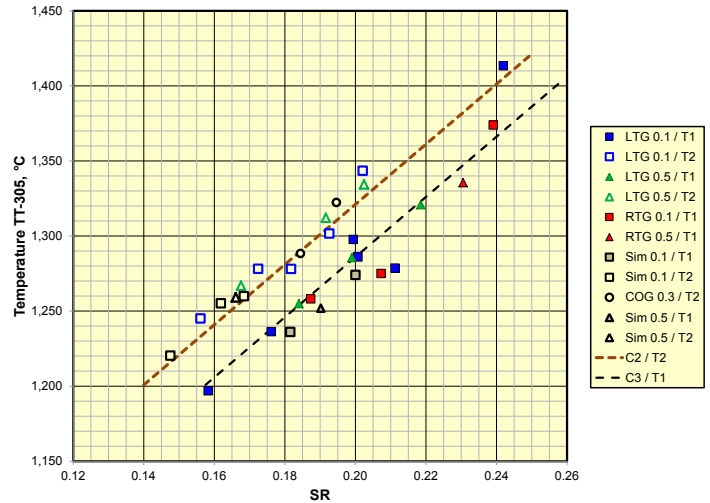


FIGURE 9 Peak Reactor Temperature vs SR in Campaign 3 (T1 < T2 are hot oxygen temperatures)

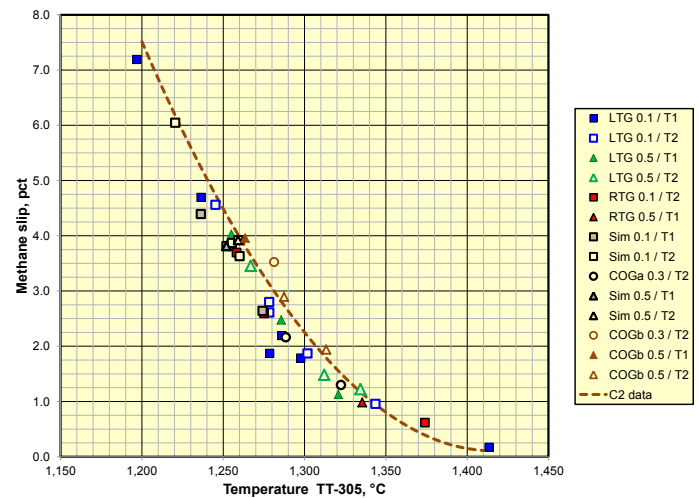


FIGURE 10 Peak Reactor Temperature versus Methane Slip from TRS® in Campaign 3

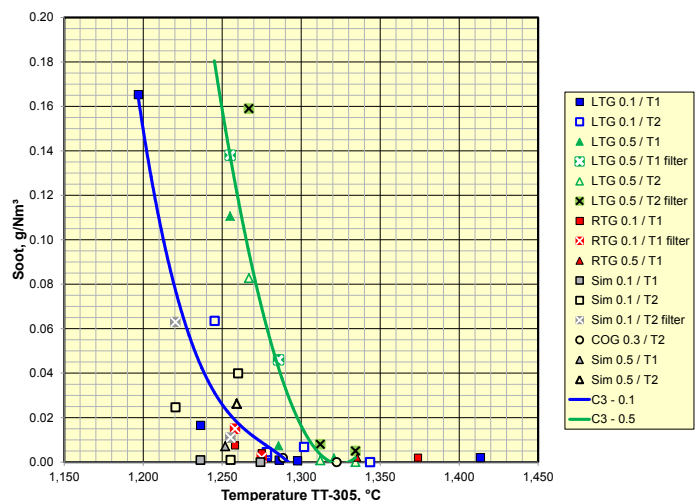


FIGURE 11 Soot Generation versus Peak Reactor Temperature in Campaigns 2 and 3



TRS® FLOWSHEET INTEGRATION

There are two TRS® flowsheet options which can be used to add syngas and produce high quality DRI from COG. Both arrangements use the MXCOL® flowsheet as the principal arrangement of equipment for managing the removal of the oxidants (H₂O and CO₂) from the process stream. The two flowsheet options are the Feed Gas TRS® and the Bustle Gas TRS®, which are shown below in *Figures 12 and 13*.

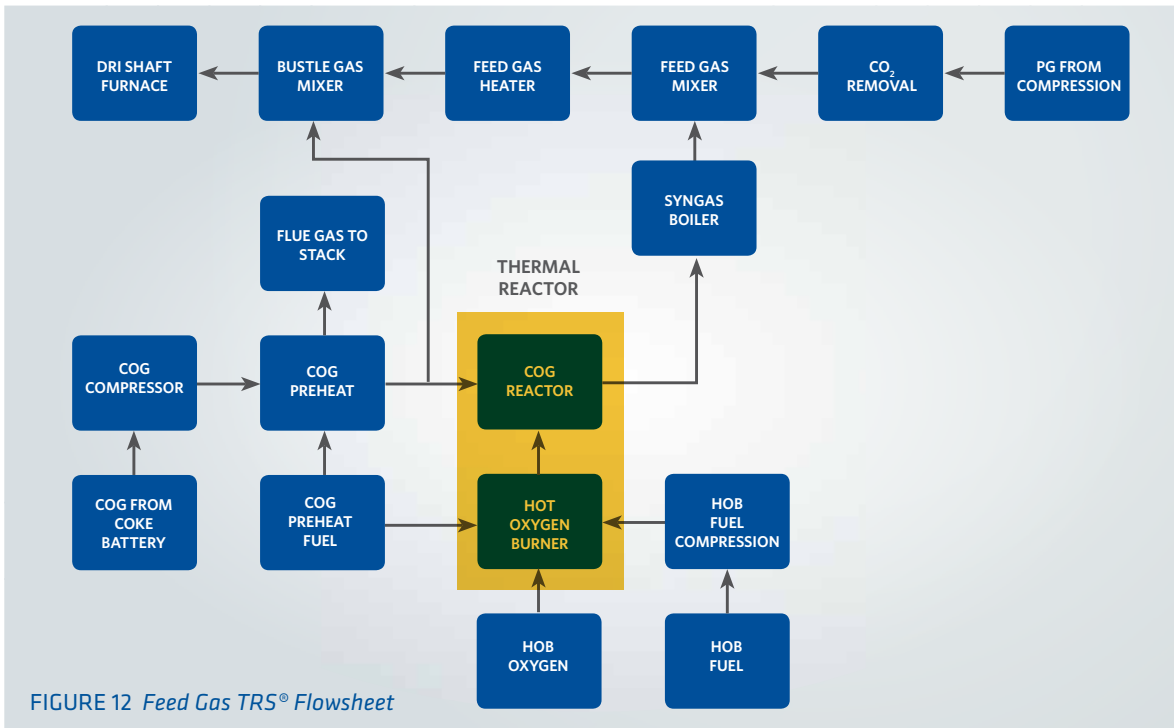


FIGURE 12 *Feed Gas TRS® Flowsheet*

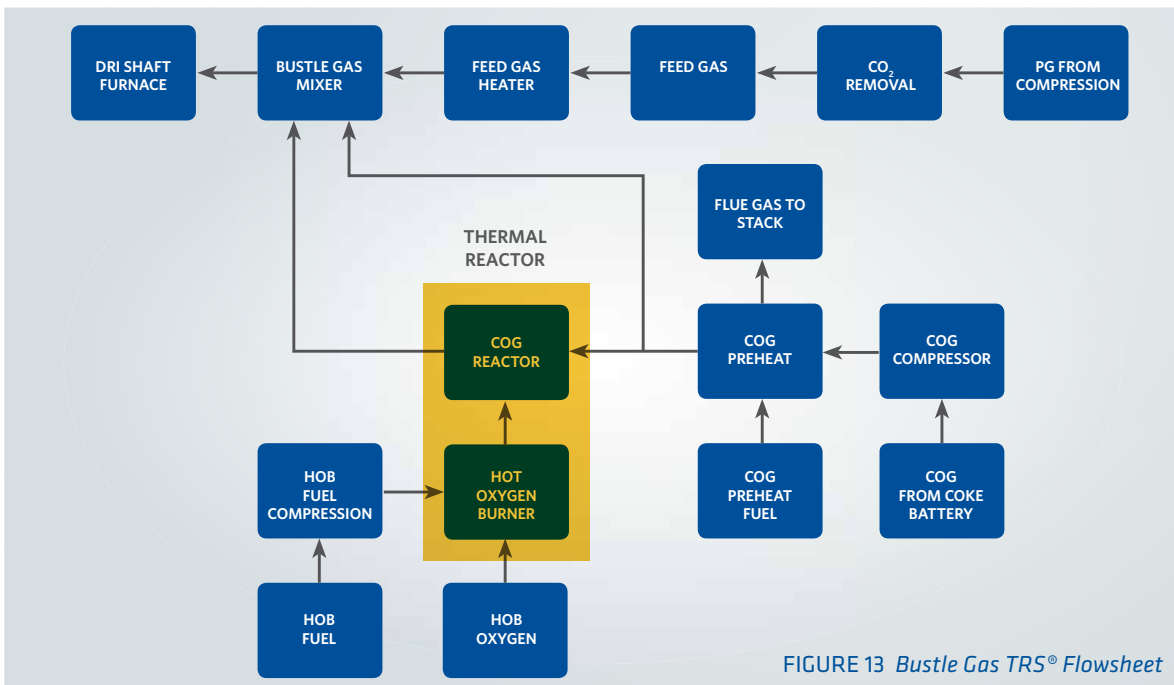


FIGURE 13 *Bustle Gas TRS® Flowsheet*



The preferred option is the Bustle Gas TRS® flowsheet because it retains the residual heat from the TRS® reactions and utilizes it directly in the DRI production process. The heat helps convert the lower quality syngas and feed gas, typically about 8.5 quality (reductant/oxidant) ratio, to a 12.0 quality ratio at equilibrated conditions. Typical MIDREX® reformed gas has a quality ratio of 10.5 and after equilibration reaches a 12.0-12.5 quality ratio. Therefore, the production performance derived from TRS® syngas fits well into the normal performance curves for a MIDREX® Direct Reduction Plant.

Midrex also has developed a flowsheet that does not incorporate a recycle of spent process gases but rather exports the gases for use as burner fuels in other plant operations. This flowsheet requires approximately twice the COG per ton of DRI produced but yields about a 60-65 % return of heating value in the export gas volumes. This option would fit best in larger integrated facilities where the DRI needs are less and the need for additional in-process furnace fuels is significant.

CONCLUSION

Based on the results achieved during their multi-campaign developmental testing program, Midrex and Praxair are ready to take their Thermal Reactor System™ (TRS®) to market. TRS® can produce clean syngas from COG and other hydrocarbon sources for DRI production in a MIDREX® Direct Reduction Furnace. Analysis of COG input and syngas output is shown in *TABLE I*.

	COG Gas Analysis	Syngas Analysis
	TRS Inlet	TRS Outlet
CO	4 to 6 %	22 to 28 %
CO ₂	1 to 3 %	1 to 3 %
H ₂	55 to 65 %	55 to 65 %
H ₂ O	0.4 to 0.8 %	0.5 to 2.5 %
CH ₄	20 to 30 %	0.5 to 3.0 %
N ₂	2 to 4 %	3 to 8 %
BTX	0.3 to 2.0 %	0.0 %
HHC	0.2 to 0.6 %	0.0 %
Soot		≤ 0.01 mg/NCM

TABLE I - Typical Results obtained from the COG Demo Test Operations

The commercial applications for iron and steelmaking are numerous. TRS® offers a solution for regions like India with limited access to natural gas for the production of DRI. TRS® technology can be retrofitted to existing plants or used for new projects, and it can provide up to 100 % of the reducing gas for a MIDREX® Plant.

TRS® also opens up new DRI production options for conventional integrated steel mills (coke oven/blast furnace/basic oxygen furnace), as seen in *Figure 14, next page*. Using TRS® technology to process COG into a high quality syngas that can be used as

reducing gas in a MIDREX® Reduction Furnace allows integrated steel producers to make optimum use of their coke resource. More iron can be produced for the same amount of coke, and that iron in the form of hot briquetted iron (HBI) can then be fed to a BF or BOF within the same integrated works. This would increase hot metal production while reducing specific coke consumption, thus greatly reducing the environmental impact of the steel produced. The HBI also could be used in place of purchased scrap in the BOF.

Benefits of TRS® when producing DRI are:

- Hot reduction zone reaction temperature (840°C)
- HDRI discharge temperatures (>700°C)
- Consistent DRI quality from close control of syngas quality and methane concentration to the furnace
- Improved product quality control flexibility, metallization and carbon
- Maximum utilization of the heavy hydrocarbons by breaking them down and then reforming to H₂ and CO
- Increased plant operating efficiency and fewer maintenance issues due to reduced hydrocarbon cracking potential in the reducing gas heater



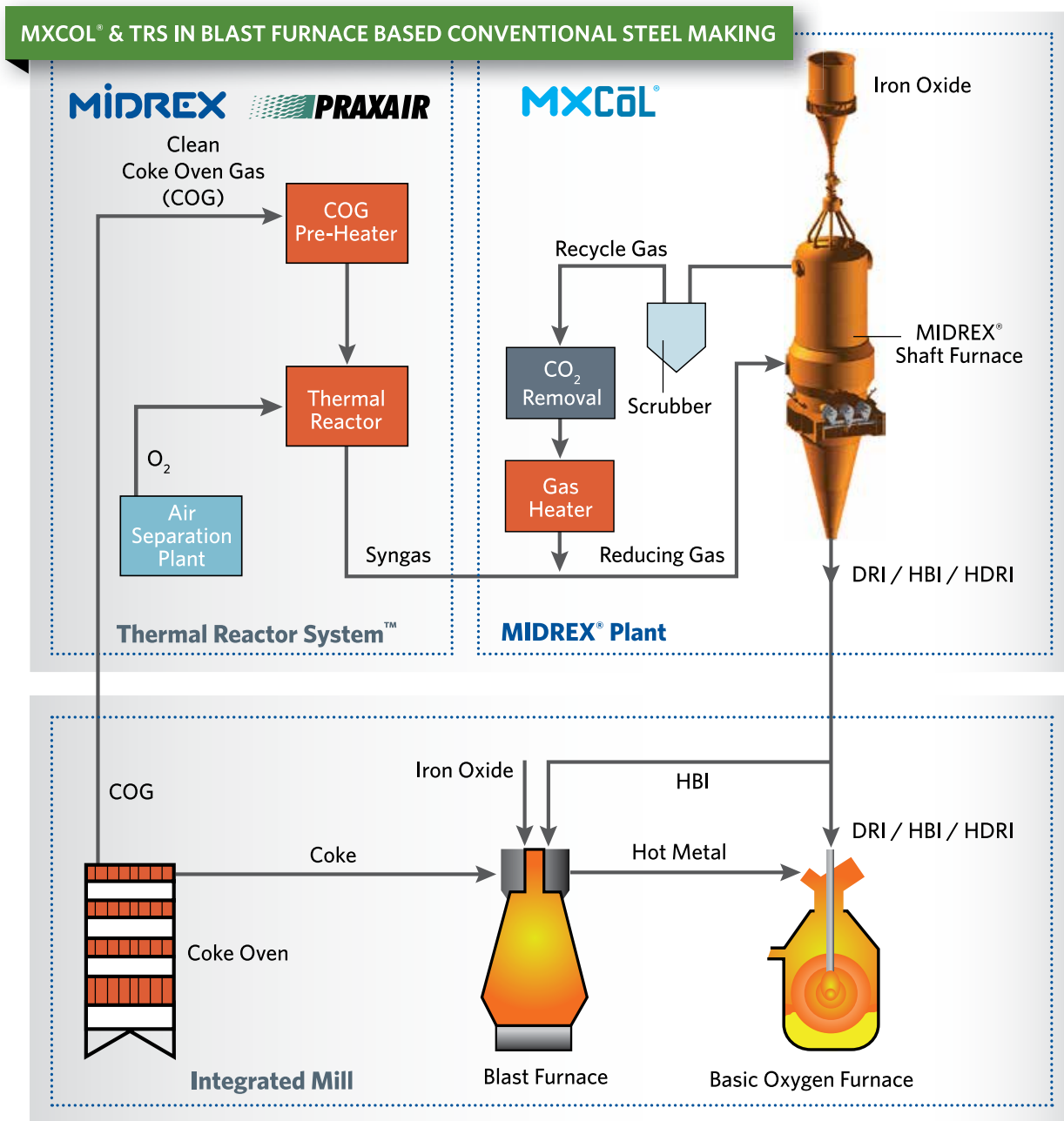


FIGURE 14 TRS® with MXCOL® Flowsheet

(This article is adapted from the paper titled, "DRI Production using Coke Oven Gas (COG): Results of the MIDREX® Thermal Reactor System™ (TRS®) Testing and Future Commercial Application", by G. Metius and H. Gaines, Midrex Technologies, Inc. USA; and M. Riley, L. Bool III and B. Damstedt, Praxair Inc. USA, and the article from 4Q2012 Direct From Midrex titled, "Increased Integrated and EAFs possibilities using Midrex/Praxair Thermal Reactor System™", by Gary Metius) ■



THE VERSATILE* OBM (Ore-Based Metallic): Part 1

Everything you ever wanted to know about Direct Reduced Iron... but were afraid to ask!

*(VERSATILE: able to adapt or be adapted to many different functions or activities)

EDITOR'S NOTE: Direct reduced iron (DRI) has been around forever. Well maybe not forever, but long enough that everyone should know pretty much everything about it, right? Maybe not.

I put forth a notion that the steelmaking industry "assumes" that everyone knows the basics of direct reduction iron and DRI products.

Commercial DRI plants came into play mid-20th century at very meager tonnages, but by the end of the century DRI facilities got bigger, and more and more steelmakers began to use and make DRI products. The first 40-50 years for many was the ramping up of the industry or the birth of it depending on your perspective. Even today, DRI products represent a fraction of the world's total iron production. Two years ago total world output set a new record at 75 million tons of DRI produced, which sounds massive until you realize blast furnaces produced nearly 1.5 billion tons.

The "evolution" of DRI product forms and pro-



duction was a give-and-take of sorts. First came cold product (CDRI), then hot briquetted iron (HBI) and finally hot DRI (HDRI). All are versatile OBMs (ore-based metallics) that provide benefit to steelmakers. Which product form to use is determined by the application and the user. And much like operation of a meltshop, the use and preference of materials varies with the complexity of the user and the market in which the company competes. There is no one product spec or form that acts as a panacea.

This two-part article is designed to alleviate some of the confusion for the novice and perhaps even reframe the understanding for the seasoned vet.

THE BASICS...

DRI – 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. 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. It is used to make a broad range of steel products – all types of sheet including exposed auto body, extra deep drawing wire, special bar quality, forging bar, plate and seamless tube. The chemical and physical characteristics of DRI make it desirable for use in the electric arc furnace

(EAF), blast furnace (BF) and basic oxygen furnace (BOF), as well as other melting and refining vessels.

DEVELOPMENT OF PRODUCT FORMS

The first modern direct reduction plants were built adjacent to the steel mills that used the DRI. 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. 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 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.

DRI PRODUCTS AND CHARACTERISTICS

New DRI product forms have been introduced to meet the changing needs of users and to address specific issues, such as long term storage, ocean carriage and size and density. Midrex has responded with direct reduction technology for hot discharge, transport and charging, as well as on-demand and simultaneous discharge options.

DRI products are available in three forms: cold DRI (CDRI), hot DRI (HDRI) and hot briquetted iron (HBI).



Cold DRI (CDRI)

Most direct reduction plants built to-date produce CDRI. After reduction, the DRI is cooled in the lower part of the reduction furnace to about 50° C. Typically CDRI is used in a nearby EAF shop as part of the primary metallic charge either in the scrap bucket or by continuous feeding. CDRI must be kept dry to prevent re-oxidation (rusting) and loss of metallization.

Hot Briquetted Iron (HBI)

HBI is the preferred DRI product for ocean carriage because it is much denser than CDRI, which reduces the re-oxidation rate and fines generation during handling and shipping. Its enhanced physical characteristics enable HBI to be stored and transported without special precautions under the International Maritime Organization (IMO) solid bulk cargo code. The size and density of HBI make it a desirable feed material for the EAF, BF and BOF.

The product characteristics of each direct reduction plant

will be determined by the availability and quality of raw materials and reducing gas and in some cases will change in response to market conditions or other factors related to steelmaking. For example, some MIDREX® Direct Reduction Plants are operated at metallization rates of 92-93 percent while others produce continuously at 97 percent metallization to optimize a specific steelmaking practice.

Hot DRI (HDRI)

This form of DRI allows the steelmaker to take advantage of the sensible heat (thermal energy whose transfer to or from a substance results in a change of temperature) to increase productivity and/or reduce production costs. HDRI can be transported from a MIDREX® Shaft Furnace to a nearby steel mill at up to 650° C by one of three methods: enclosed and insulated conveyor, specially configured transport vessel or HOTLINK®, a system for direct feeding of HDRI to an EAF.



Remember that while some carbon is necessary in DRI, increasing the carbon content beyond what is needed to optimize the steel cycle time reduces the total iron present in the DRI and can actually increase tap-to-tap time in the EAF (for burning off the excess carbon or decarburization). In addition, the off-gas handling system must be sized to handle the large volumes of gases released during decarburization.

DRI USE IN IRON & STEEL PRODUCTION

The versatility of DRI can be best appreciated by its range of applications in iron and steelmaking. BF operators, who are under intense pressure to lower CO₂ emissions while maintaining productivity levels, are looking to HBI as a solution.

Electric Arc Furnace (EAF)

EAF steelmaking and DRI have been closely associated for half a century. You might say they have grown up together - from producing low cost, carbon steel long products to making high quality flat products that meet the most exacting specifications.

Today DRI is still used primarily to make long products, such as reinforcing bars and

TYPICAL CHARACTERISTICS OF MIDREX® DIRECT REDUCED IRON

	CDRI	HBI	HDRI
Fe Total (%)	90 - 94	90 - 94	90 - 94
Fe Metallic (%)	83 - 90	83 - 90	83 - 90
Metallization (%)	92 - 97	92 - 96	92 - 96
Carbon (%)	1.0 - 3.0	0.5 - 1.5	1.0 - 3.0
P* (%)	0.005 - 0.09	0.005 - 0.09	0.005 - 0.09
S* (%)	0.001 - 0.03	0.001 - 0.03	0.001 - 0.03
Gangue* (%)	2.8 - 6.0	2.8 - 6.0	2.8 - 6.0
Mn, Cu, Ni, Cr, Mo, Sn, Pb, and Zn (%)	trace	trace	trace
Bulk Density (kg/m ³)	1,600 - 1,900	2,400 - 2,800	1,600 - 1,900
Bulk Density (lbs/ft ³)	100 - 120	150 - 175	100 - 120
Apparent Density (g/cm ³)	3.4 - 3.6	5.0 - 5.5	3.4 - 3.6
Product Temperature (° C)	50	80	600 - 700
Typical Size (mm)	4 - 20	30 x 50 x 110	4 - 20

*Depends on iron ore source

light structural steel where scrap supplies are limited and costly to import. However, the chemical purity of DRI dilutes the copper and other undesirable constituents in the scrap charge when the EAF is called upon to make high quality flat products and low nitrogen steels.

DRI is ideally suited for use as either a replacement or supplement for scrap in the EAF. DRI provides EAF operators the flexibility to tailor their furnace charges to achieve the desired product quality at the lowest cost per ton of liquid steel.

VIRGIN IRON SOURCE | Typical levels of residual elements in scrap and DRI/HBI

	% of element in scrap / DRI/HBI								
	%Cu	%Sn	%Ni	%Cr	%Mo	%Mn	%S	%P	%Si
No. 1 Bundles	0.07	0.008	0.03	0.04	0.008	0.03	0.02	0.01	0.005
Shredded	0.22	0.03	0.11	0.18	0.02	0.4	0.04	0.025	0.01
No.1 HMS	0.25	0.025	0.09	0.1	0.03	0.3	0.4	0.02	0.01
No.2 Bundles	0.5	0.1	0.1	0.18	0.03	0.3	0.09	0.03	0.01
No.2 HMS	0.55	0.04	0.2	0.18	0.04	0.3	0.07	0.03	0.01
DRI/HBI	0.002	trace	0.009	0.003	trace	0.06-0.10	0.002-0.007	0.03-0.07*	*

* Both Phosphorus and Silica are contained in the oxide form; they are not in the elemental form.



This “metallics partnership” not only provides economic and operational flexibility, it brings even the highest steel specifications within reach of the EAF.

The benefits of DRI products go beyond their chemical properties. They can be charged either in scrap buckets or continuously fed to an EAF. When batch charged, the density of CDRI and HBI can eliminate the need for a second or third scrap charge, which results in lower energy losses, fewer interruptions of power-on time, improved tap-to-tap time and increased productivity. Typically CDRI or HBI is used as up to 30 percent of the batch charge.

Continuous charging systems are used when CDRI, HDRI or HBI make up higher percentages of the total charge. Most commonly, a bucket of scrap is charged initially and then the DRI or HBI is continuously fed. This allows the furnace roof to remain closed and the power to stay on during most of the heat. Maintaining a consistent temperature improves bath heat transfer

and speeds up metallurgical reactions.

HDRI can be transferred by either a hot transport conveyor system or in hot transport vessels to a nearby EAF at temperatures $\geq 600^{\circ}\text{C}$ or it can be fed directly into an EAF from the reduction furnace by the **HOTLINK[®] System**.

A MIDREX[®] Plant equipped with any of the hot transport options can be designed to produce CDRI or HBI as alternate product streams when the melt shop does not need the HDRI. These plants can be switched from one DRI product to another quickly and without disrupting product flow or can produce multiple products simultaneously.

There are two primary benefits of charging HDRI into an EAF: lower specific electricity consumption and increased productivity. Less energy input is required to heat HDRI to melting temperature, which results in a shorter overall melting cycle. The rule-of-thumb is that electricity consumption can be reduced about 20 kWh/t liquid steel for each 100°C increase in DRI charg-

MIDREX HOT CHARGING METHODS

HOTLINK[®]
(Distances < 40m)



Reference: Jindal Shadeed (Oman)

HOT TRANSPORT CONVEYOR
(Distances < 200m)



Reference: Hadeed Mod E (Saudi Arabia)

HOT TRANSPORT VESSELS
(Distances > 100m)



Reference: Lion DRI (Malaysia)

In a MIDREX[®] Hot Discharge Plant, HDRI can be transferred by one of three methods to an EAF meltshop:

1. HOTLINK[®] for distances of less than 40 meters using gravity transport
2. Hot Transport Conveyor (HTC) for distances of less than 200 meters using hot conveyors provided by Aumund
3. Hot Transport Vessel (HTV) for distances of more than 100 meters

Commercial results of temperature of up to 650°C have been typical of these systems.



ing temperature. Therefore, charging HDRI at over 600° C can yield electricity savings of 120 kWh/t or more.

A shorter overall melting cycle also reduces electrode and refractory consumption by at least 0.5 kg/t and 1.8 kg/t of liquid steel, respectively.

The increased productivity from HDRI charging is significant. Use of HDRI reduces the tap-to-tap time, resulting in a productivity increase of up to 20 percent versus charging DRI at ambient temperature.

BLAST FURNACE (BF)

The overburden pressure of a large BF could crush CDRI; therefore, HBI is the best form of DRI for use in the BF due to its enhanced physical properties. It can be used to increase hot metal production and lower coke consumption as up to 30 percent of the BF charge with no significant equipment or process changes.

The addition of HBI increases hot metal production by boosting BF burden metallization ... 8% more hot metal production when burden metallization is increased by 10%. This is highly desirable when:

- Hot metal availability is insufficient to meet demand
- Hot metal requirements are not matched to blast furnace output
- One blast furnace is offline for maintenance

HBI use in the BF has an environmental benefit as well. A 10% increase of BF burden metallization results in a 7% decrease of the coke rate, which in turn reduces CO₂ emissions.

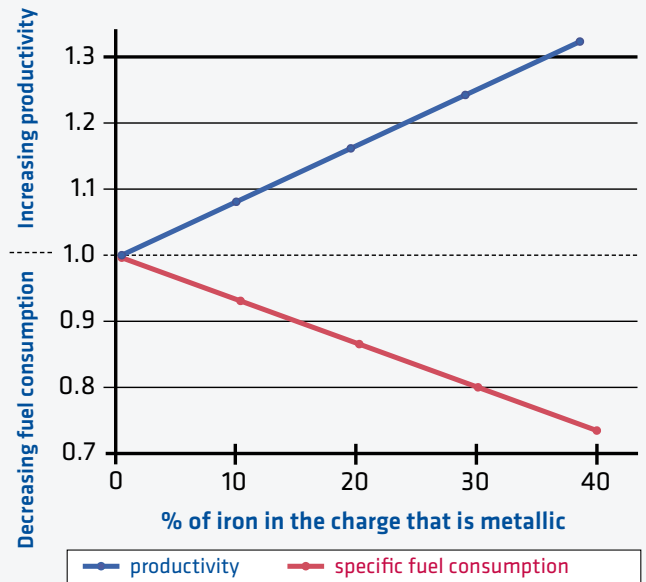
HBI has been used as part of the regular, routine operation of a commercial blast furnace in North America for over 25 years, as well as at other blast furnaces around the world. voestalpine AG will start-up a 2 million tons per year MIDREX® HBI Plant on the US Gulf Coast later this year. The HBI will be used in voestalpine's own blast furnaces in Austria, making it the first plant primarily intended to produce HBI for BF use.

BASIC OXYGEN FURNACE (BOF)

HBI is the form of DRI best suited for use in the BOF because of its bulk density and physical strength. It is a preferred alternative to scrap in the initial cold furnace charge because:

- Residuals levels are low
- Bulk density is high
- Mass and heat balances are more accurate
- Steel chemistry is easier to control

EFFECTS OF ADDING METALLIC IRON AS A PORTION OF THE BLAST FURNACE CHARGE



BASIC OXYGEN FURNACE





HBI also performs well in the BOF as a portion of the cold charge, often as up to 1/3 of the total charge. Advantages of using HBI include:

- The cooling effect of HBI is approximately 10% greater than the cooling effect of scrap steel
- There is no increase in slopping, relative to using all scrap as the cold charge
- There is no sculling on the oxygen lance
- HBI can be used for low sulfur steels
- HBI has lower levels of copper and other undesirable metals than scrap steels

HBI can be charged to the BOF either from an overhead bin or by adding it to the charging box as up to 1/3 of the charge. HBI should be placed in the back of the box so that it will fall into the BOF last.

DRI OPERATIONAL VALUE & FLEXIBILITY

Through the years advances in production technology have continued to increase the value of DRI to iron and steelmakers and has earned the reputation of the steel industry's most flexible charge material. As a result, the DRI industry has experienced phenomenal growth ... from less than 1 million tons in 1970 to 75 million tons in 2014.

As the leading supplier of direct reduction technology, Midrex has made DRI more accessible, more economical to produce and more profitable to use through market-driven innovations and improvements.

Examples include:

- hot briquetting for safer shipping and easier handling
- oxide coating to increase DRI production
- combination plants capable of simultaneous, on-demand discharge of various DRI products
- hot DRI transport and charging to increase EAF productivity, reduce cost/ton of liquid steel
- flexible production rates to accommodate changing market conditions
- reductant sources options when natural gas is not available or affordable
- ability to operate effectively with any commercially available iron oxide pellets, lump ores and blends of the two ■



Glossary of Direct Reduction Terms

These terms are commonly used when discussing direct reduction products and the methods/procedures for handling, shipping, and storing these products.

Carbon Content (%): total carbon present in DRI as a percentage of total weight of DRI. Carbon in DRI can be both in free form and as cementite (Fe_3C).

Cementite (also known as Iron Carbide): a hard, brittle compound of iron and carbon (93.3% iron and 6.67% carbon by weight).

Cold DRI (CDRI): product that is cooled in the lower part of the reduction furnace to approximately 50° C prior to discharge. Most DRI plants built to-date produce CDRI.

Degree of Reduction (%): amount of iron-bound oxygen removed during the reduction process.

Direct Reduced Iron Feedstock:

Pellets (DR-grade): iron ore concentrate that has been formed into round balls (agglomerated), fired, and indurate at a temperature of about 1360° to 1400° C. Total iron content is typically 66 to 67%, and particle size ranges from 9 to 16 mm diameter.

Lump: natural iron ore chunks as mined, having a particle size between 9 to 25 mm and a total iron content of 63 to 65%.

Fines: natural iron ore particles as mined or as



Glossary of Direct Reduction Terms

produced during the crushing of large particles of natural, coarser particles. Fines are classified as pelletizing fines or sintering fines. Pelletizing fines have a particle size between 0 and 12 mm and are used in fluidized bed direct reduction processes.

Direct Reduced Iron (DRI): the product of iron oxide pellets, lump ores or fines that have been reduced (i.e., oxygen removed) in a direct reduction process at temperatures in excess of 900° C, thereby increasing the percentage (by weight) of total iron in the reduced product. All other oxides in the ore remain in their natural state.

DRI products include:

Cold DRI (CDRI): product that is cooled in the lower part of the reduction furnace to approximately 50° C prior to discharge. Most DRI plants built to-date produce CDRI.

Hot DRI (HDRI): product that is discharge from the reduction furnace without cooling and transported to a nearby steel shop by an insulated conveyor or transport vessel or directly charged by gravity flow in the case of MIDREX HOTLINK®.

Hot Briquetted Iron (HBI): product that is discharged from the reduction furnace without cooling and compressed into dense ($\geq 5 \text{ g/cm}^3$), pillow-shaped briquettes (30x50x110 mm) at a temperature $\geq 650^\circ \text{ C}$ without the use of a binder material.

The International Maritime Organization (IMO) identifies direct reduced iron as:

Direct Reduced Iron (A) Briquettes, hot-moulded: IMO classification for Hot Briquetted Iron (HBI).

Direct Reduced Iron (B) Lumps, pellets and cold-moulded briquettes: IMO classification for pellet and lump DRI.

Direct Reduced Iron (C) By-product fines: IMO classification for DRI fines and other byproducts from the production and handling of DRI (A) and (B).

DRI Fines: the result of physical degradation of the particle size distribution of pellets, lumps, and fines during the reduction process caused by the action of rubbing, crepitation, shear stresses, etc. Fines also can be generated during the processing, handling and screening of DRI (A) and DRI (B) prior to use in iron and steel production processes. Normal size distribution depends on the feedstock and can range from 0 to 12 mm. Metallic iron content is in the range of 1.0 to 75.0% by weight.

Gangue: non-Fe components of iron ore that are retained in DRI products (e.g., SiO_2 , Al_2O_3 , CaO , MgO , MnO , TiO_2 , P_2O_5 and S). Gangue content of DRI typically is 3-5%.

Gangue Basicity: weight ratio of basic (CaO and MgO) to acid (SiO_2 and Al_2O_3) gangue components in DRI products.

IMSBC Code: International Maritime Solid Bulk Cargoes Code, as published by the International Maritime Organization (IMO), which contains provisions governing the carriage of solid bulk cargoes and the carriage in bulk of dangerous goods in solid form.

Iron Yield (%): total iron present in DRI that is recovered as liquid steel by melting.

Liquid Steel (or Melting) Yield (%): total DRI weight that is recovered as liquid steel by melting.

Metallic Iron Content (%): total DRI weight present as metallic iron exclusive of iron-bound oxygen (FeO).



Glossary of Direct Reduction Terms

Better understood in steelmaking as a direct function of the total iron percentage of the DRI feedstock and the metallization percentage of the DRI product.

Metallization (%): total iron present in DRI as metallic iron. Commonly used by the direct reduction industry (in relation to energy consumption) to define the efficiency of the direct reduction process.

Phosphorus Content (%): total phosphorus present as a percentage of total DRI weight, typically as P_2O_5 .

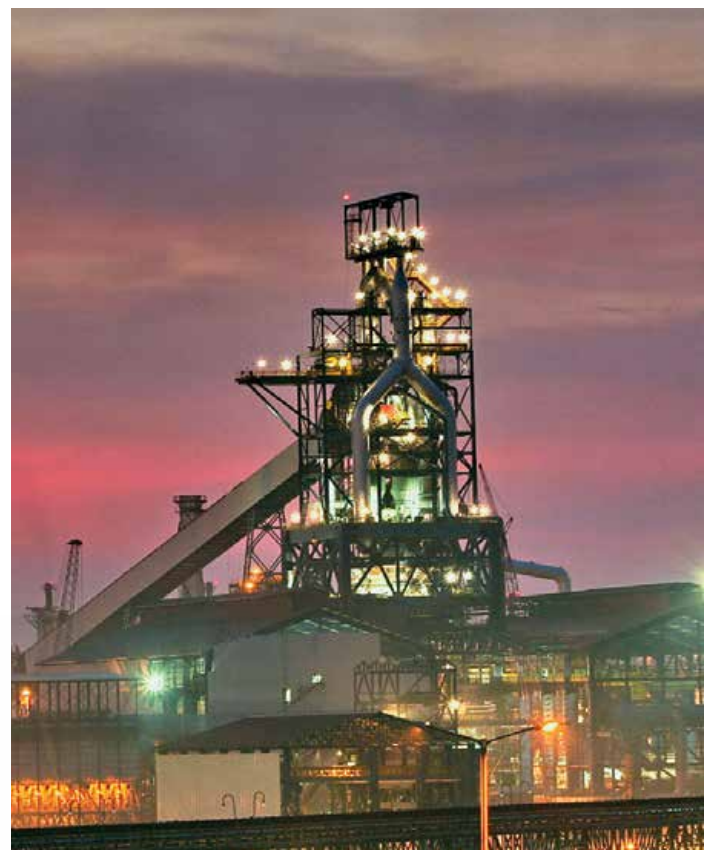
Pre-reduced Iron: partially reduced iron product in pellet, lump or briquette form produced from iron ore without melting. Metallization is less than 85%, and it is not suitable for steelmaking.

Residual Elements: non-ferrous metals that are volatilized or remain in the liquid steel bath upon melting. The most common residual elements in steelmaking are Cu, Ni, Cr, Sn, Mo, Pb, V and Zn. Total content of residual elements in DRI products is less than 0.02%.

Sponge Iron: term used in the early days of the direct reduction industry to describe non-briquetted DRI and pre-reduced iron.

Total Iron Content (%): total iron present in DRI products (metallic iron + oxygen-bound iron) as a percentage of total DRI weight.

Tramp Elements: term used for residual elements plus sulfur and phosphorus.





MIDREX News & Views

Société Internationale Métallique (SIM) selects Midrex and Primetals Technologies to build HBI plant in Quebec

Société Internationale Métallique (SIM) has chosen MIDREX® Direct Reduction Technology for a 2.0 million annual tons hot briquetted iron (HBI) plant to be located in the Bécancour Waterfront Industrial Park, a public-owned industrial park on the shores of the Saint-Lawrence River in Quebec, Canada. The site includes a year-round deep water port and is connected to major North American rail and road infrastructure.

Midrex Technologies, Inc. and its construction licensee Primetals Technologies will furnish the equipment and manage the technological aspect of the project. Construction is expected to begin in 2017, and the plant would start operations in 2019.

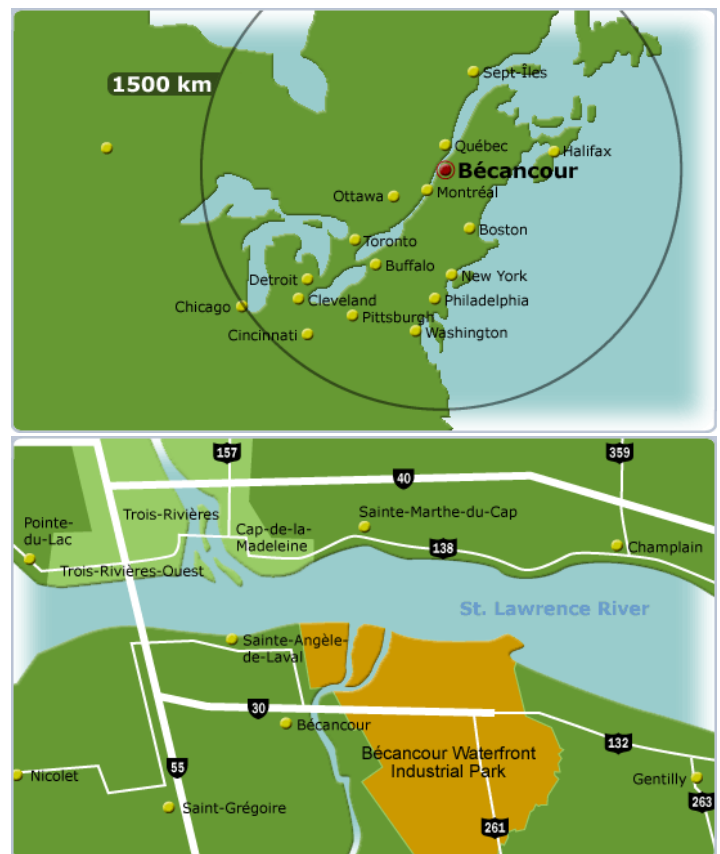
SIM was incorporated in 2014 specifically to develop an HBI plant in the Bécancour Waterfront Industrial Park. The project developer is International Metallics Corporation Inc., (IMC), an American project development company, whose sponsoring investors have a track record of developing similar projects of scale in the natural resources area. Involvement with direct reduced iron (DRI) by IMC principals dates back to the 1980s.

Daubeny B. Cooper III, President of Société Internationale Métallique, said, "The MIDREX® Process is the technology responsible for nearly two thirds of the world's annual DRI production, thus it was a logical choice for us. SIM is positioned to be a global leader in clean iron reduction and in the secondary processing of iron ore resources located in the province of Quebec."



James D. McClaskey, President and CEO of Midrex Technologies, Inc., said, "Midrex built two of its first ironmaking plants in Quebec nearly 40 years ago, so it is a pleasure for us to come back to Canada with our latest technology advances."

Heiner Röhr, CEO of Primetals Technologies (formerly Siemens VAI) Austria, said, "From the first HBI plant in Malaysia in the 1980s up to the HBI plants currently under construction in Russia and Texas, USA, Primetals Technologies has played a major role in building most of the world's HBI plants and has contributed with its iron and steel industry expertise to the development of this technology." ■





Technology should be...

- designed to fit your needs
- designed to work reliably
- designed to make life easier

DRI Technology **is** designed
by Midrex to work for **you.**

Christopher M. Ravenscroft: Editor

DIRECT FROM MIDREX is published quarterly by Midrex Technologies, Inc.,
2725 Water Ridge Parkway, Suite 100, Charlotte,
North Carolina 28217 U.S.A.,
Phone: (704)373-1600 Fax: (704)373-1611,
Web Site: www.midrex.com under agreement
with Midrex Technologies, Inc.

The publication is distributed worldwide by email
to persons interested in the direct reduced iron (DRI)
market and its growing impact on the iron
and steel industry.

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