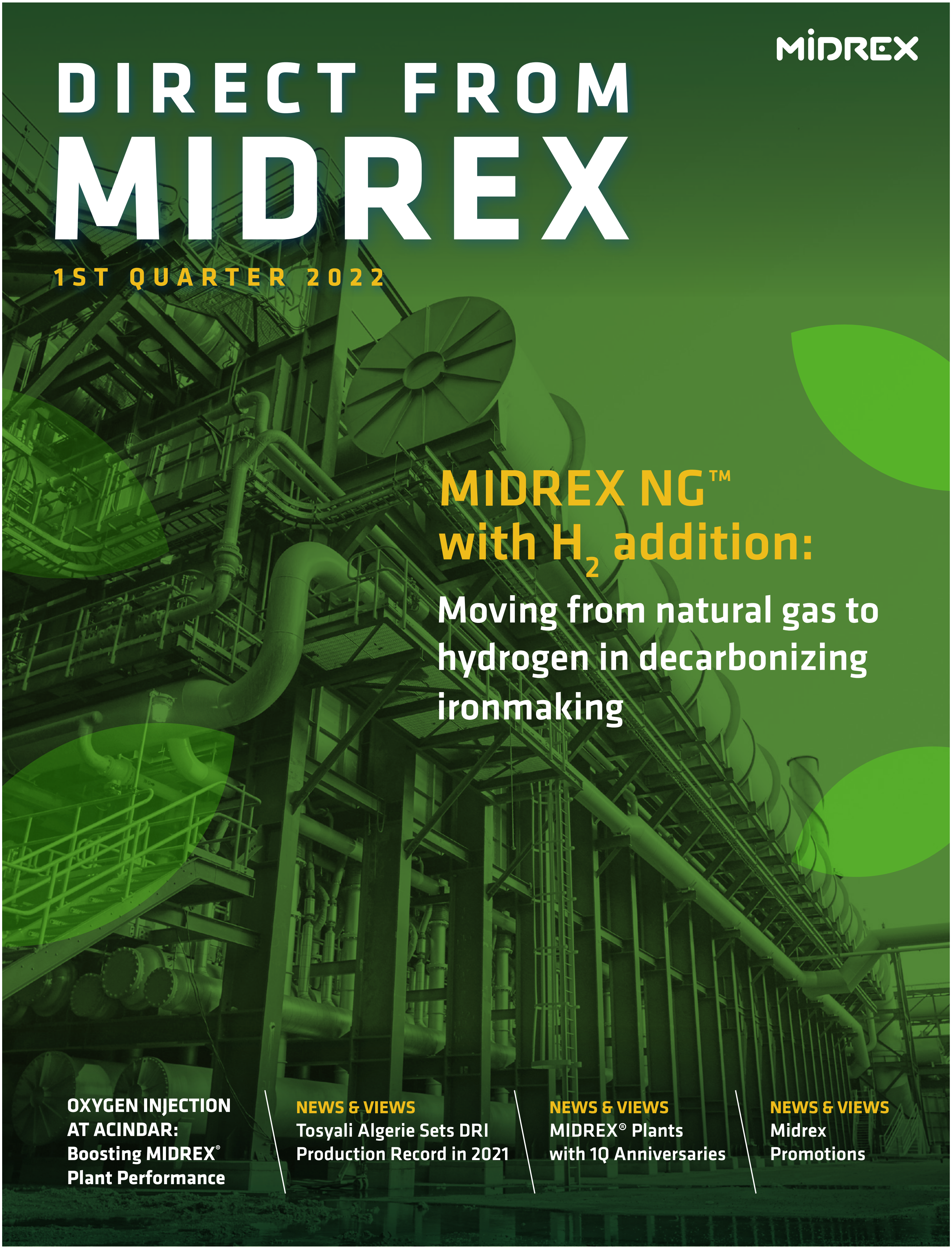
MIDREX

DIRECT FROM MIDREX

1ST QUARTER 2022



MIDREX NG™ with H_2 addition:

Moving from natural gas to hydrogen in decarbonizing ironmaking

OXYGEN INJECTION AT ACINDAR: Boosting MIDREX® Plant Performance

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COMMENTARY

MAKING THE MOST OF MOMENTUM

By Stephen C. Montague
President & CEO

2021 was a good year for Midrex despite various global social and corporate challenges, particularly those related to COVID. It is likely that each of us has been touched in some way by COVID, and we must reflect on these experiences to gain insight about how better to love and serve one another.

I have been involved in the direct reduction business since 1987 and can confidently say that no other time in my experience has shown more promise for our industry than today. It is being driven by the realization that we must reduce carbon dioxide (CO_2) emissions in iron and steel production.

In my early days, I remember our marketing team working to establish an identity for DRI as something more than a means to keep scrap prices "under control." We saw DRI as a complement to scrap, a source of low residual iron units to use with scrap that would allow the electric arc furnace (EAF) to compete with traditional integrated iron and steelmaking (blast furnace/basic oxygen furnace) to produce higher grade steel products. Today, more than 70 percent of all steel made in the US is by EAFs, and that includes all grades.

Part of the "why use DRI" story always has been lower CO_2 emissions when compared to the BF/BOF route. But it has only become mainstream since decarbonization of steelmaking became the industry focus. Even traditional integrated steel producers are looking to charge DRI in hot briquetted form (HBI) as a way to sustain their operations while reducing CO_2 emissions.

The International Energy Agency (IEA) forecasts an increase of almost 300 million tons of DRI production in the next 30 years (115 million tons in 2019 to 411 million tons in 2050), and momentum to secure low CO_2 DRI is already building. For example, Midrex signed three major plant contracts in 2021 totaling approximately 6.5% of the 2020 global DRI production. Even so, there's a long

COMMENTARY

"Midrex is well-positioned as we enter 2022 with a business model that takes the long view on products and services and focuses on the further development of green iron and steelmaking anchored by a corporate commitment to the growth and empowerment of our teammates."

way to go to reach annual production of 400 Mt.

I am very proud of the way Midrex has responded to the call to decarbonize steel production. It starts with how we view what we do. We want all of our teammates to be engaged in "innovation engineering" as we build a technology platform that offers flexible energy and iron ore options to move into hydrogen-based ironmaking at the client's pace. Finding affordable green energy or places to sequester CO_2 is going to be difficult in the near term and that's why we give our clients the flexibility to determine their pace of change: start with MIDREX H2™ using 100% hydrogen where green electricity is available or start with MIDREX NG™, capture and store CO_2, and easily transition to hydrogen over time utilizing MIDREX NG with H_2 addition.

There also will be challenges finding high-Fe iron ore at affordable prices as the market surges towards DRI. Referring to high-Fe iron ore as "DR-grade" is a misnomer because MIDREX® Plants have processed many commercially available iron oxide pellets and lump ores having low-Fe (62-65%). The primary reason DR plants use high-Fe iron ore is because of increased slag volumes and yield losses in the EAF – so high-Fe iron ores really should be classified as EAF-grade.

We are working with our owner, Kobe Steel, Ltd., and other leading steel industry engineering and equipment suppliers to help develop a more efficient melter to utilize DRI produced from low-Fe iron ore sources. In addition, we are creating a hot briquetted product specifically for use in blast furnaces that also makes use of low-Fe iron ores.

Midrex is well-positioned as we enter 2022, with a business model that takes the long view on products and services and focuses on the further development of green iron and steelmaking anchored by a corporate commitment to the growth and empowerment of our teammates. The world's oldest form of ironmaking, direct reduction, could be the steel industry's route to a sustainable future and Midrex has the momentum and right technology to lead the way.

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This issue of *Direct From Midrex* includes a case study of the addition of oxygen injection at the Acindar – Acindar Grupo ArcelorMittal MIDREX Plant and an article co-authored by Kobe Steel and Midrex on environmental sustainability with MIDREX NG™ with H_2 addition. Also, the News & Views section contains noteworthy Midrex-related events occurring during 1Q2022.

MIDREX NG™ with H_2 Addition:

Moving from natural gas to hydrogen in decarbonizing ironmaking



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INTRODUCTION

A lot has changed in the world of iron and steel production in the last 50 years. The cost efficiencies of oxygen steelmaking – a method in which pure oxygen is blown into large quantities of molten blast furnace iron (hot metal) and scrap to oxidize impurities such as carbon, silicon, phosphorus, and manganese – sounded the death knell for open hearth steelmaking. Today, the majority of global steel production (about 66%) is produced in basic oxygen facilities. [1]

The emergence of the electric arc furnace (EAF) provided the coup de grace for the open hearth.* Initially used for specialty steels and the manufacturing of steel alloys, the EAF began competing for the production of carbon steels (long products). Because EAFs could be sized to meet the needs of a specific market and used local or regional scrap resources for their iron charge, they became known as mini-mills or market mills. The percentage of EAF-based steelmaking has been steadily increasing due to its flexibility, economy-of-scale, and cost-competitiveness and now accounts for about 33% of global steel production [1] and over 70% in the US [2].

On the ironmaking side, coke-fueled blast furnaces were producing large volumes of hot metal to satisfy the growing need for steel products to support global industrial expansion. Direct Reduced Iron (DRI), introduced commercially in the late 1950s, was viewed as a niche material for use in EAFs where vast amounts of steel were not needed or where adequate supplies of scrap were not available. However, progressive EAF-based steel companies took notice of the positive effect DRI had on inclusions in scrap and found that they could produce even the highest-grade steels – and at a cost that few traditional integrated steelmakers could match.

However, the use of significant percentages of DRI in EAFs has given rise to one of the biggest iron and steel industry facelifts in history – decarbonization. Steel production via the DRI-EAF route has the lowest carbon dioxide (CO_2) emissions of any iron ore-based method. MIDREX® Plants based on clean-burning natural gas (MIDREX NG™) are seen as the most viable near-term response to the need to reduce CO_2 emissions associated with iron and steel production. As the means of producing sufficient volumes of hydrogen at competitive prices develop for use as fuel and reductant in direct reduction plants, Midrex can modify existing plants to replace natural gas with hydrogen and design new plants to use up to 100% hydrogen for their fuel and reductant (MIDREX H2™).

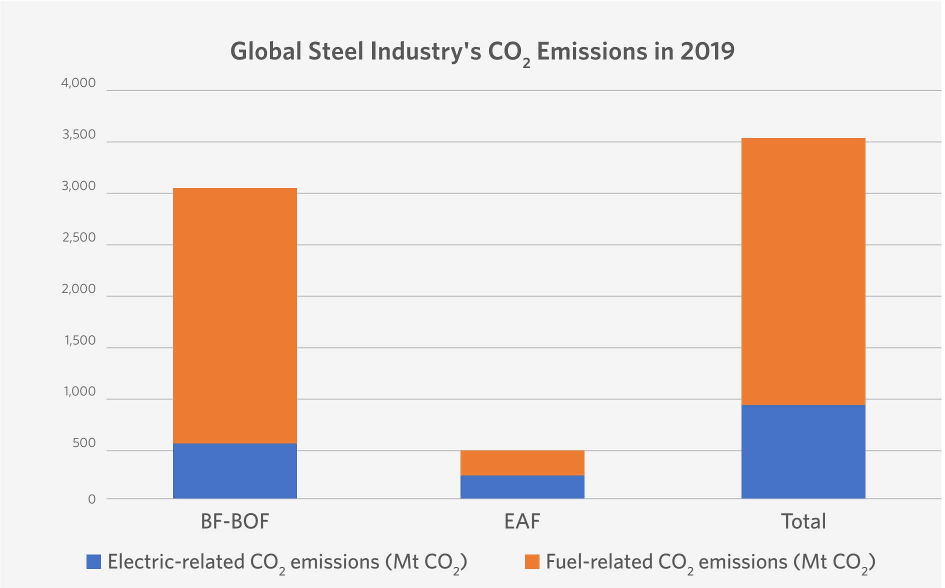

FIGURE 1. *The global steel industry emitted around 3.5 gigaton of CO_2 emissions in 2019. Of this, 2.6 Gt were from fuel use (direct emissions) and 0.9 Gt was from electricity use (indirect emissions). Source: Global Efficiency Intelligence blog, January 6, 2021*

IRON & STEEL CO_2 INTENSITY

The direct CO_2 intensity of crude steel has been relatively constant (within a 20% range) during the past two decades, and in the last couple of years has returned to roughly the 2000-08 level [3]. According to the International Energy Agency (IEA), the CO_2 intensity of crude steel needs to fall an average of 2.5% annually between 2018 and 2030. Achieving this reduction and maintaining it after 2030 will not be easy.

Energy efficiency improvements spurred much of the reduction in recent years, returning CO_2 intensity to previous levels, but opportunities for further efficiency improvements will likely soon be exhausted. Thus, innovation to commercialize new low-emissions process routes, including those integrating CCUS (Carbon Capture, Utilization, and Storge) and hydrogen, in the upcoming decade will be crucial to realize the long-term transformational change required.

While the energy intensity of steel has gradually fallen since 2009, expanding production from 2009 to 2014 raised total energy demand and CO_2 emissions. After a small decline between 2014 and 2016, energy demand and CO_2 emissions increased in 2017 and 2018, primarily as a result of higher steel production. Based on total steel industry emissions ***(see Figure 1)*** and global annual CO_2 emissions (52 Gt, as reported in UN Emissions Gap Report 2020, or 33 Gt in 2019, as reported by IEA), the global steel industry accounts for around 7-11% of total global CO_2 emissions [4].

Substantial cuts in total energy demand and CO_2 emissions will be needed by 2030 to be on track with the IEA Sustainable Development Scenario (SDS), which envisions a major transformation of the global energy system that is in keeping with the three main UN Sustainable Development Goals (SDG): social development, environmental protection, and economic growth.

Short-term CO_2 emissions reductions could come largely from energy efficiency improvements and increased scrap collection to enable more scrap-based production. Longer-term reductions would require the adoption of new DRI and smelt reduction technologies that facilitate the integration of low-carbon electricity (directly or through electrolytic hydrogen) and CCS (carbon capture and storage), as well as material efficiency strategies to optimize steel use.

IRONMAKING USING HYDROGEN

Using hydrogen (H_2) to make iron is not a new concept. Therefore, it is more of an evolution than a breakthrough that the MIDREX Process can be adapted to accommodate more hydrogen as it becomes economical to do so. The MIDREX Process uses CO and H_2 to accomplish reduction, which is the removal of oxygen from ore (opposite of oxidation). There are many reactions occurring in the direct reduction reactors, but the primary ones are shown in *Figure 2*. Iron is represented by Fe and methane (primary component of natural gas) is represented by CH_4.

In the case of the standard MIDREX Process using natural gas (MIDREX NG), the typical gas content is 55 mol % H_2 and 36 mol % CO with the balance comprised of H_2O, CO_2, N_2, and CH_4. Since reduction occurs between 800 and 900°C, temperature control is a very important consideration. Reaction 1 is endothermic (requires heat) while reaction 2 is exothermic (gives off heat). Reforming reactions are highly endothermic and mostly done in the reformer, although some in-situ reforming is taking place in the shaft furnace. The thermal balancing of Reactions 1 & 2 makes the MIDREX Process easy to control because the temperature in the furnace stays relatively constant. Since 1969, MIDREX Plants have produced more than 1 billion tons of DRI made with over 50% hydrogen.

Direct reduction with higher levels of hydrogen has been proven in a MIDREX Shaft Furnace. The FMO MIDREX Plant in Venezuela uses a steam reformer, and H_2/CO has varied from 3.3 to 3.8. There are also six MIDREX Modules that utilize gas made from coal, and these have H_2 to CO ratios from 0.37 to 2.0. Thus, the MIDREX Process has successfully produced DRI at H_2/CO ratios from 0.37 to 3.8.

On a smaller scale, Midrex has vast experience with hydrogen reduction. In the late-1970s to mid-1980s, Midrex operated a pilot plant at its Research & Development Technology Center, which is shown in *Figure 3*. The pilot was built to test and demonstrate the Electrothermal Direct Reduction Process (EDR). While the purpose of this pilot plant was not to test hydrogen reduction, several campaigns utilized a very high hydrogen content – as high as 4.2 H_2/CO in 1986.

Reduction (removal of oxygen from iron ore)

1. $Fe_2O_3 + 3H_2 \longrightarrow 2Fe + 3H_2O$ (endothermic)
2. $Fe_2O_3 + 3CO \longrightarrow 2Fe + 3CO_2$ (exothermic)

Carburization (addition of carbon to iron)

3. $3Fe + CO + H_2 \longrightarrow Fe_3C + H_2O$
4. $3Fe + CH_4 \longrightarrow Fe_3C + 2H_2$
5. $3Fe + 2CO \longrightarrow Fe_3C + CO_2$

Reforming (conversion of CH_4 to CO and H_2)

6. $CH_4 + CO_2 \longrightarrow 2CO + 2H_2$
7. $CH_4 + H_2O \longrightarrow CO + 3H_2$

FIGURE 2. *Ironmaking Reactions*

FIGURE 3. *Multi-purpose Pilot Plant at Midrex R&D Technology Center circa 1990.*

MIDREX HYDROGEN IRONMAKING

Steelmakers - especially European steelmakers – face a daunting challenge in transitioning to near carbon-free ironmaking. Traditional operation of blast furnace/basic oxygen furnace (BF-BOF) steel mills is unlikely to meet the target CO_2 reductions in the Paris Agreement of 2016, and BFs are generally old and need expensive relines. EAFs will need significant amounts of ore-based metallics (pig iron and DRI/HBI) to dilute the residuals in scrap. Pig iron production is predominantly BF-based and there is but one DRI plant currently operating in the European Union (EU), ArcelorMittal Hamburg. Hydrogen is not available in the quantities nor the cost needed to be competitive, and no one can predict when it will be.

However, the same basic process technology that is in use by ArcelorMittal Hamburg – MIDREX NG – is the first step in the Midrex transition to 100% hydrogen ironmaking. MIDREX NG already uses significant amounts of hydrogen in its reducing gas and can cut CO_2 emissions by 35% compared to the coke oven/blast furnace (CO/BF) ironmaking route. For a typical MIDREX NG plant, up to 30% of the natural gas input to the plant can be replaced with hydrogen without any changes to the process equipment. Operation with higher percentages of hydrogen is achievable with low-risk equipment modifications.

Therefore, a MIDREX NG plant operating with 100% natural gas could be built now, while the availability of hydrogen in sufficient quantities and at a competitive cost is being developed, and later transitioned to use up to 100% hydrogen.

Midrex can design greenfield plants based on MIDREX H2 technology specifically for 100% hydrogen operation or for majority hydrogen operation with minimal natural gas usage. Hydrogen for a MIDREX NG with H_2 addition or MIDREX H2 plant can be obtained from various sources including carbon capture (see later in this article).

MIDREX NG with H_2 Addition

A MIDREX NG plant can be equipped to operate with H_2 substituted for some or most of the natural gas normally utilized by the plant. This evolutionary plant technology provides the flexibility to replace any percentage of the natural gas (NG) feedstock with H_2 based on the plant's operating goals. This provides the flexibility the plant needs to respond to ever changing market needs and feedstock availability. The flowsheet shown in *Figure 4* indicates the three H_2 injection points when utilizing MIDREX NG with H_2 addition technology. Any existing MIDREX NG plant can be easily converted for hydrogen addition.

Table I indicates the H_2 injection point and when it is used based on the percentage of NG replaced by H_2.

In the early stages of H_2 transition, the small amount of H_2 added is injected downstream of the reformer without preheating. From 0-75% NG replacement, the hydrogen is only utilized in the process downstream of the MIDREX Reformer. This facilitates optimizing reformer operation so it can be held as close to the MIDREX NG operating conditions as possible during H_2 transition while maximizing the reducing gas quality to the reduction furnace. In order to maintain the DRI product carbon as far into the replacement as possible and still continue to reduce the carbon footprint, when the NG replacement percentage reaches ~75%, H_2 is added to the reformer burners. H_2 injection is introduced upstream of the MIDREX Reformer between ~85-100% NG replacement to maintain reducing gas quality and enhance energy efficiency in the process.

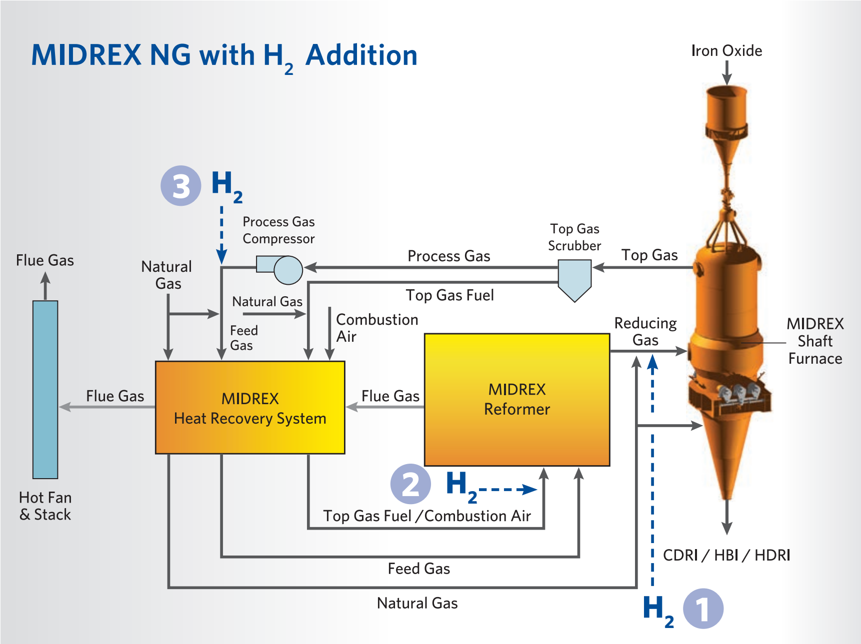

FIGURE 4. *H_2 Injection Points Based on Percentage of NG Replaced by H_2*

	H_2 injection point	NG replacement by H_2 (%)
1	Downstream of Reformer	0 - 90%
2	Burner fuel	75 - 100%
3	Upstream of Reformer	85 - 100%

TABLE I. *H_2 Injection Point Based on Percentage of NG Replaced by H_2*

Conversion to MIDREX NG with H_2 Addition – Philosophy

The Midrex philosophy for converting from MIDREX NG to MIDREX NG with H_2 addition is as follows:

- Maintain full plant capacity across the full transition range.
- Maximize the DRI carbon at each point across the full transition range.
- Maintain optimum reducing gas quality >9.5 to the reduction furnace can be achieved with H_2 addition downstream of the reformer up to 80% NG

replacement by H_2. Above 80% NG replacement, the H_2 addition is transitioned to the feed gas side of the reformer.
- Apply the standard type of centrifugal compressors used by Midrex (with the addition of a 3rd stage of compression for higher NG replacement >80%).
- Maintain the required amount of thermal mass flow to support the increasing endothermic reduction load. Higher H_2 endothermic reduction load in the furnace requires a larger thermal mass flow at the bustle since the H_2/CO increases as H_2 addition increases ***(See Figure 5)***. The bustle gas flow per ton is increased steadily over the transition to 100% H_2, as the H_2/CO ratio rises to infinity.
- Minimize equipment modifications or the addition of new equipment to the plant.

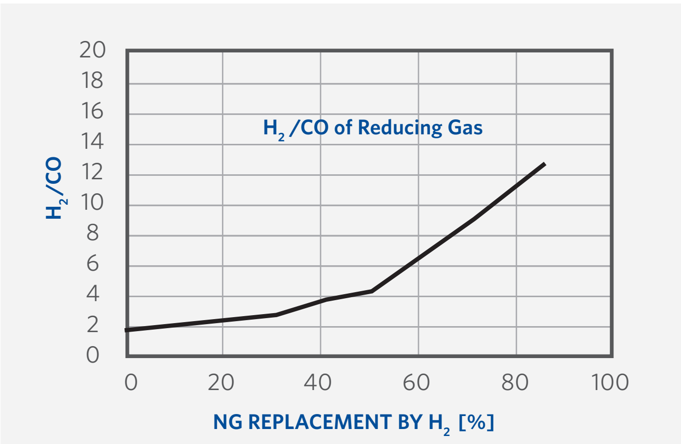

FIGURE 5. *H_2/CO Trend of Reducing Gas*

Conversion to MIDREX NG with H_2 Addition – Equipment

An existing MIDREX NG plant requires very little equipment modification to be converted for H_2 addition. No equipment modifications are required to the feed/discharge systems, reduction furnace, scrubbers, process piping, reformer, oxygen injection systems, carburizing gas injection systems, product cooler, and HBI cooling systems. This section describes the major plant areas that need to be considered and modified to accommodate the full range of operation from 100% NG to 100% H_2.

1. Process Gas Compressors

Increasing addition of H_2 to the loop requires that the total process gas flowrate needs to increase. The increasing flow is driven by the fact that reduction by hydrogen is more endothermic than reduction by CO. The higher process gas flowrate is needed to maintain the energy balance (thermal mass) in the shaft furnace. For an existing plant, the process gas compressor capacity will become limiting at about 30% NG replacement. The addition of a single additional compression stage allows for operation across the full transition range.

2. Heat Recovery Area

The heat transfer load on the heat recovery system decreases as H_2 addition increases. In order to maintain high energy efficiency and operational flexibility, some modifications are needed for the heat recovery system. For example, additional piping and valving adds the ability to control and balance the performance of the heat recovery bundles, which along with some minor equipment additions allows the system to operate across the full range of the transition.

3. Cooling Gas Compressor Area

If the MIDREX NG Plant is designed to discharge CDRI (cold DRI) either directly from the reduction furnace or through an external product cooler at NG replacement levels > ~70%, an additional small parallel compression step needs to be installed. As the NG replacement progresses and NG is withdrawn from the cooling zone, the gas composition reverts to mostly N_2 or a mixture of H_2 and N_2, which drives the cooling gas requirement from 650 Nm^3/t-DRI up to as much as 1,000-1,100 Nm^3/t-DRI.

4. Process Water Areas

The load of cold process water and hot process water changes as H_2 addition increases. ***Figure 6 (next page)*** indicates one example of this water flow trend with NG replacement. To take advantage of this reduction in hot water demand and increase in cold water demand, the installation of piping and valves to support this operational change need to be made. Additionally, more cooling tower capacity, recirculation and supply pumps with interconnecting piping for the higher H_2 operation are required to support the higher condensation and cooling loads on these systems.

Effect on Plant Operation and DRI Carbon

DRI carbon is derived from the NG consumed in a MIDREX Plant. Maintaining carbon in HDRI (hot DRI) is possible across most of the range from 0-100% H_2 within specified limitations. As the transition to 100% NG replacement progresses, maintaining higher percent product carbon is not possible. For example, HDRI carbon would be ~1.5-2.0% in the case of 30% NG replacement and ~1.3-1.5% in case of 75-85% NG replacement ***(See Figure 7)***.

Though carbon in CDRI is higher than in HDRI since carbon loss occurs at the hot transport conveyor, this drop in carbon content is directly related to the removal of carbon atoms from the process by NG replacement. Operation of the process and the priority given to which NG users are replaced first is optimized to retain as much carbon in the HDRI as possible for as long into the transition as possible.

Carbon Capture, Utilization & Storage (CCUS)

CO_2 removal is not necessary in a MIDREX NG plant or a MIDREX NG with H_2 addition plant because the CO_2 is recycled back into the reformer and converted into CO – a kind of carbon loop. However, it is possible to include a CO_2 removal system in these plants if it is economical (e.g. carbon tax credits) and if there is a means to store or utilize the CO_2. Additionally, Midrex has engineered CO_2 removal systems for plants based on coal gasification – which is required for the process – that can take advantage of carbon capture and storage (CCS).

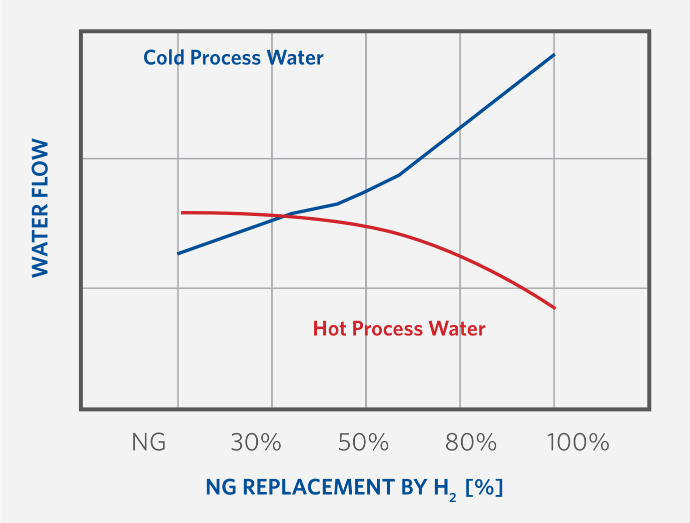

FIGURE 6. *Cold and Hot Process Water Flow during H_2 Transition*

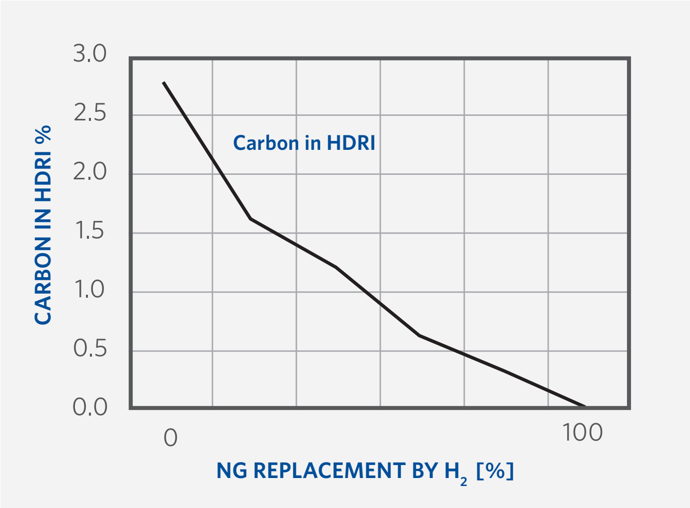

FIGURE 7. *Carbon in the DRI as H_2 Replacement increases*

There are two options to separate CO_2 and capture it:

1. Remove CO_2 from the top gas fuel, which is used in the reformer for heating. CO_2 emissions can be reduced by 0.25 to 0.35 t/t DRI.
2. Remove CO_2 from the flue gas of the reformer, after heat recovery. CO_2 emissions can be reduced by ~0.5 t/t DRI (for a 2.0 million t/y plant, that means an additional 500,000 to 1,000,000 t/y of CO_2}.

The two options can be used together. Each option removes about half of the CO_2 being emitted, making it is possible to achieve near zero CO_2 emissions. Any MIDREX Plant can be built with CO_2 removal or provisions to install CO_2 removal at a later date, when the economics are more favorable.

CONCLUSION

Iron and steelmaking are a large contributor to the emission of greenhouse gases, notably CO_2. The industry is facing increasing pressure to de-carbonize, but there are many challenges to overcome. Hydrogen ironmaking is a real possibility for future (near) carbon-free steelmaking, but there are significant uncertainties around the availability of hydrogen in volumes needed for ironmaking and at a competitive cost.

The best possibility for reducing the steel industry's CO_2 footprint is the use of hydrogen as an energy source and reductant for iron ore in the MIDREX Process. Today, reduction of CO_2 emissions by 50% (over BF/BOF) is achievable and well proven. Although the hydrogen comes from natural gas ('blue hydrogen'),the process is flexible enough to accept 'green' hydrogen produced from water electrolysis as it becomes available and economical, which will further reduce CO_2 emissions.

Midrex offers technologies that bridge the transition from 100% natural gas to 100% hydrogen direct reduction: MIDREX NG, for the immediate and mid-term future allowing up to 30% natural gas replacement with hydrogen without equipment modifications, MIDREX NG with H_2 addition, which provides a plant the flexibility to operate on any mixture of natural gas and hydrogen (up to 100% hydrogen) with some low-risk modifications, and MIDREX H2, which is designed to use up to 100% hydrogen in a MIDREX Shaft Furnace as the feed gas. All MIDREX Process configurations can operate on the industry's broadest range of raw materials and reducing gas sources including hydrogen from carbon capture, utilization, and storage (CCUS).

Ultimately, MIDREX H2 holds great promise for advancing the decarbonization of ironmaking leading to near zero-emission steelmaking. However, investments for the future can be made today in plants based on MIDREX NG technology, knowing they are readily adaptable as we advance toward the Hydrogen Economy.

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OXYGEN INJECTION AT **ACINDAR**

BOOSTING MIDREX® PLANT PERFORMANCE

By GEOFF WALLWORK,
Principal Process Engineer - Midrex Global Solutions

INTRODUCTION

There are various designs of the oxygen injection system presently installed in MIDREX® Direct Reduction Plants. These designs range from the original system installed at SIDOR in Venezuela, where air and oxygen were simply injected into the reformed gas duct, to the first oxygen injection nozzles installed in the enrichment natural gas ports at Acindar* in Argentina, to similar systems installed in recent years with minor variations to the original design. While oxygen injection systems have become a common feature in many MIDREX Plants, Midrex continues to research potential improvements to the system, especially with the advancement of Computational Fluid Dynamics (CFD) modeling.

This article will trace oxygen injection from research and modeling to improvements in the new system implemented at the Acindar plant. We will present an overview of the oxygen injection system, as it is helpful to understand the purpose of oxygen injection and its relationship to the operation of a MIDREX Plant. Then we will discuss recent design and operational changes to the oxygen injection system developed through CFD modeling and implemented in the Acindar plant.

PURPOSE OF OXYGEN INJECTION

Reduction reaction rates occurring inside the shaft furnace increase as the temperatures in the reduction zone increase. There are limitations on how much the temperature can be increased but generally, for each 10° C increase in the bustle gas temperature, a plant can realize 1.5-2.0% increase in production.

The oxygen reacts exothermically, producing mostly H_2O and CO_2, thereby raising the bustle gas temperature before reaching the furnace. When the oxygen reacts with methane in the bustle gas, it also will generate H_2 and CO, thereby increasing the bustle gas flow. Part of this increase is achieved when oxygen reacts with methane from the reformed gas and the enrichment natural gas in the bustle line, and part is achieved when the bustle gas enters the furnace bed and reaches equilibrium through reforming and carbon deposition reactions on the DRI (acting as a catalyst), referred to as in-situ reforming.

There is a drop in temperature from the bustle gas to the bed temperature due to the endothermic reforming and carbon deposition reactions as they go to equilibrium. So, there are two factors at work: 1) additional bustle gas flow with additional H_2 and CO for reduction, and 2) additional temperature not only in the bustle gas but more importantly in the furnace bed where it will improve the reduction kinetics.

Without oxygen injection, the maximum bustle gas and bed temperatures are limited by the reformed gas temperature exiting the reformer minus heat losses due to the piping, as well as the addition of relatively cooler enrichment natural gas. To overcome these temperature losses and raise the bed temperature, oxygen may be injected at the reformed gas mixer.

However, there are limitations. The upper limit of oxygen injection is determined primarily by the maximum bustle gas temperature allowed before coated DRI starts to form clusters and disrupts the material flow in the furnace. It should be noted that the oxide should be coated prior to entering the furnace to permit higher reduction zone temperatures and minimize the potential for clustering. The amount of oxygen utilized by a particular MIDREX Plant will vary but is typically ~15 Nm^3/t DRI.

PURPOSE OF ENRICHMENT NATURAL GAS

It is helpful to understand the role of enrichment natural gas when discussing oxygen injection, as these gases are being injected in the same location within the plant. Common to all MIDREX Plants, natural gas is injected into the reformed gas at the reformed gas mixer. This natural gas injection is referred to as enrichment natural gas (ENR). Adding enrichment natural gas to the bustle prevents uncontrolled methanation reactions from occurring in the shaft furnace. When enough methane is added, the reaction between methane and CO_2 and H_2O shifts to reforming and generates reductants for reducing the oxide and promotes in-situ reforming in the shaft furnace.

In-situ reforming is the reforming of natural gas over the metallic iron in the reduction zone of the furnace. The metallic iron acts as a catalyst to increase the rate of the reforming reaction. To promote in-situ reforming, it is necessary to have three key parameters: heat, oxidants, and hydrocarbons (methane or higher). Sufficient heat must be available, as the reforming reaction is endothermic. By increasing bustle gas temperature, oxygen injection provides the heat necessary for the in-situ reforming reactions, as described in ***Figure 1***.

Oxidants (CO_2 and H_2O), as well as hydrocarbons (CH_4 and higher) must be available to react and form the reductants (CO and H_2) for in-situ reforming. Oxidants are available from the bustle gas CO_2 and H_2O, while hydrocarbons are available from the enrichment natural gas.

With sufficient heat, methane, and oxidants, the reforming reaction proceeds to the right (***see Figure 1***), forming the reductants until reaching equilibrium in the reduction zone. If there is insufficient methane, the reactions proceed in the reverse direction to the left (***see Figure 1***), producing methane and is referred to as methanation. This direction is undesirable.

Enrichment natural gas also is used to increase the amount of carbon in the direct reduced iron product. Once enough enrichment natural gas is added to prevent methanation, the operator has the flexibility to add additional enrichment natural gas depending on the type of product and amount of carbon desired. The hydrocarbons in the enrichment natural gas "crack" to form carbon and hydrogen. The carbon is deposited on the bed, while the hydrogen becomes additional reductant in the furnace.

CO2 Reforming
$CH_4 + CO_2 + Heat \dashrightarrow 2CO + 2H_2$

H2O Reforming
$CH_4 + H_2O + Heat \dashrightarrow CO + 3H_2$

FIGURE 1. *In-situ reforming reactions*

Oxygen Injection System Description

The oxygen injection system can be divided into two parts: the oxygen injection control skid and the reformed gas mixer. They are highlighted on this drawing of the oxygen injection system ***(Figure 2***).

Oxygen Injection Control Skid

The oxygen injection control skid (***see Figure 3***) typically is located near the reformed gas mixer. The control skid contains the equipment and instruments required for controlling the flow and pressure of the oxygen. The control skid also contains the purge gas accumulator and controls required for purging the oxygen nozzles before and after oxygen injection operation. The horizontal tank is the purge gas accumulator. The control skid has not undergone any significant changes and is not a primary focus for improvement.

Reformed Gas Mixer

The reformed gas mixer is located on the reformed gas duct between the reformer and the shaft furnace. The enrichment natural gas is injected through a type of bustle ring header, shown in ***Figure 4***. The natural gas fills the bustle ring header and enters the reformed gas duct typically through eight ports. Once the operator enters the desired bustle gas percent methane, the flow of enrichment natural gas is modulated by a control valve to achieve the desired methane percentage. The methane analyzer provides the measured methane content in the bustle gas and adjusts the flow of enrichment natural gas accordingly.

Figure 5 (next page) shows both an outside and inside picture of the reformed gas mixer. In the outside picture, you can see the natural gas inlet pipeline and the bustle ring header. Note that the mixer includes oxygen injection with the nozzles inserted into the enrichment natural gas ports. The inside picture shows the brick orifice, enrichment natural gas ports and the

Oxygen Injection System

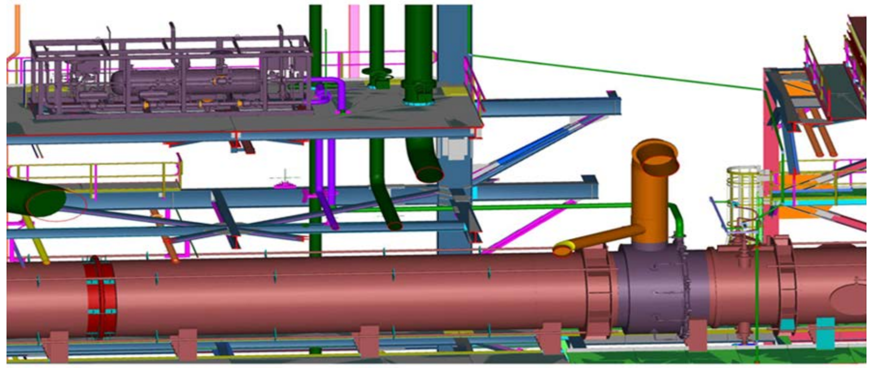
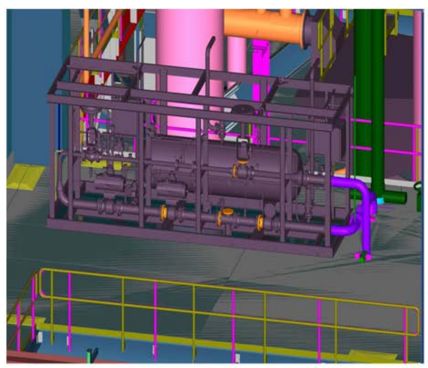


FIGURE 2. *Locations of oxygen injection control skid and reformed gas mixer.*

Oxygen Injection Control Skid



Typically located near the reformed gas mixer

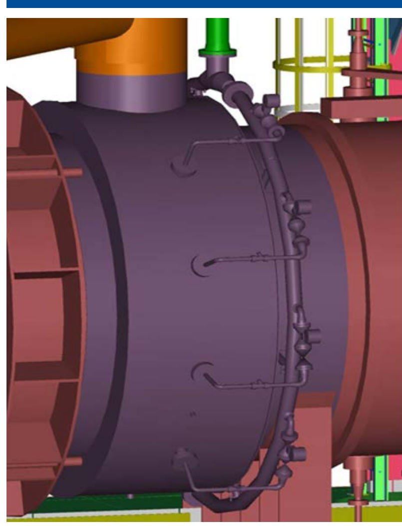
Contains the equipment and instruments required for controlling the flow and pressure of the oxygen

Contains the purge gas accumulator and controls required for purging the oxygen nozzles

Has not undergone any significant changes

FIGURE 3. *The oxygen injection control skid.*

Reformed Gas Mixer



Enrichment Natural Gas

- Bustle Ring Type Header
- Eight Gas Ports (Typically)
- Controlled via Bustle Gas Methane Percent
- Control Instruments include Methane Analyzer and Modulating Control Valve

FIGURE 4. *The reformed gas mixer - enrichment natiral gas.*

oxygen injection nozzles.

The reformed gas mixer is also the location for injecting oxygen into the reformed gas duct. The oxygen nozzles are inserted into the enrichment natural gas ports. By locating the nozzles in these ports, the enrichment natural gas provides cooling to the oxygen injection nozzles. The oxygen nozzles slightly protrude from the enrichment natural gas ports.

The brick orifice upstream of the oxygen nozzles and enrichment natural gas ports protects the flames from being blown out by the reformed gas and allows the flames to be sufficiently away from the refractory wall.

Once the operator enters the desired bustle gas temperature, the flow of oxygen is modulated by a control valve until the desired bustle gas temperature is achieved. Control logic will automatically open and close oxygen nozzles per a set sequence based on the total oxygen flow required to achieve the desired bustle gas and bed temperatures.

RECENT SYSTEM DESIGN CHANGES

To gain a better understanding of the typical system, a CFD model was generated of the duct between the reformer and the shaft furnace, which includes the reformed gas mixer ***(Figure 6)***. At Acindar, there is a second smaller 90-tube reformer that can feed additional reformed gas into the system. This is labeled as the secondary RG inlet in the model picture. Once the model was generated for the system, changes were implemented and studied to develop an optimized system based on the modeling results.

Reformed Gas Mixer

FIGURE 5. *Reformer Gas Mixer- Outside / Inside Views*

CFD Modeling

CFD Modeling was carried out to better understand what would be occuring in the Acindar system and design a new, optimized system to the extent possible.

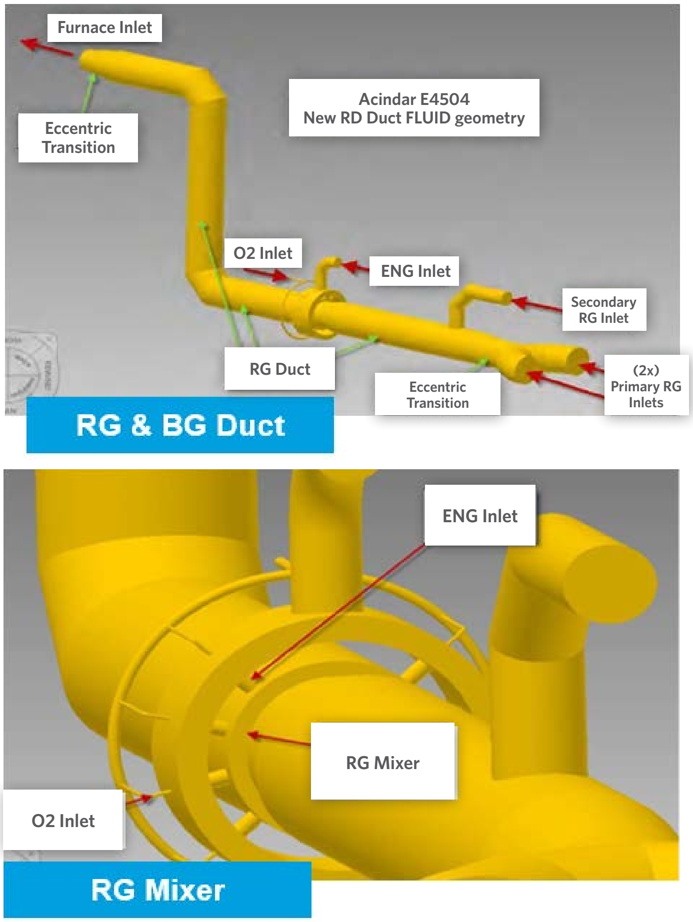


FIGURE 6. *CFD Modeling*

At the beginning of the study for optimizing the oxygen injection system for Acindar, there were three primary goals:

- **to increase the flexibility of the oxygen injection system.** The target was to accommodate a wide range of reformed gas, oxygen, and enrichment natural gas flows over a broad range of production rates, all while maintaining a stable and reliable flame at the oxygen nozzle. Typically, oxygen injection is used as a sort of booster once the reformer is nearing its capacity. However, ArcelorMittal Acindar has determined that oxygen injection has a benefit even if the reformer is not at full capacity. Acindar desired the flexibility to operate oxygen injection at both relatively low production rates as an example when suffering natural gas curtailments, or low market, as well as at high production rates.
- **to improve the oxygen injection nozzle life.** The oxygen injection nozzle is primarily protected with the enrichment natural gas acting as a shroud gas. However, relatively high temperatures can be present at the nozzle tip with the potential for damage to the nozzle.
- **to improve the refractory life, especially in the area of the oxygen nozzles on the reformed gas mixer.** The same relatively high temperatures that could potentially damage the nozzle tips could also potentially shorten the life of the refractory in the duct.

PRIMARY SYSTEM CHANGES

After extensive CFD modeling, changes were made to the system to achieve the stated goals. The primary changes included the enrichment natural gas (ENG) port diameter, the oxygen injection nozzle tip penetration into the duct, minimum and maximum flows for oxygen and for enrichment natural gas, and the addition of a secondary enrichment natural gas port.

ENG Port Diameter

After review of the CFD models, an optimum velocity range for the enrichment natural gas at each port in the reformed gas mixer was determined. This velocity range ensured adequate cooling of the oxygen nozzles and refractory wall while maintaining a stable flame at the nozzle. To achieve the optimum velocity range, the enrichment natural gas port diameters were decreased.

Oxygen Injection Nozzles Velocity

Similar to the enrichment natural gas, an optimum velocity range for each oxygen injection nozzle was determined. The optimum velocity range maintained a stable flame while penetrating further towards the center of the reformed gas duct and away from the refractory wall. To obtain the optimum velocity range, minimum and maximum oxygen flows per nozzle were determined. Control logic was established to automatically open and close the individual nozzles as required based on maintaining the oxygen velocity while reaching the desired bustle gas temperature.

Figure 7 shows an example of the velocity vectors at the enrichment natural gas port and oxygen nozzle from the CFD model. The enrichment natural gas port is shown in blue and the oxygen nozzle is shown in green.

Enrichment Natural Gas & Oxygen Flow
Velocity Vectors

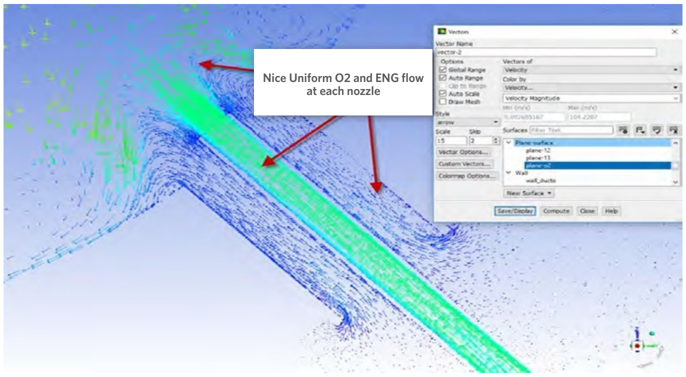


FIGURE 7. *Enrichment natural gas port and oxygen nozzle.*

Oxygen Nozzle Tip Penetration

Various oxygen nozzle tip penetrations were modeled and reviewed. Penetration is defined in this article as how far the nozzle tip protrudes into the reformed gas duct beyond the refractory wall. To determine the optimum penetration, various parameters were reviewed including the flame shape, temperature at the nozzle tip and the refractory wall temperatures.

An optimum penetration length provided acceptable temperatures at both the nozzle tip and refractory wall.

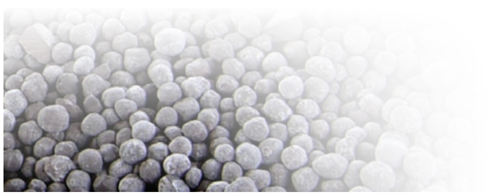
Figure 8 is an example of the CFD model when comparing two different nozzle tip penetration lengths. On the first model (Detail 2.1.1), the temperature profile at the nozzle tip is relatively high, so it was recommended to change the penetration length. In the second model (Detail 2.1.2), the penetration length has been decreased, and the temperature profile at the nozzle tip is much cooler.

Also, from these models, it can be seen that the temperature profile at the refractory wall or hot face is relatively cool and should lead to an improved life of the refractory. (Note that the flames reach temperatures as high as 2500˚ C.)

Min and Max ENG flows

The CFD modeling also determined the minimum and maximum flows of enrichment natural gas when operating with oxygen injection. The range of flows had to provide a stable flame when varying the reformed gas flow and oxygen flow while sufficiently cooling the oxygen nozzle and refractory wall.

It was determined that the maximum enrichment flow allowed at the oxygen nozzles was less than the amount of enrichment natural gas required to produce high carbon DRI at high production. Therefore, a secondary enrichment natural gas inlet nozzle was added to the bustle gas downstream of the reformed gas mixer ***(Figure 9)***. By splitting the enrichment natural gas flow between the reformed gas mixer and the secondary inlet nozzle, the plant has the flexibility to operate within the full range of enrichment natural gas flows. The flow at the reformed gas mixer can be safely limited when operating with oxygen while the secondary inlet fulfills the requirements for high carbon product at high production.



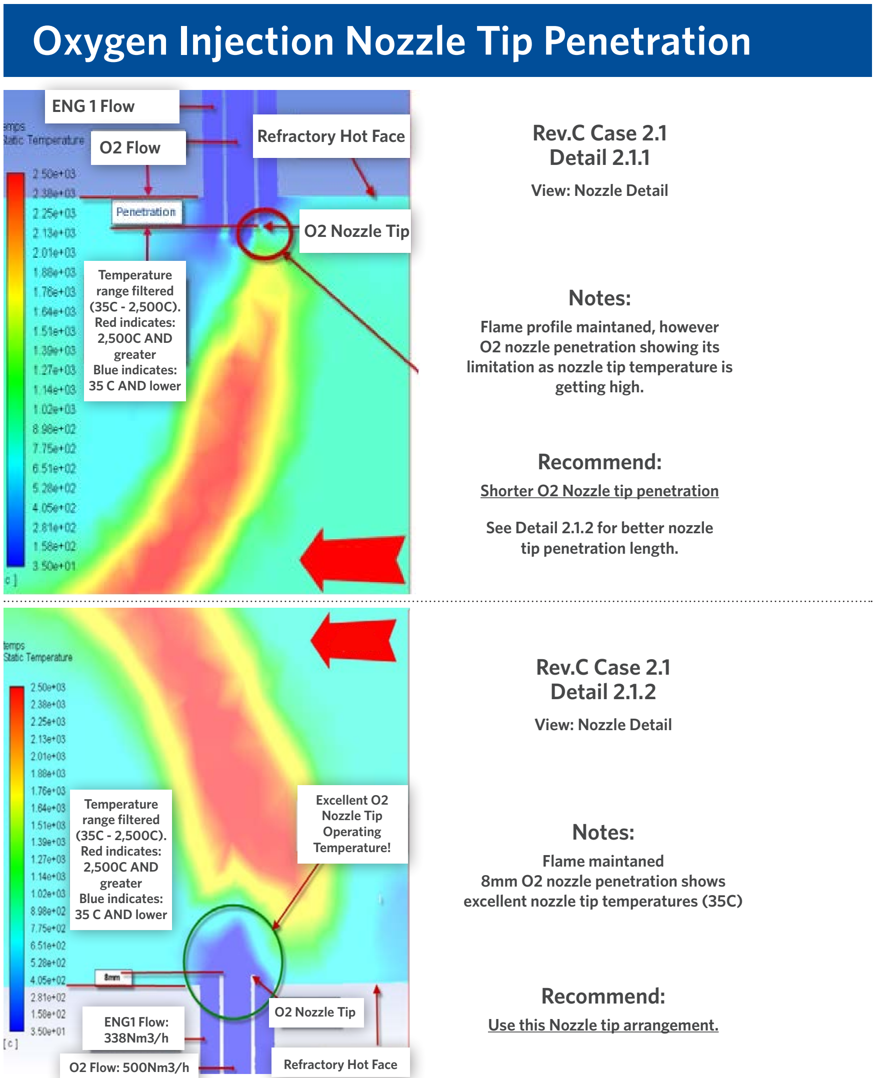


FIGURE 8. *CFD model when comparing two different nozzle tip penetration lengths*

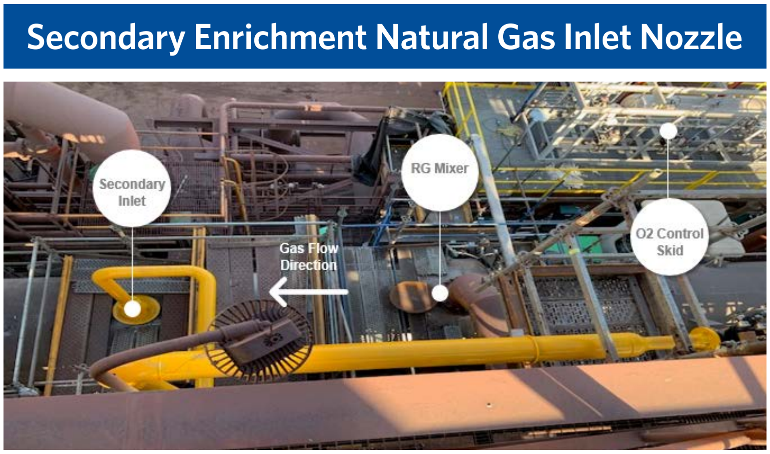


FIGURE 9. *Secondary enrichment natural gas inlet nozzle*

As an additional benefit to limiting the amount of enrichment natural gas flow at the reformed gas mixer, the ratio of oxygen to natural gas (methane) is controlled to a more optimal range to minimize soot or carbon formation in the bustle gas duct. Midrex is continuing to investigate options to decrease carbon generation in the bustle gas duct and improve the quality of the reducing gas generated. Early indications from Acindar show minimal carbon deposition, as compared to the typical system design and operation.

SUMMARY

Oxygen injection leads to higher bustle gas temperatures and more reductants, which leads to higher bed temperatures and higher reaction rates in the furnace, which ultimately leads to an increase in production. Enrichment natural gas prevents methanation, increases product carbon, and promotes in-situ reforming in the furnace.

Midrex developed CFD models of the oxygen injection system to evaluate potential improvements. Primary targets included flexibility for ensuring a stable flame over a wide range of flows and production rates, improved oxygen injection nozzle life, and improved refractory life. As a result, the following design changes were implemented at Acindar:

- Decreased the enrichment natural gas port diameter to provide an optimum natural gas velocity range.
- Determined the optimum oxygen nozzle penetration into the duct for improving the life of the nozzle
- Determined the minimum and maximum flows of enrichment natural gas specifically at the reformed gas mixer. Control logic was modified to maintain the flow within the required range.
- Determined the minimum and maximum flows of oxygen injection to provide an optimum velocity range. Again, control logic was modified to maintain the optimum range of flows. The control logic automatically opens and closes the individual oxygen nozzles as required.
- Added a secondary inlet for the enrichment natural gas.

After implementing these changes, Acindar has reported the system is operating successfully over a range of production rates and the carbon generation in the bustle gas duct has decreased compared to the previous operation and system.

ACINDAR

* Founded in 1942 by a group of businessmen led by engineer Arturo Acevedo, Acindar Industria Argentina de Aceros S.A. (Acindar) is one of Argentina's oldest steel companies. Its headquarters are located in the city of Villa Constitución and it has plants in the cities of Rosario , Villa Mercedes , La Tablada, and San Nicolás. Acindar merged with Arcelor subsidiary Belgo Mineira in 2001 and became part of the ArcelorMittal Group in 2006. ArcelorMittal has controlled 100% of the company since 2008.

Midrex News & Views

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Tosyali Algerie Sets DRI Production Record in 2021, Contracts Second DRI Plant

MIDREX® Plant produces more than 2.28 million tons

Tosyali Algerie A.Ş. established a new world record in 2021 for annual direct reduced iron (DRI) production by a single module plant, producing more than 2.28 million tons. The former record was set in 2020 by Tosyali in only its second year of operation.

Tosyali Algerie Integrated DRI-EAF Steel Mill in Bethioua (Oran), Algeria

Contract for Second MIDREX Plant

In July 2021, Tosyali Holding awarded Midrex and its partner Paul Wurth a contract to build a second DRI plant at the Tosyali Algerie steelworks in Bethioua (Oran), Algeria. The new DRI plant will produce 2.5 million tons of cold DRI (CDRI) and hot DRI (HDRI), similar to the original plant, with the capability of all MIDREX Plants to operate with even more hydrogen in the future.

TOSYALI ALGERIE 2 CONTRACT SIGNING CEREMONY (left to right): ***Todd Ames,*** *Senior Key Account Manager, Midrex Technologies;* ***KC Woody,*** *COO, Midrex Technologies;* ***Dr. Suhat Korkmaz,*** *CEO, Tosyali Holdings;* ***Dr. Thomas Hansmann,*** *Head of Metallurgy, SMS Group;* ***Fuat Tosyali,*** *President, Tosyali Holding;* ***Stephen Montague,*** *President & CEO Midrex Technologies;* ***Guido Bonelli,*** *Head of Ironmaking Sales, Paul Wurth Italia,* ***Fabio Muscolino,*** *Senior Sales Manager, Paul Wurth Italia; and* ***Antonio Durighello,*** *Lead Estimator, Paul Wurth Italia.*

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MIDREX® Plants with 1Q Anniversaries

Midrex is known for designing, engineering, and servicing reliable direct reduction plants, as well as for making certain that these plants have long and successful operating lives. Beginning with this issue, ***Direct From Midrex*** will recognize the start-ups of various MIDREX Plants during the quarter. The first three are OEMK III, Hadeed C, and LGOK HBI-3, which were started up during 1Q 35, 30 and 5 years ago, respectively:

Oskol Electrometallurgical Kombinat (OEMK) Module III

Number of years: 35
Name of plant: OEMK III
Type of plant – CDRI
Location: Stary Oskol, Russia
Start-up date: January 1987

SABIC Hadeed Steel Plant (Hadeed) Module C

Number of years: 30
Name of plant: Hadeed C
Type of plant – CDRI
Location: Al-Jubail, Saudi Arabia
Start-up date: March 1992

(Hadeed A, B, and C pictured with Hadeed C in the foreground)

Lebedinsky GOK HBI-3

Number of years: 5
Name of plant: Lebedinsky GOK HBI-3
Type of plant – HBI
Location: Gubkin, Belgorod Region, Russia
Start-up date: March 2017

(pictured right to left: LGOK HBI-3 [MIDREX], LGOK HBI-2 [MIDREX], and LGOK HBI-1 [HYL])

Midrex Promotions

David Durnovich

David Durnovich has been promoted to Director – Global Solutions. His leadership of Global Solutions, the Midrex aftermarket and services arm, has been instrumental in growing that aspect of Midrex's business including the addition of water treatment solutions and shutdown supervision and opening the Midrex Gulf Services office in Dubai.

Midrex News & Views

The full news articles are available on **www.midrex.com**

Midrex Promotions

Chris Clancy

Chris Clancy has been named Director – Procurement. He joined Midrex in late 2007, with a solid background in the metals industry. He has held positions in procurement, plant sales, and aftermarket service through which he has gained a strong understanding of how procurement group plays a vital role in the success of Midrex projects.

In his new role, Chris will work to expand the Midrex vendor base and focus on ensuring that Midrex continues to deliver quality goods and services at a competitive prices.

Lauren Lorraine: **Editor**

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All references to tons are metric unless otherwise stated.

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