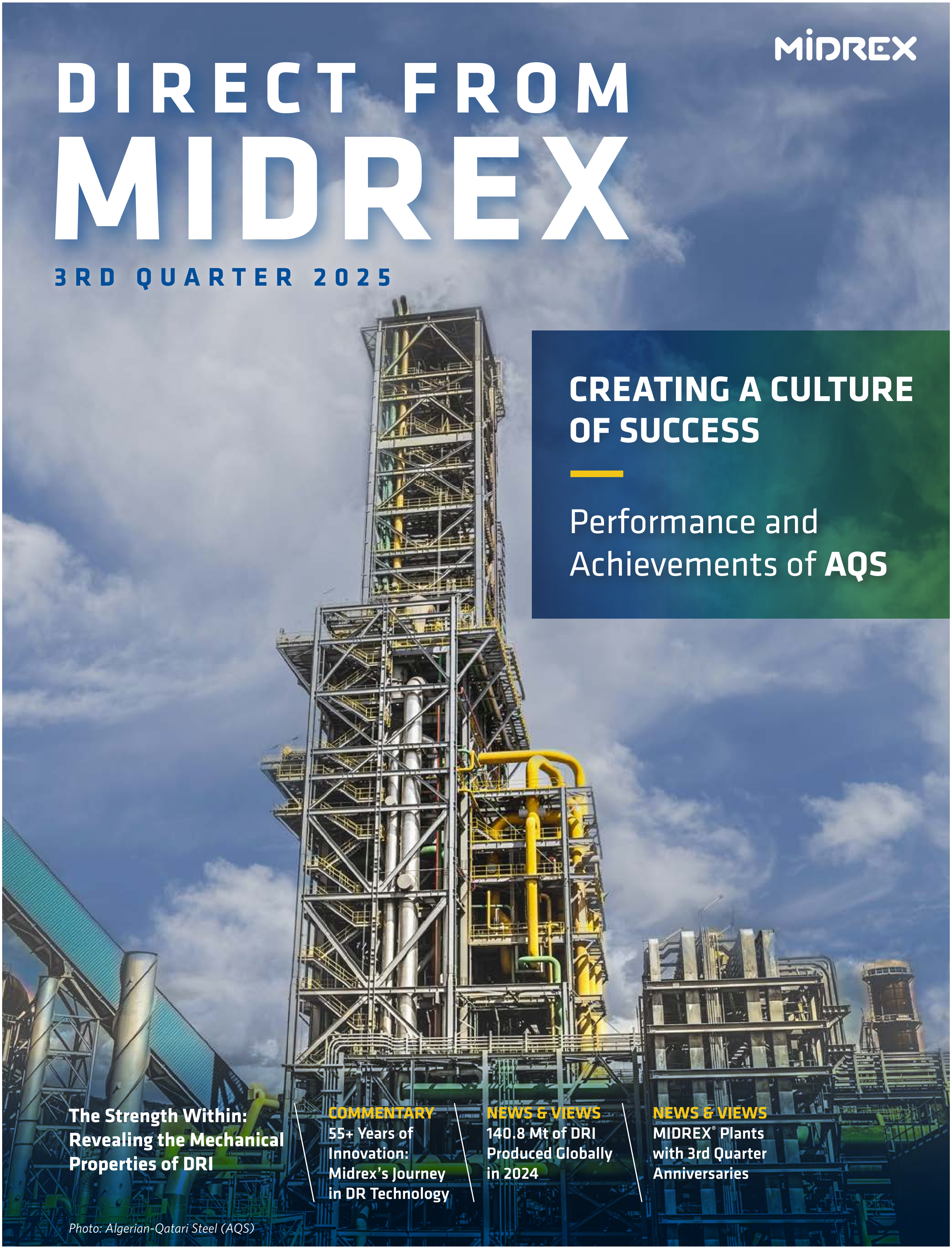
# DIRECT FROM MIDREX

3RD QUARTER 2025



## CREATING A CULTURE OF SUCCESS

Performance and Achievements of **AQS**

**The Strength Within: Revealing the Mechanical Properties of DRI**

**COMMENTARY**
55+ Years of Innovation: Midrex's Journey in DR Technology

**NEWS & VIEWS**
140.8 Mt of DRI Produced Globally in 2024

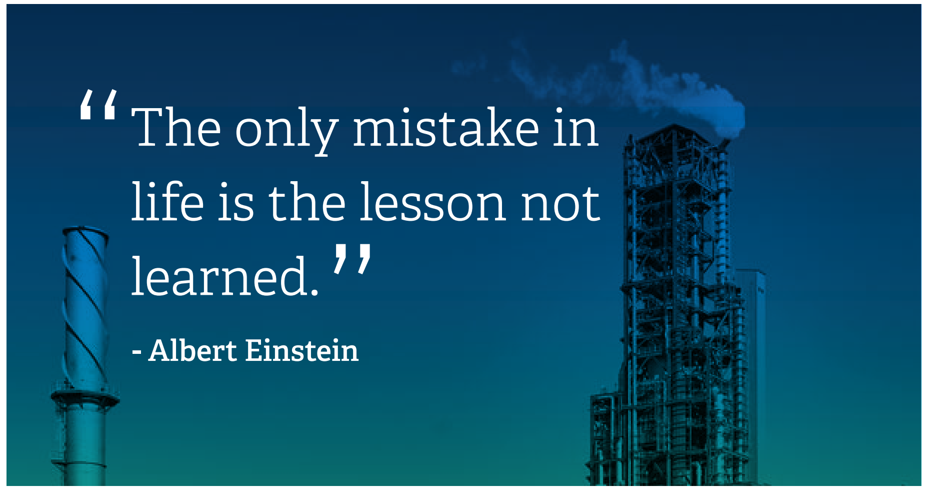
**NEWS & VIEWS**
MIDREX® Plants with 3rd Quarter Anniversaries

*Photo: Algerian-Qatari Steel (AQS)*

COMMENTARY

# 55+ YEARS OF INNOVATION:

## MIDREX'S JOURNEY IN DIRECT REDUCTION TECHNOLOGY



By Sean Boyle
*Vice President – Commercial*

**From time to time, I go back through the issues of *Direct From Midrex*, and I never cease to be amazed by the exploits of those who have devised the process technology, designed the equipment and systems, and operated the plants over the past 55+ years. But alongside these technical achievements stand the equally significant milestones of leading the development of the merchant iron market and creating an appreciation for the intrinsic value of direct reduced iron (DRI).**

The very thing that powered the environmental benefits of direct reduction and the MIDREX® Process versus blast furnace ironmaking – the use of natural gas as reductant and fuel – also limited where plants were built to locations that possessed abundant and competitively priced natural gas. As more steelmakers discovered the value of adding DRI to their feed mix, the need arose to ship the material great distances by water. Due to the porous nature of DRI, the hydrogen molecules in water tend to reverse the reduction process, which produces heat that can lead to fires in the cargo holds.

At the time, Midrex was supplying a plant in Emden, West Germany, that used a proprietary coating to protect DRI from oxidation when in contact with water. However, a denser form of DRI was needed to broaden its use beyond electric arc furnaces (EAFs) to blast furnaces (BFs), basic oxygen furnaces (BOFs), and specialty iron and steel production. Midrex responded with hot briquetted iron (HBI). Just as Midrex was not the first developer of a direct reduction process, it improved how HBI was produced and the stability of the product and devoted staff to promoting the idea of merchant iron.

The rise of EAF-based steel production resulted in increased demand for steel scrap. Its dependence on scrap tended to limit the products of the EAF to construction-grade steel and drove up the price of scrap, especially in areas without a well-established supply network. DRI was often used to moderate scrap prices in the US and Europe. Midrex championed the belief that scrap and DRI should be seen as complimentary materials which, when used together, produced steel quality equal to the traditional BF-BOF route. Now, even steel flat products with the strictest specifications can be made in EAFs as long as a low-impurity, virgin metallic such as DRI is used as a part of the feed mix.

## COMMENTARY

Today, steelmakers are facing a different and daunting challenge – to significantly reduce their $CO_2$ emissions. Midrex is applying its extensive research and development capabilities and lessons learned from decades of designing and optimizing direct reduction plants to making low carbon-DRI production a commercial reality.

The fundamentals of hydrogen reduction have been published for more than 70 years, and producing and using a hydrogen-rich syngas to reduce iron oxide has been practiced for well over half a century from small- to industrial- scale. Therefore, going from natural gas-based direct reduction to hydrogen-based is evolutionary not revolutionary. The main difference is that the reduction of iron oxide by hydrogen is endothermic (absorption of heat) rather than exothermic (release of heat) when carbon monoxide is included in the reducing gas.

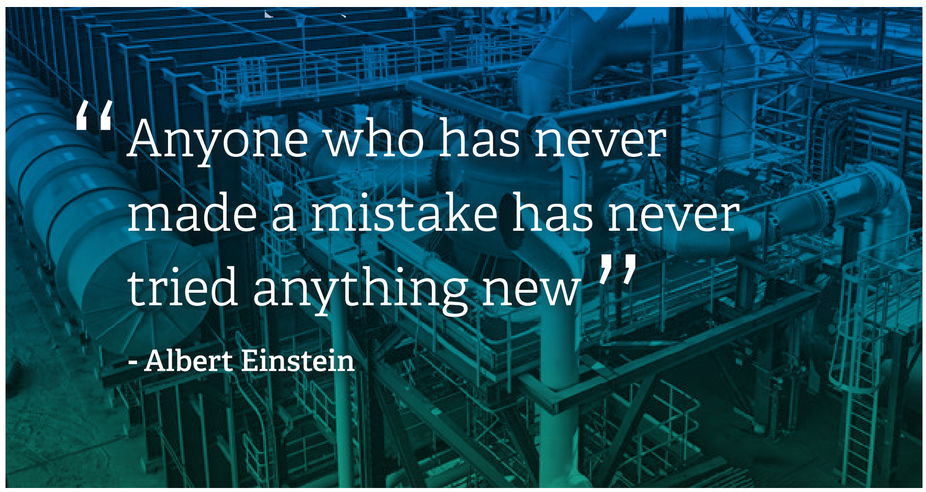
Through a combination of process modeling with our proprietary furnace modeling and CFD software, innovation engineering-driven designs, and in-house laboratory testing Midrex now offers full-scale commercial plants that operate on up to 100% hydrogen (MIDREX H2™), as well as natural gas-based plants that can be transitioned to hydrogen operation at the owner's discretion (MIDREX Flex®).

As in all operational MIDREX Plants worldwide, assuring the safety and security of personnel and equipment is paramount; therefore, hydrogen safety is the first priority.

**THROUGHOUT ITS HISTORY, MIDREX HAS BEEN COMMITTED TO FOUR GUIDING PRINCIPLES:**

1. Improvements and innovations must be relevant to customer wants and needs
2. Designs must be reliable, in step with technology, and easily serviceable
3. Interactive information exchange must be maintained with customers
4. Teammates and customers must be empowered to take ownership and responsibility

MIDREX




This issue of *Direct From Midrex* features articles about the successful journey of Algerian Qatari Steel (AQS) along the DRI-EAF learning curve and test work at the Midrex Research & Technology Development Center to better understand the mechanical properties of DRI produced with natural gas and with hydrogen. News & Views reports on recent happenings in the global DRI industry and recognizes MIDREX Plants with significant 3Q anniversaries.

# CREATING A CULTURE OF SUCCESS

## PERFORMANCE AND ACHIEVEMENTS OF AQS

By ING BELLAH OUSSAMA,
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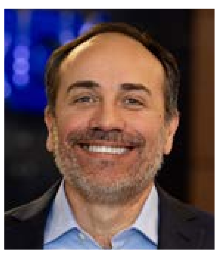
*Field Engineer – Global Solutions, Midrex Technologies, Inc.*

ING BELLAH OUSSAMA,
*Algerian-Qatari Steel Co.*



BRIAN DE CASTRO
*Midrex Technologies, Inc.*

## INTRODUCTION

Algerian-Qatari Steel (AQS) was established in December 2013, as a joint venture between Qatar Steel International (49%), SIDER Investment Group (46%), and the Algerian National Investment Fund (5%). The relations between Algeria and Qatar are long-standing and growing, highlighted by decades of co-operation and synergy in economy and trade, industry, energy, mining, agriculture, and social and political initiatives.

AQS operates a 2 million metric tons per year (Mt/y) steel mill in the industrial zone of Bellara, in El-Milia, an administrative district of Jijel, located 400 km from Algiers. The steel complex occupies a total area of 216 hectares (> 553 acres) and includes:


- MIDREX® Direct Reduction Plant – production capacity of 2.5 Mt/y hot and cold direct reduced iron (HDRI and CDRI)
- Two 120-ton electric arc furnaces (EAFs) – total production capacity of 2.2 Mt/y
- Three rolling mills – total production capacity of 2 Mt/y of reinforcing bars and wire rods

Supporting these production units are an industrial gas plant, lime production unit, station for receiving & transporting raw materials, water treatment plant, and electrical substation.

The AQS project was launched in March 2015. The first rolling mill (for reinforcing bars) and the water treatment plant began operation in 2017. In 2018, the complex continued to take shape with start-up of a second rolling mill (for wire rods) and the industrial gas plant, and SNTF (The National Rail Transportation Company) completed installation of a line between the plant and the international port. The third rolling mill and the first EAF were put into service in 2019, followed by the second EAF and the MIDREX Plant in 2020, and the air separation plant, lime plant, and the materials handling system in 2021.

## AQS MIDREX COMBINATION (CDRI-HDRI) PLANT

First direct reduced iron (DRI) was produced in February 2021, and HDRI was initially charged to the EAF in March 2021. The AQS direct reduction plant (DRP) achieved its hourly design capacity (312 t/h) in September 2021, and was operating at 9% over design capacity by March 2022. During its first full year of operation (2022), 74% of total production (1.7 Mt) was HDRI in response to melt shop demand. In 2024, the HDRI-to-CDRI ratio was 63%-to-37%, with average HDRI metallization 94%, metallic iron content 85%, and product carbon 2.5% (max monthly average up to 2.77% in March). AQS shipped 80,000 metric tons of CDRI to customers in the region.

The AQS DRP is equipped with an enclosed and insulated metallic conveyor for feeding HDRI to the EAF melt shop. The HDRI is delivered to bins at 580° C (average) for direct charging to the EAF to ensure there are no fugitive dust emissions.

The transporting and feeding system is designed so HDRI and CDRI can be mixed at the discretion of the melt shop or HDRI can be diverted to a product cooler and stored as CDRI. During 100% HDRI production, some "trickle discharge" is maintained to avoid static DRI at the product cooler.

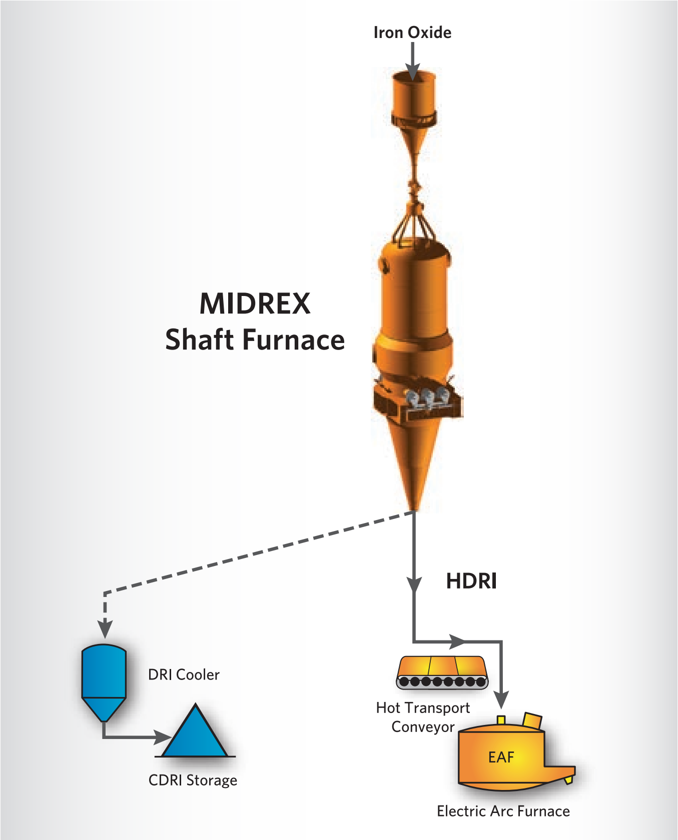



**FIGURE 1.** *Reduction furnace product discharge options*

The product discharge arrangements ***(see Figure 1)*** allow AQS to produce HDRI and CDRI from the same shaft furnace. Therefore, when the melt shop does not require HDRI, the material can be cooled and stored for shipment as CDRI throughout the MENA region.

### AQS DIRECT REDUCTION PLANT (DRP)

**Capacity (rate)**
Annual: 2.5 Mt
Daily: 7,500 t
Hourly: 312.5 t

**DRI Products**
Metallization: 94%
Metallic Fe: 85%
Carbon: 2.55%
HDRI Temperature: 580° C *(at bins)*

**Operating Hours (rated)**
8,000 Hrs

**Feed**
DR-grade Fe oxide pellets*

**Shaft furnace diameter:** 7.65 m
**Reformer tubes:** 720, 11" dia.
**Reformer bays:** 18 bays
**Reformer rows *(per bay)*:** 8 rows

** Up to 5% low-grade Fe pellets*

To ensure a continuous and secure supply of high-quality (DR-grade) iron oxide pellets, AQS utilized multiple sources during 2024 and is planning to install a desulfurization unit. This unit will enable the use of pellets with higher sulfur content without adversely affecting the catalyst, which will significantly reduce raw material costs while maintaining product quality and process stability.

## STEADILY INCREASING PERFORMANCE

From the outset, AQS has been committed to continuous improvement, guided by four strategic priorities: safety, production, quality, and problem-solving. Creating a culture of cooperation and adherence to established work procedures and safety instructions, advocating for team training, and learning from past experiences have contributed to maintaining a safe work environment and steadily improving performance and quality.

AQS DRP received three awards during the 2024 International Conference on MIDREX Technology in recognition of outstanding operational excellence in 2023, when the plant set three local plant records: 7,208 operating hours, 1.8 Mt annual production volume, and 95.6 kWh/t electricity consumption.

It is worth noting that all the plant records achieved in 2023 were broken in 2024, as AQS DRP set new annual production volume, electric power consumption, natural gas consumption, and production yield milestones ***(see Figure 2)***. These figures demonstrate steady advancement of the DRP team on the plant operation and maintenance learning curve.

| | 2023 RECORD | 2024 RECORD |
|---|---|---|
| Annual production | 1.89 Mt | 2.00 Mt |
| Monthly production | 214,000 t | 215,000 t |
| Electricity consumption | 95.57 kWh/t | 89.9 kWh/t |
| Natural gas consumption | 2.33 Net Gcal/t | 2.28 Net Gcal/t |
| Production Yield (MRMR) | 1.46 | 1.44 |

**FIGURE 2.** *AQS DRP performance*

In 2024, the DRP produced approximately 2.0 Mt of DRI, the highest annual production volume since start-up in 2021 ***(see Figure 3)***, demonstrating consistent progress along the learning curve and a positive trajectory. 2024 was impacted by a number of issues, which in cooperation with Midrex Global Solutions are being successfully focused on during 2025. Through July 2025, the plant is running at design tonnage with ongoing efforts for improving of furnace feed conveyor reliability and operational practices of the reformer. The timing between carbon burnouts has increased from ~1 month to 3+ months without addition of any natural gas pretreatment to remove heavy hydrocarbons. Throughout the first half of 2025, AQS has produced 1.11 Mt of DRI and is targeting an annual total of 2.5 Mt of DRI , with consistent product quality targeted at metallization of 94% and carbon content averaging 2.5%.

Electricity consumption has been reduced by more than 25% since AQS DRP was started up in 2021 ***(see Figure 4)***.

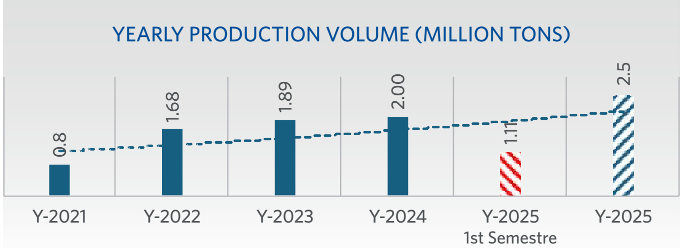



**FIGURE 3.** *Annual DRI production since start-up*

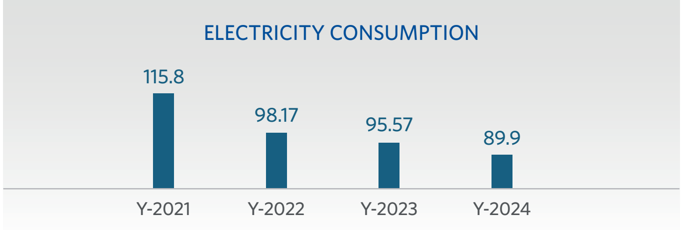



**FIGURE 4.** *Electricity consumption since start-up*

In keeping with AQS's customer-centric approach, DRP ensures that its customers – be they internal or external – receive consistently high product quality. Carbon content has been boosted every year since initial start-up and has averaged >2.5% since 2024 ***(see Figure 5)***, and metallization has been maintained at 94%.

In October 2024, DRP conducted a planned annual shutdown during which several key maintenance milestones were achieved: replacement of the oxide feeding conveyor, thorough cleaning of the water system, shaft furnace refractory inspection and repairs (with Midrex assistance), eddy current testing and replacement of 100 reformer tubes, and leak testing of the heat recovery bundles.

Plant availability has consistently improved since the initial start-up ***(see Figure 6)***.

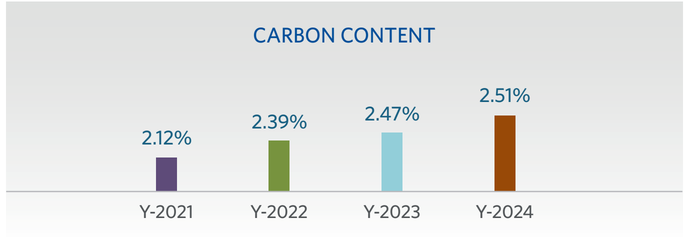



**FIGURE 5.** *Carbon content of DRI since start-up*

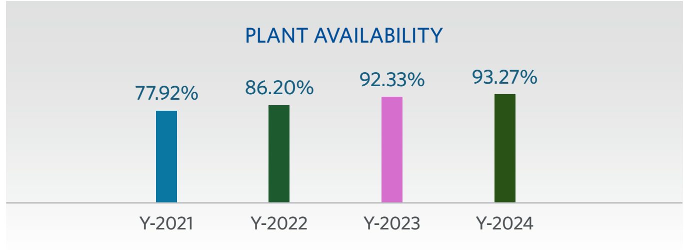



**FIGURE 6.** *Plant availability since start-up*

## MIDREX GLOBAL SOLUTIONS AND SUPERDATA

Since 2023, AQS DRP has cooperated closely with Midrex Global Solutions, the aftermarket service arm of Midrex, for a range of activities: plant monitoring, pro-active identification and resolution of potential issues, and application of lessons learned. Through more than 50 online meetings, AQS and the Remote Professional Service (RPS) team of Midrex Global Solutions have resolved 44 service tickets, which have been instrumental in achieving the outstanding performance record of the DRP.

Beginning in 2023, Midrex Global Solutions, through its RPS team, has used Eddy Current Testing (ECT) to monitor the AQS reformer tubes. The purpose of this service to determine the life of the tubes, ensure the tubes perform as expected, and identify issues such as tube imbalance or growth. ECT is now performed on an annual basis.

A primary tool used by Midrex RPS is Superdata, which is instrumental in establishing a plant's process center line utilizing:

- mass and energy balance
- process performance monitoring (reduction furnace, reformer, and heat recovery system)
- furnace gas utilization, reformer productivity/ approach to equilibrium, flue gas data
- reductant calculations (based on gas analysis data)
- identifying specific measurements for calibration or other checks

## Superdata – Then and Now

Access to Superdata drives innovation, identifies process ranges, tracks operational behavior, and facilitates recommendations for improvements. Although Superdata has been available to MIDREX Plant operators for some time, it has had limited use because it was considered too specialized, not user-friendly, time-consuming to learning, and required training, experience, and judgment to use it. However, The Midrex RPS team is digitalizing Superdata to create a powerful plant operation and optimization tool *(see Table 1)*.

↓

For further information about Algerian-Qatari Steel Company and its products, visit the AQS website at **https://aqs.dz**

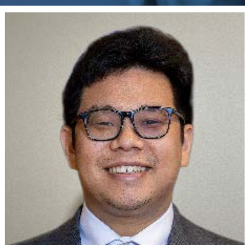
To learn more about Midrex Global Solutions, visit: **https://www.midrex.com/global-solutions**

| | Original Superdata | Digital Superdata |
|---|---|---|
| REPORTS | 4 hours | ¼ hour |
| BASIS OF DECISIONS | await outcome | real-time trends |
| EVALUATION EXPERTISE | individual experience | Midrex process limits |
| DATA ENTRY | manual | automated |
| DEVICES | computer | computer, tablet, smartphone |

**TABLE 1.** *Midrex Superdata comparison*

# THE STRENGTH WITHIN: REVEALING THE MECHANICAL PROPERTIES OF DRI

## Midrex, Kobe Steel Shaft Furnace Simulation Captures Industrial-Grade DRI Data

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### INTRODUCTION

Understanding the relationship between reducing gas compositions and the mechanical properties of Direct Reduced Iron (DRI), especially swelling behavior and strength, is an area of research of growing importance in the quest to decarburize steelmaking. A promising decarburization pathway is to replace some or all of the energy from fossil fuels with green hydrogen ($H_2$) to produce DRI in a MIDREX® Shaft Furnace.

Two studies performed in 2017 and 2022 (M. Mizutani et al. in 2017[1] and Z. Zhao et al. in 2022[2]) indicated that there is less possibility of swelling and disintegration when DRI is produced under a pure hydrogen ($H_2$) atmosphere than with an $H_2$ and carbon monoxide (CO) gas composition. However, unlike in a real shaft furnace, where the counter current flow of the reducing gas against the solid flow results in a non-isothermal and non-constant gas composition condition, these studies were carried out under isothermal and constant gas composition conditions.

To better represent the actual shaft furnace and the mechanical properties of DRI produced therein, Midrex Technologies and Kobe Steel developed a test procedure called Shaft Furnace Simulated Condition (SFSC). SFSC simulates the reducing condition in a MIDREX Plant using natural gas as reductant and compares the obtained mechanical properties with those obtained from the conventional isothermal test method and a commercial plant.

## BACKGROUND

Corem, a research institute specialized in the area of mining and mineral processing, developed a non-isothermal reduction test called R180, which compared the microstructure of the reduced pellets with those obtained from the conventional isothermal test (R90) specified by ISO 11258[3]. The Corem test also compared the porosity, strength, and microstructure of the DRI produced by the R180 procedure with industrial DRI. They found the properties to be similar; however, it is not clear how many pellet brands were tested or whether all of them had similar physical properties as the industrial ones.

## SFSC Furnace Setup

The purpose of SFSC is to reproduce the metallization and mechanical properties of industrial DRI for most of the recognized oxide pellet brands in a specially-designed bench-scale reduction furnace (see ***Figure 1***). For each test, 14 pieces of oxide pellets (approximately 50 grams) are placed in a hand-made sample holder so the location of each sample can be tracked during the reduction test. The sample holder is suspended inside a 75 mm (dia.) ceramic retort from an electronic balance. This setup enables the monitoring of volume change before and after each test and weight change of the sample during the test. Both the upper and lower end of the retort are tightly sealed by water-cooled flanges with O-rings. The reducing gas consists of $H_2$, CO, and $CO_2$, and is mixed well before it is introduced into the retort. The exhaust gas from the top of the retort is combusted by a burner to ensure operator safety.

## SFSC Test Procedure

Before each reduction test, the pieces of oxide pellets are heated to the initial reduction temperature under a nitrogen ($N_2$) atmosphere. The heat pattern simulates that of an actual industrial plant.

The SFSC test conditions are shown in ***Table 1***, below. At the beginning of the test program, the gas composition is set to the same Gas Oxidation Degree (GOD*, Eq. 1) as the representative composition of the exhaust gas from the shaft furnace in a MIDREX Plant. The GOD decreases as the test proceeds and eventually reaches the same value as the bustle gas, which in an industrial plant comes from a MIDREX Reformer and is introduced to the shaft furnace. The transition of GOD between the bustle gas and the exhaust gas is simulated by Computer Fluid Dynamics (CFD) technology and applied to the SFSC. Gas composition is changed 17 times (every 10 minutes)

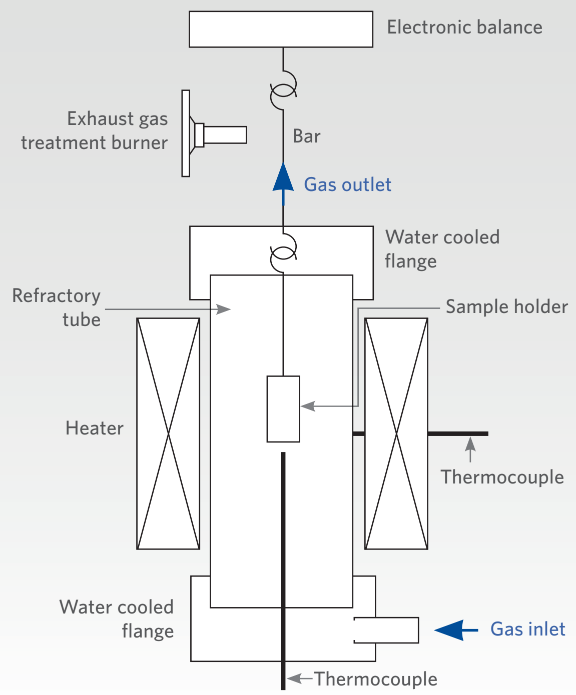


**FIGURE 1.** *Schematic of SFSC furnace*

*(Eq.1)*

$$\text{Gas oxidation degree} = \frac{(Vol\%H_2O+Vol\%CO_2)}{(Vol\%H_2+Vol\%H_2O+Vol\%CO+Vol\%CO_2)}$$

| TIME | HEAT PATTERN | | | *GOD |
|---|---|---|---|---|
| | Initial temperature | Final temperature | Gradient | |
| 0-30 min | < 680 °C | 800 °C | > 4 °C/min | < 0.4 |
| 30-80 min | 800 °C | 830 °C | 0.6 °C/min | 0.075 - 0.4 |
| 80-160 min | 830 °C | 850 °C | 0.25 °C/min | |
| 160-180 min | 830 °C | 850 °C | 0 °C/min | 0.075 |

**TABLE 1.** *SFSC Test Conditions*

* **GOD is defined by Eq.1.** Gas with a lower GOD is a better reductant.

during the 180 minutes of the test to better simulate the real reduction condition. In comparison, the R180 procedure developed by Corem only has three steps of gas composition change.

Three initial temperature setpoints were examined to reproduce the microstructure of industrial DRI. The transitions of microstructure in an industrial oxide pellet (oxide pellet A in ***Table 2***) with varied initial temperature are shown in ***Figure 2***. Both porous and dense microstructure can be seen at approximately 30% and 100% of reduction degree (RD**, Eq. 2) while the raw material shows only the dense one. As can be seen in ***Figure 2***, as the initial reduction temperature increases from Case I, Case II, and Case III, the proportion of porous particles of the partially reduced DRI (30% RD) increases as well. The order of porous particle proportion of the DRI at 100% RD follows that of the 30% RD. High initial reduction temperature leads to high porosity DRI. The conclusion was that the microstructure shown in ***Figure 2F*** is the closest to that of industrial DRI ***(Figure 2H)***. Consequently, Case II, with the medium initial reduction temperature, was determined to be the best setup for the reproduction of the microstructure of industrial DRI. Therefore, in the rest of this article, SFSC will refer to Case II.

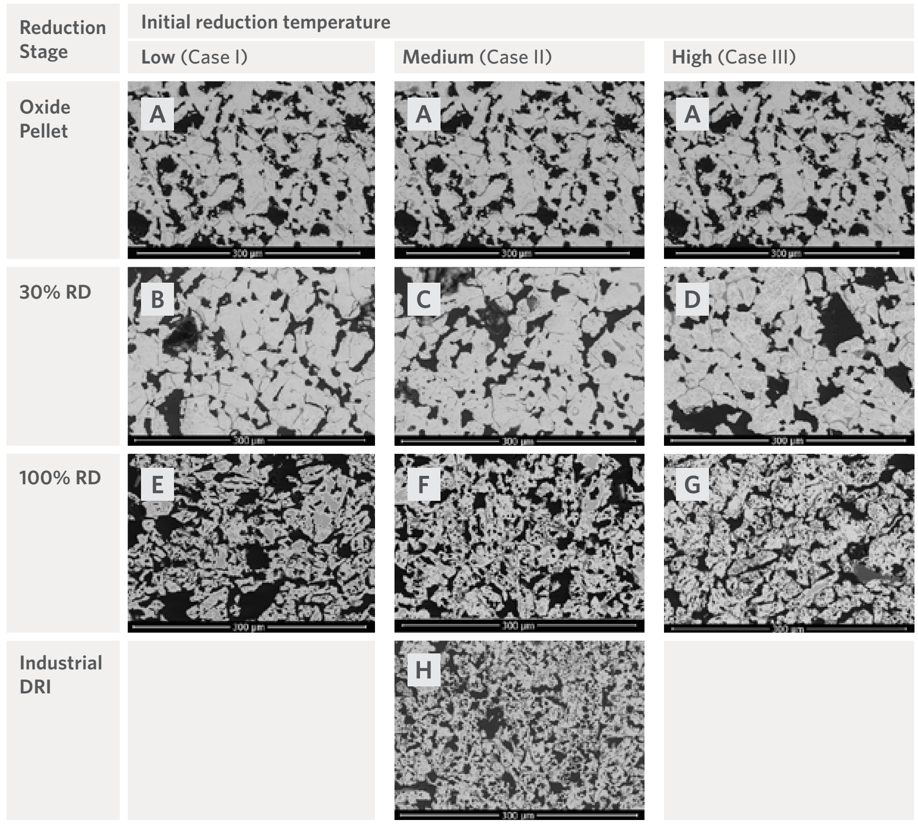


**FIGURE 2.** *CT-Photos of oxide pellet A and reduced samples made from oxide pellet A:*

| | |
|---|---|
| A | Oxide pellet A (common to Cases I, II, & III) |
| B | Sample with approximately 30% of RD, reduced under the modified SFSC with lower initial temperature |
| C | Sample with approximately 30% of RD, reduced under the SFSC |
| D | Sample with approximately 30% of RD, reduced under the modified SFSC with higher initial temperature |
| E | Sample with approximately 100% of RD, reduced under the modified SFSC with lower initial temperature |
| F | Sample with approximately 100% of RD, reduced under the SFSC |
| G | Sample with approximately 100% of RD, reduced under the modified SFSC with higher initial temperature |
| H | Industrial DRI made from Oxide Pellet A |

*(Eq.2)*

$$\text{Reduction degree} = \frac{\text{Weight of oxygen removed by reduction}}{\text{Weight of oxygen combined with iron in oxide pellet}}$$

*(Eq.3)*

$$\text{Metallization} = \frac{\text{Metallic iron (wt\%)}}{\text{Total iron (wt\%)}}$$

** **RD is defined by Eq.2,** which represents the reduction progress besides metallization***. The higher the reduction degree, the farther the reduction progresses.

***__Metallization is defined by Eq.3__.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| T.Fe, wt% | 68.0% | 67.5% | 67.8% | 67.2% | 67.3% | 67.3% | 66.4% | 67.8% | 68.0% | 68.1% |
| $CaO/SiO_2$, | 0.433 | 0.758 | 0.547 | 0.781 | 0.510 | 0.188 | 0.416 | 0.381 | 0.361 | 0.590 |
| Mean size, mm | 12.6 | 13.2 | 11.4 | 13.2 | 11.2 | 11.5 | 10.6 | 12.2 | 11.8 | 0.75 |

**TABLE 2.** *Characteristics of Oxide Pellets Tested*

## Raw materials and other conducted tests

To better predict the mechanical properties of industrially produced DRI in a laboratory test, the test procedures must be applicable to a wide selection of oxide pellet brands. Therefore, 10 brands of commercial oxide pellets were used in the SFSC study. The major characteristics of these oxide pellets are shown in ***Table 2***. The pellets also were subjected to a Basket Test in an industrial DR plant as part of the reduction study. In a Basket Test, soft or hard baskets filled with oxide pellets are fed to the top of a shaft furnace and collected from the bottom of the shaft after reduction. In this article, the DRI obtained from a Basket Test is called Industrial DRI.

Three of the 10 brands of commercial oxide pellets (designated A, B, and C) also were examined in an extended R90 test, where the temperature and gas composition were the same as specified by ISO 11258 at isothermal condition, except the test duration was extended from 90 minutes to 180 minutes. The extended R90 was performed to allow the oxide pellets to undergo full reduction[3]. The same test furnace as developed for SFSC was used for the extended R90 test.

Further tests (called Stop Tests) were performed on oxide pellet A to examine the transition of the mechanical properties of the oxide pellets at varying Reduction Degrees, and 14 samples were used in each Stop Test at every target Reduction Degree. Both SFSC and the extended R90 conditions were applied for the Stop Tests. ***Table 3*** summarizes the various test characteristics.

| NAME | Characterstics | Oxide pellet brand used |
|---|---|---|
| Basket test | Industrial/non-isothermal/non-constant gas composition | A,B,C,D,E,F,G,H,I,J |
| SFSC | Laboratory/non-isothermal/non-constant gas composition | A,B,C,D,E,F,G,H,I,J |
| Extended R90 | Laboratory/isothermal/constant gas composition | A,B,C |

**TABLE 3.** *Summary of Test Characteristics*

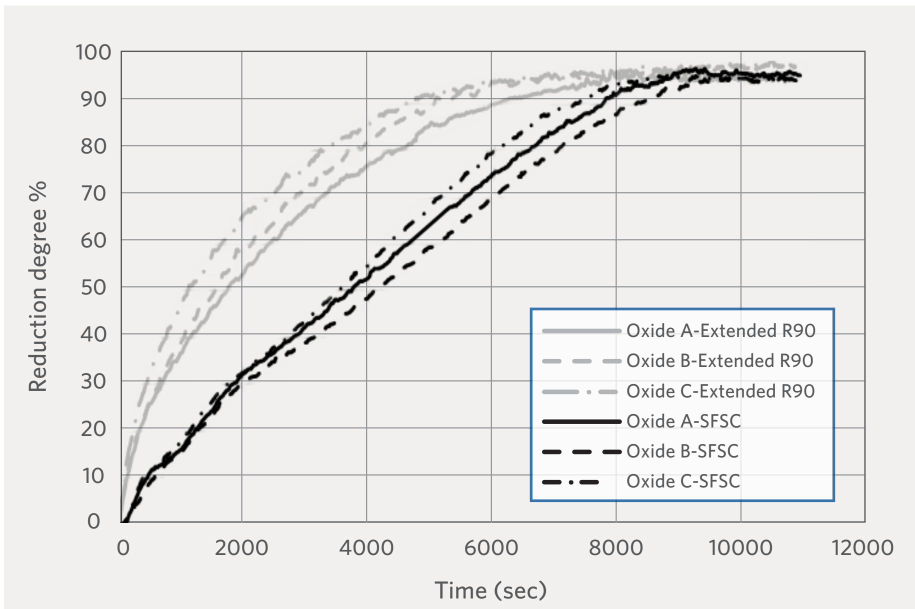


**FIGURE 3.** *The reduction curve (relationship between the Reduction Degree and the elapsed time) in the extended R90 and SFSC laboratory test for three oxide pellet brands*

## Reduction

The reduction curves (relationships between the Reduction Degree and the elapsed time) obtained from the extended 90 and SFSC are shown in ***Figure 3***. For each oxide pellet brand, the reduction rate in the extended R90 is faster than that in SFSC while the final Reduction Degrees are in same range.

The metallization results of the same oxide brand obtained from the Basket Test and the laboratory test are shown in ***Figure 4, (top of next page)***.

The DRI in the extended R90 tests exhibited an opposite metallization trend relative to the industrial DRI. The pellets that showed the highest metallization in the extended R90 test produced the lowest metallization when they were subjected to the Basket Test. On the other hand, the metallization results obtained from SFSC showed good agreement with that of the industrial DRI. Therefore, it can be said that the SFSC is similar to the reducing condition in an actual DR plant.

## Mechanical properties

Fourteen samples were collected from each laboratory test (the extended R90 or SFSC) and their weight and volume were measured. The Swelling Index, or the volume ratio of each reduced sample relative to its initial state, was calculated. A Swelling Index greater than 1 implies that the volume of the reduced sample is higher than that of the raw oxide pellet.

Swelling Index obtained from the extended R90, SFSC, and Basket Test are compared in ***Figure 5.*** Only for the industrial sample, the Swelling Index was calculated, as described in the Appendix since it is impossible to track a single oxide pellet during the entire reduction. For extended R90 and SFSC, the volumes before and after reduction were directly measured to calculate Swelling Index. For each oxide pellet brand, the Swelling Index of the extended R90 is the highest and different from those of SFSC and industrial DRI. This means the oxide pellets expanded significantly, in an unnatural way. While the Swelling Index of SFSC is slightly lower than the industrial DRI, the reproduction of the microstructure of industrial DRI may have resulted in similar swelling behavior to that of industrial DRI.

Cold Crushing Strength (as specified by ISO 4700) of the sample obtained from the extended R90, SFSC, and Basket Test is compared in ***Figure 6, (top of next page)***. For each oxide pellet brand, the Cold Crushing Strength of the extended R90 is the lowest and SFSC is the highest. The industrial DRI is between the extended R90 and SFSC. In the extended R90, the extreme volume expansion may have resulted in the lower strength than that of the industrial one. For SFSC, the strength was higher than the industrial DRI even though the volume change during reduction was similar. One explanation is the sintering of iron particles in DRI after the completion of reduction. In the industrial plant, DRI is carburized and cooled just after the

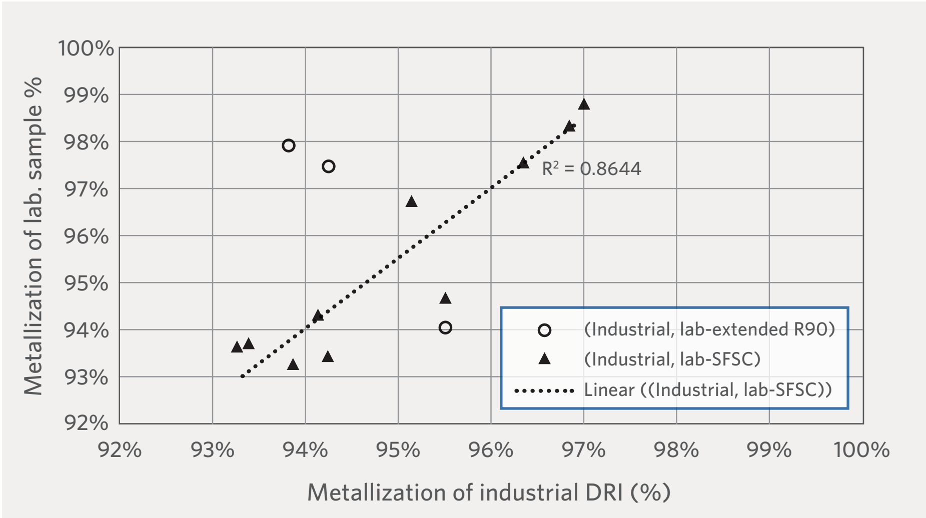


**FIGURE 4.** *Comparison of metallization between each laboratory test and an industrial test*

(Metallization is defined as the ratio of the mass percentage of metallic Fe to the mass percentage of total Fe in DRI. For the laboratory tests, the mass percentage of metallic Fe was measured by Kobe Steel, Ltd. using the Bromine methanol titration method specified by ISO 5416. For an industrial test, the mass percentage of metallic Fe was measured by Midrex using the Ferric chloride titration method specified by ISO 16878.)

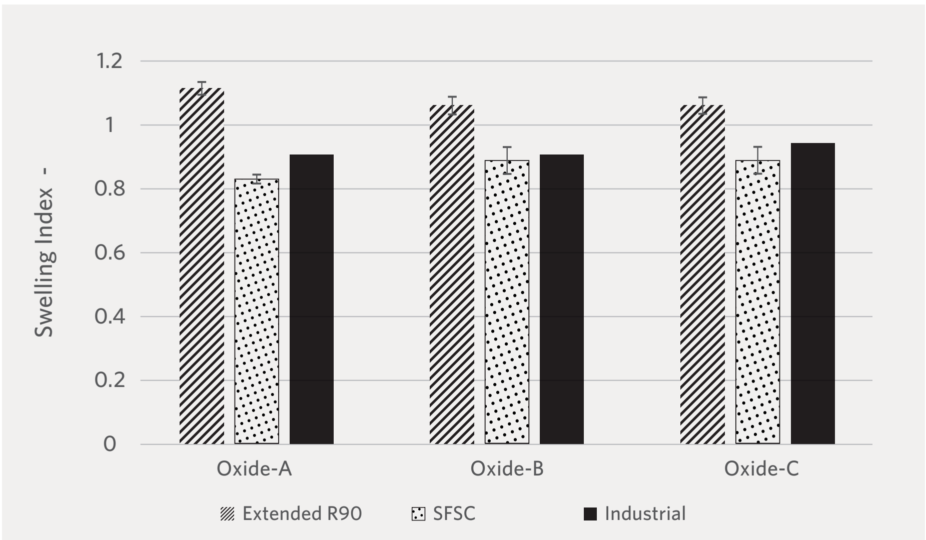


**FIGURE 5.** *Comparison of Swelling Index among two laboratory tests and an industrial DRI test.*

completion of reduction. So, there is little sintering of DRI iron particles in the shaft furnace. However, in SFSC testing, the fully reduced DRI was held for an additional 20-30 minutes at 850 °C in the furnace after reduction was completed ***(see Figure 3)***. The iron particles in the DRI may sinter during this period, which may lead to the enhancement of strength and higher Cold Crushing Strength than that of industrial DRI. Therefore, shortening the test time of SFSC could better reproduce "true" Cold Crushing Strength of industrial DRI.

The relationship between Swelling Index and Reduction Degree obtained from the Stop Test on oxide A is shown in ***Figure 7***. Before the reduction begins, the Swelling Index of raw material is 1. Once reduction occurs, the sample expands until its volume reaches the maximum at a certain reduction degree, and then it shrinks. For extended R90 testing, the Swelling Index reaches its peak (1.2) at 30% Reduction Degree and lowers slightly after 30%. On the other hand, in SFSC, the Swelling Index reaches its peak (1.1) at 10% of Reduction Degree and then decreases more sharply than in the extended R90.

The relationship between Cold Crushing Strength and Reduction Degree is shown in ***Figure 8***. Before reduction tests, the average Cold Crushing Strength is higher than 300 kgf/piece, which is within the normal range for oxide pellets. Once reduction occurs, the strength immediately drops to approximately 50 kgf/piece. In extended R90 testing, once the strength drop occurs, the strength remains unchanged until the end of the reduction test. On the other hand, recovery of strength in accordance with the progress of reduction was observed

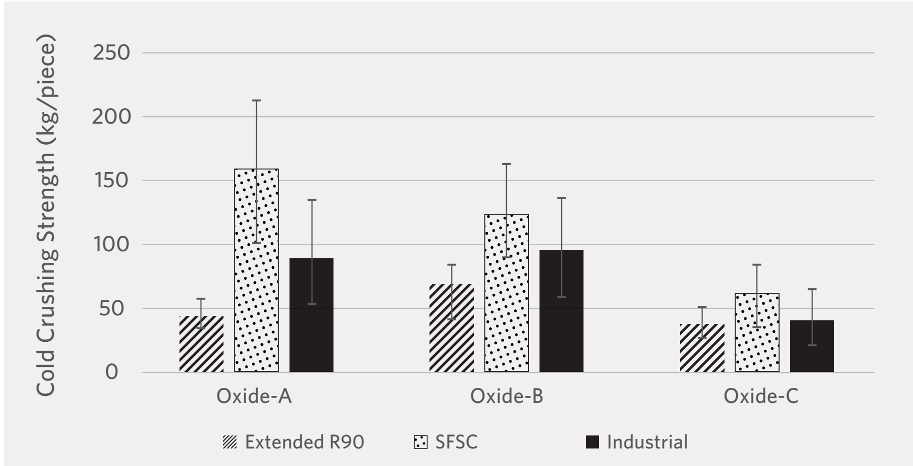


**FIGURE 6.** *Comparison of Cold Crushing Strength among two laboratory tests and an industrial test*

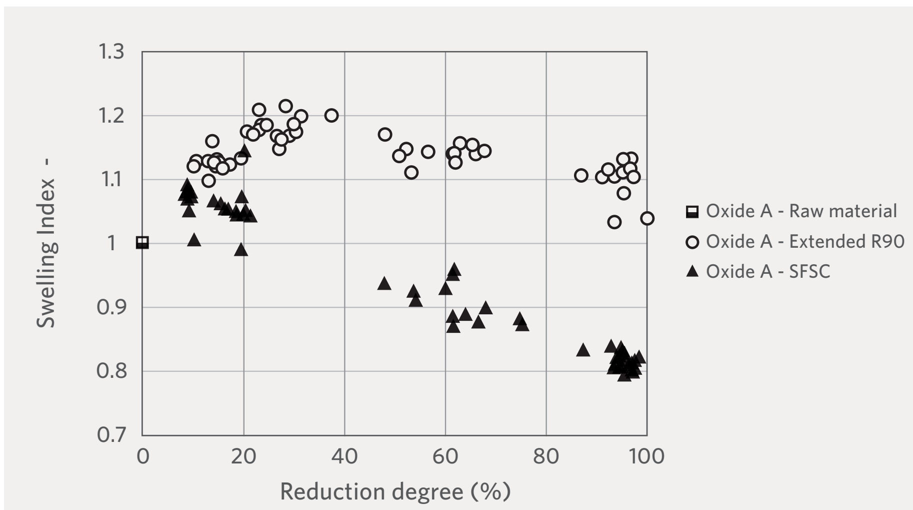


**FIGURE 7.** *Transition of Swelling Index of oxide A both in the extended R90 and SFSC testing*

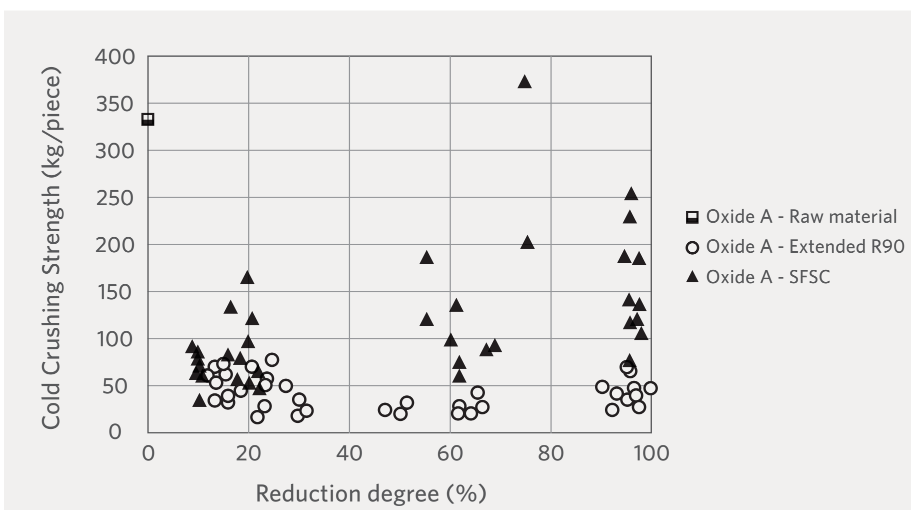


**FIGURE 8.** *Transition of Cold Crushing Strength of oxide A both in the extended R90 and SFSC testing*

in SFSC testing. Consequently, the Cold Crushing Strength of DRI obtained from SFSC is higher than that obtained in the extended R90 test.

## CONCLUSIONS

Midrex Technologies and Kobe Steel have developed and optimized Shaft Furnace Simulated Condition (SFSC), a laboratory test under non-isothermal and non-constant gas composition conditions that can vary the initial reduction temperature so the microstructure of the reduced sample resembles that of industrial DRI using a specially designed furnace. The reduction characteristics, metallization, and mechanical properties obtained from SFSC testing were compared with those obtained from an extended R90 test (isothermal and constant gas composition conditions) and from an industrial DR plant, using various oxide pellets, with the following results:

1. The Reduction Rate in the extended R90 test was faster than in SFSC test, while the final Reduction Degrees were in same range.
2. The Metallization results obtained from the SFSC test showed good agreement with that of the industrial DRI. Therefore, it can be said that the SFSC test is similar to the reducing condition in an actual DR plant.
3. The Swelling Index of the extended R90 test was the highest and different from those of the SFSC test and industrial DRI; i.e., the oxide pellets expanded significantly, in an unnatural way.
4. The Cold Crushing Strength obtained in the SFSC test was higher than that of industrial DRI, possibly due to the sintering of iron particles in the DRI.
5. There was a recovery of strength in accordance with the progress of reduction in the SFSC test.

Therefore, it can be said that SFSC testing is a valid measurement of the reduction characteristics and mechanical properties of DRI.

This article was developed from the paper titled, "Mechanical Properties of Direct Reduced Iron (DRI) Reduced Under a Simulated Shaft," presented at AISTech, May 5-8, 2025, in Nashville, TN, USA, by Katsuma Fujiwara of Midrex Research & Technology Development Center.

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## Appendix

(Eq.A-1)

$$W_{Fef} = W_{Fei} = W_i \cdot \frac{(\%T.Fe)_i}{100}$$

The amount of atomic iron (including metallic iron, Fe++, and Fe+++) in solid (both oxide pellet and DRI) is conserved during reduction

(Eq.A-2)

$$W_{M.Fef} = W_{Fef} \cdot \frac{(\%Met)_f}{100}$$

The amount of metallic iron is presented using metallization, which is commonly used to evaluate the quality of DRI.

(Eq.A-3)

$$W_{Fe^{2+}f} = W_{Fef} - W_{M.Fef}$$

By assuming there is no Fe+++ remained in DRI

## **Appendix** *(cont'd)*

**(Eq.A-4)**

$$W_{Of} = W_{Fe^{2+}f} \cdot \frac{M_O}{M_{Fe}}$$

By assuming there is no Fe+++ remained in DRI

**(Eq.A-5)**

$$W_{Fe^{2+}f} = W_i \cdot \frac{(\%T.Fe)_i}{100} \cdot \left\{1 - \frac{(\%Met)_f}{100}\right\}$$

By substituting the equations (A-1) and (A-2) to the equation (A-3)

**(Eq.A-6)**

$$W_{Of} = W_i \cdot \frac{(\%T.Fe)_i}{100} \cdot \left\{1 - \frac{(\%Met)_f}{100}\right\} \cdot \frac{M_O}{M_{Fe}}$$

By substituting the equation (A-5) to the equation (A-4)

**(Eq.A-7)**

$$W_{Oi} = W_i \cdot \frac{(\%T.O)_i}{100}$$

From the mass balance of oxygen

**(Eq.A-8)**

$$\Delta W_O = W_{Oi} - W_{Of}$$

**(Eq.A-9)**

$$\Delta W_O = W_i \cdot \frac{(\%T.O)_i}{100} - W_i \cdot \frac{(\%T.Fe)_i}{100} \cdot \left\{1 - \frac{(\%Met)_f}{100}\right\} \cdot \frac{M_O}{M_{Fe}}$$

By substituting the equations (A-6) and (A-7) to the equation (A-8)

**(Eq.A-10)**

$$W_i - W_f \cdot \left(1 - \frac{(\%C)_f}{100}\right) = \Delta W_O$$

Since there is no reduction of gangue or flux in oxide pellet, the major weight change between oxide pellet and DRI is caused by the removed oxygen from iron oxide. Considering the carburization.

**(Eq.A-11)**

$$W_f = \frac{W_i - \Delta W_O}{1 - \frac{(\%C)_f}{100}}$$

**(Eq.A-12)**

$$\frac{W_f}{W_i} = \frac{1 - \frac{\Delta W_O}{W_i}}{1 - \frac{(\%C)_f}{100}}$$

**(Eq.A-13)**

$$\frac{W_f}{W_i} = \frac{1}{1 - \frac{(\%C)_f}{100}} \cdot \left[1 - \left\{\frac{(\%T.O)_i}{100} - \frac{(\%T.Fe)_i}{100} \cdot \left\{1 - \frac{(\%Met)_f}{100}\right\} \cdot \frac{M_O}{M_{Fe}}\right\}\right]$$

By substituting the equation (A-9) to the equation (A-12)

**(Eq.A-14)**

$$Swelling\ Index\ (SI) = \frac{V_f}{V_i} = \frac{\rho_{ai}}{\rho_{af}} \cdot \frac{W_f}{W_i}$$

From the definition of Swelling Index

**(Eq.A-15)**

$$SI = \frac{\rho_{ai}}{\rho_{af}} \cdot \frac{1}{1 - \frac{(\%C)_f}{100}} \cdot \left[1 - \left\{\frac{(\%T.O)_i}{100} - \frac{(\%T.Fe)_i}{100} \cdot \left\{1 - \frac{(\%Met)_f}{100}\right\} \cdot \frac{M_O}{M_{Fe}}\right\}\right]$$

By substituting the equation (A-13) to the equation (A-14)

Midrex News & Views

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# 140.8 Mt of DRI Produced Globally in 2024

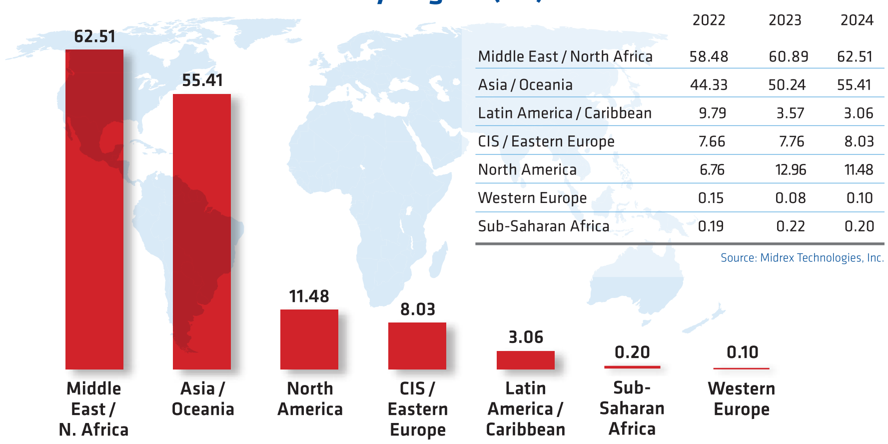
## MIDREX PUBLISHES *2024 WORLD DIRECT REDUCTION STATISTICS*

Global direct reduced iron (DRI) production in 2024 was 140.8 million tons (Mt), up by 5.1 Mt (3.8%) from the previous record of 135.7 Mt set in 2023. Since 2019, worldwide DRI output has grown by 32.7 million tons per annum (Mta), or approximately 30.3%.

MIDREX® Plants produced 76.2 Mt of DRI in 2024, which is 0.6% more than the 75.7 Mt produced in 2023, both annual records. The MIDREX Process accounted for 54.1% of total DRI produced and 80.1% of the DRI produced in shaft furnaces. MIDREX Plants have produced a cumulative total of over 1.46 billion tons (Bt) of all forms of DRI (CDRI, HDRI, and HBI).

Each year Midrex Technologies, Inc. compiles and publishes World Direct Reduction Statistics as a resource for the global iron and steel industry. World Steel Dynamics (WSD) audits the data collection and preparation processes used by Midrex to confirm that the methodology and accuracy of the data to be published is representative of the global direct reduction industry in a given year.

### 2024 World DRI Production by Region (Mt)




| | 2022 | 2023 | 2024 |
|---|---|---|---|
| Middle East / North Africa | 58.48 | 60.89 | 62.51 |
| Asia / Oceania | 44.33 | 50.24 | 55.41 |
| Latin America / Caribbean | 9.79 | 3.57 | 3.06 |
| CIS / Eastern Europe | 7.66 | 7.76 | 8.03 |
| North America | 6.76 | 12.96 | 11.48 |
| Western Europe | 0.15 | 0.08 | 0.10 |
| Sub-Saharan Africa | 0.19 | 0.22 | 0.20 |

Source: Midrex Technologies, Inc.

**2024** World Direct Reduction Statistics is available for download at **www.midrex.com**


Midrex Technologies, Inc. compiles and publishes ***World Direct Reduction Statistics*** annually as a resource for the global iron and steel industry. To prepare the annual statistics, Midrex requests inputs from every known direct reduction producer either directly or indirectly through partner organizations. Where plant information is not available directly or indirectly from producers, Midrex obtains the information from publicly available data.

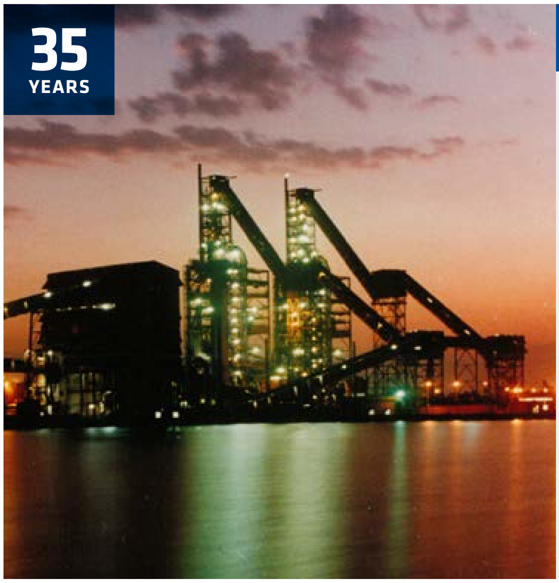
World Steel Dynamics (WSD) audits the data collection and preparation processes used by Midrex to confirm that the methodology and accuracy of the data to be published is representative of the global direct reduction industry in a given year.

## Midrex News & Views

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

# MIDREX® Plants with 3rd Quarter Anniversaries

We are proud to celebrate these remarkable milestones with our customers – **35 years** since start-up for **ArcelorMittal Nippon Steel India Module 2** and **45 years** for **TT Iron** I (formerly ArcelorMittal Point Lisas I and ISCOTT I)!




## ArcelorMittal Nippon Steel India (AM/NS India) Module II

**Location:** Hazira, Gujurat, India
**DR Plant:** 2nd of 6 MIDREX® Modules

- **Start-up:** July 1990
- **Product:** HDRI/HBI
- **Rated Capacity:** 0.44 M t/y

Module II was one of two MIDREX Modules acquired from Nordeutsche Ferrowerke in Emden, Germany, disassembled, and relocated to India by Essar Steel India Limited (ESIL). AM/NS India acquired the assets of ESIL in December 2019.

Module II was adapted for hot discharge/hot transport to the melt shop in 2000, and oxygen injection was added.

Module II has produced more than 15.5 million metric tons (tonnes) since initial start-up, and all six modules combined have produced over 96 Mt of hot DRI (HDRI), hot briquetted iron (HBI), and cold DRI (CDRI) since start-up of Modules I and II in 1990.

Read more about ArcelorMittal Nippon Steel India at: **https://www.amns.in**


## TT Iron Module I

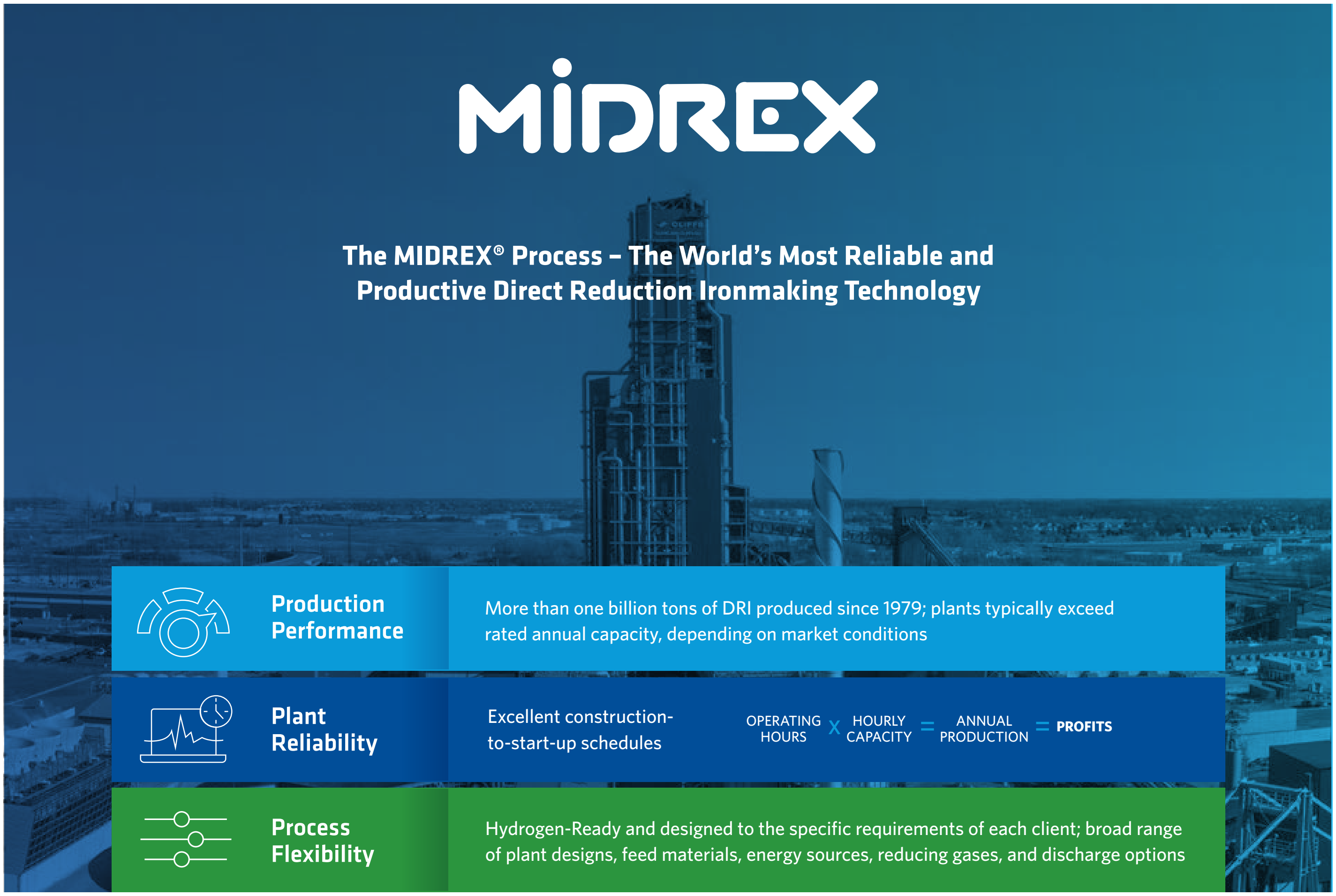
**Location:** Point Lisas, Trinidad and Tobago
**DR Plant:** 1st of 3 MIDREX® Modules

- **Start-up:** August 1980
- **Product:** CDRI
- **Rated Capacity:** 0.44 M t/y

TT Iron Steel Company (TT Iron) purchased the electric arc furnace-based (EAF) steel mill located in the Point Lisas Industrial Estate, Couva, Trinidad and Tobago, in mid-2023, and intends to produce low carbon emissions "green" steel using scrap and direct reduced iron (DRI) from a trio of MIDREX® Modules. The iron and steel complex was originally constructed for ISCOTT – the Iron and Steel Company of Trinidad and Tobago – and was most recently owned and operated by Arcelor Mittal Point Lisas Ltd.

TT Iron plans to refurbish the facilities, starting with the EAF melt shop, and including the natural gas-based MIDREX Modules. ArcelorMittal ceased operations in 2016.

Read more about TT Iron Steel Company (TT Iron) at: **https://ttiron.com**




Lauren Lorraine: **Editor**

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All references to tons are metric unless otherwise stated.

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