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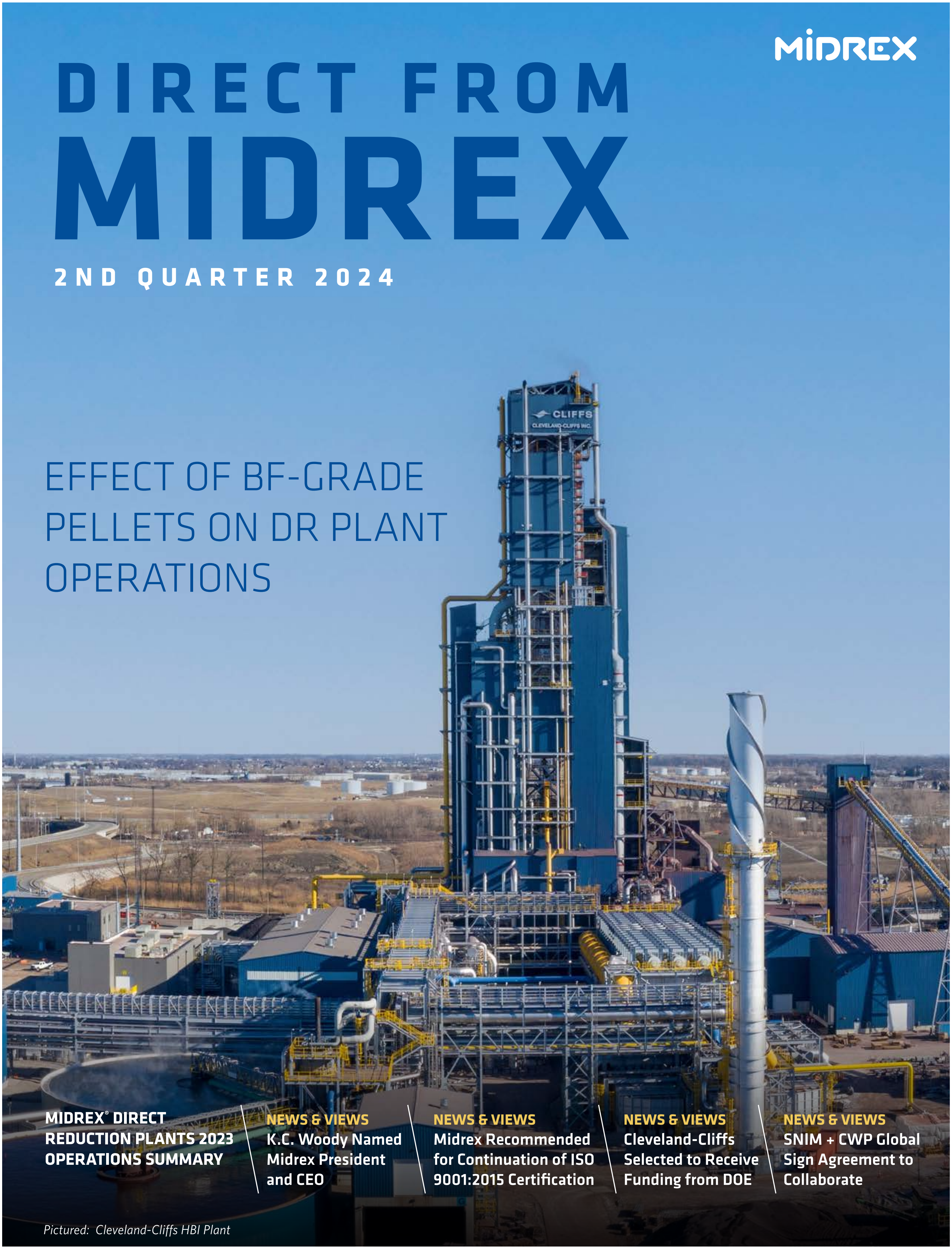

EFFECT OF BF-GRADE PELLETS ON DR PLANT OPERATIONS

Pictured: Cleveland-Cliffs HBI Plant

COMMENTARY

MIDREX TECHNICAL SERVICES
The Tie That Binds

By Ivan Simunovic
Manager, Technical Services

There are plants in operation today from every decade of the 50+ years that Midrex has been a company – a testimony to the reliability and flexibility of MIDREX® Direct Reduction Technology and the effectiveness of our approach to technology transfer. Midrex was one of the first US companies to embrace the idea of licensing its technology with ongoing support and services to promote national industrial development through local ownership, operation, and management.

Each time a MIDREX Plant is sold a Process License Agreement is signed that provides the customer with access to the latest technical innovations and improvements and the experience and expertise of successful plant operators who comprise the extended Midrex family. The free exchange and sharing of information between Midrex and its Process Licensees and among the plants themselves has been critical to the success of the MIDREX Process. Through this cooperation within the Midrex family, the technology is continually evaluated and upgraded to ensure it remains at the leading edge of modern ironmaking.

The primary function of Technical Services is to assist MIDREX Plant operators in maximizing plant performance and profitability. Often this involves coordinating responses from within Midrex by Process, Mechanical, Electrical & Instrumentation Engineering and Operations. We also contact equipment and materials vendors for their particular expertise on behalf of our licensees.

We are in contact with most MIDREX Plants throughout the year to see how process operations are going and whether they need additional support. In addition, we are responsible for suggesting design improvements for our plants and issuing Innovation & Improvement Bulletins, as well as Technical Services Bulletins to further aid in plant operations.

Perhaps the most effective tool for technology exchange and sharing is the International Conference on MIDREX® Technology (a.k.a. Operations Seminar) for Process Licensees. This annual event is organized by Technical Services to ensure the agenda is of timely interest and technical relevance to MIDREX Plant operators globally. We poll the plants to gear the program to their specific needs and schedule informative presentations by Midrex, relevant plants, and equipment/materials suppliers to address as many topics of interest as possible in an open forum.

I am privileged to follow in the footsteps of two men who were totally committed to representing the interests of the plants within Midrex – Anthony Elliot and Roy Ogden. They recognized that technology must be dynamic to flourish, a blending of theoretical knowledge and practical know-how. The close cooperation of Midrex and its Process Licensees has been instrumental in addressing the evolving wants and needs of the global iron and steel market in a sustainable manner.

Technical Services is the tie that binds together the Midrex family, and our value-added support is the hallmark of the commitment and dedication of Midrex to the continued success of the best direct reduction plant operators in the world.

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This issue of ***Direct From Midrex*** features an article about the effects of blast furnace-grade pellets on the operation of the Cleveland-Cliffs Toledo HBI plant and a report of on the operation of MIDREX Plants in 2023. News & Views reports on K.C. Woody being named President & CEO of Midrex and other notable executive promotions, recertification of Midrex to ISO 9001:2015, and plans of CWP Global and SNIM to build a green iron plant in Mauritania.

EFFECT OF BF-GRADE PELLETS ON DR PLANT OPERATIONS

By LISA YOUNG, *Sr. Operations Engineer, SP Cleveland-Cliffs Inc.*

INTRODUCTION

As Cleveland-Cliffs, Inc. (Cliffs) has grown as a steel producing company, hot briquetted iron (HBI) has been utilized across its facilities to reduce carbon footprint and increase throughput. Cliff's Toledo HBI plant was built to use a singular direct reduction (DR) grade pellet feedstock for production of low silica HBI for electric arc furnace (EAF) customers. However, with a change in down-stream customers, the sole use of DR-grade feedstock is no longer necessary.

The plant was designed by Midrex Technologies, Inc. with an 18-bay reformer and has a demonstrated annualized production capacity of 1.9 million tons per year (Mt/y) of HBI. The plant is equipped with six briquette machines having 1-meter diameter rolls. Initial quality targets were for low carbon HBI of approximately 95% metallization and 1.8% carbon. During commissioning, the feedstock was entirely DR-grade iron oxide pellets from Cliffs' Northshore Mine (NSM).

This article will provide an evaluation of how different pellet feed grades, both direct reduction (DR)-grade and blast furnace (BF)-grade, affect key plant operating parameters and product quality in a MIDREX® Shaft Furnace and the hot briquetting system.

	Total Iron (%)	SiO_2 (%)	Compression (kg)	Linder (760°C) Metallization (%)	Linder (760°C) Degradation (%)	Clustering Index* (%)
Preferred	67.0 (min)	2.0 (max)	250 (min)	93 (min)	2 (max)	20
Practical	66.0 (min)	3.5 (max)	150 (min)	91 (min)	5 (max)	-
NSM DR	67.5	2.0	220	93.8	2.1	27.5

TABLE I. *DR-Grade Pellet Characteristics*

** No coating applied*

EARLY STAGES OF PLANT OPERATION

Cliffs' Toledo HBI plant, as previously stated, was fully commissioned using NSM DR-grade pellets. This pellet has been sold externally and has undergone lab testing to determine pellet characteristics and to ensure its performance in the HBI plant. ***Table I*** displays the primary physical quality and reduction characteristics of pellets accepted for use in the Toledo HBI plant in comparison to the Midrex pellet design specifications.[1,2] Further pellet specifications can be found in ***Table II***.

The total iron content of the NSM DR-grade pellet and amount of gangue fit within the ranges stated in the Midrex specification. This was of prime importance because the Cliffs plant was built to supply HBI on the open market to EAF customers in the region. Silica content of the pellet feedstock is not normally an operational concern for DR plants but impacts downstream EAF customers.

The compression strength of the NSM DR-grade pellet was the largest variation from the preferred pellet specification, although it was still above the practical specification. Fines either inherent in the pellets or generated in the material off-loading and handling system contributed to issues in early operation including material build-up/plugging the chutes, hoppers, and furnace feed distribution legs, which caused operational upsets. The in-line pellet fines screen size was increased from 3.5 mesh to 3/8 inch to address the issue and modifications were made to the feed system, such as the addition/use of flushing water and chute redesign. These actions lessened the issues with feed delays to the furnace attributed to fines in the material.

	Northshore DR Grade	Hibbing High Compression	Hibbing Standard Compression
% Fe	67.20	65.90	66.19
% FeO	0.50	0.50	0.92
% SiO_2	2.00	4.50	4.47
% Al_2O_3	0.30	0.20	0.21
% CaO	1.00	0.63	0.37
% MgO	0.30	0.35	0.36
% Mn	0.15	0.10	0.10
% P	0.016	0.012	0.013
% S	0.002	0.002	0.002
% Na_2O	0.030	0.020	0.019
% K_2O	0.010	0.017	0.016
Compression Average, Kg	220	245	225

TABLE II. *Typical Cliffs Pellets Characteristics*

Pellet compression/breakage, while tolerable in the MIDREX® Shaft Furnace, tended to produce elevated fines in the top gas offtake, ultimately resulting in higher solids loading in the process water system.

For example, the highly metallized material would stick to the briquetter feed screws, as shown in ***Figure 1***. However, the issue with build-up on the briquetter feed screws was manageable due to the low frequency of occurrence.

FIGURE 1. *Build-up on Briquetter Feed Screw*

Performance data on the NSM DR-grade pellets was evaluated at bench-scale using clustering index testing (ISO11256) and Linder reducibility testing (ISO11258). The Linder test showed that NSM DR-grade pellets are more easily metallized than the preferred pellet standard and approached the preferred maximum degradation of a pellet in the furnace (mass fraction –3mm). This testing proved evident in early operation, with the typical plant metallization consistently exceeding 97% at the recommended process gas flow per ton (PGF/t). The PGF/t was decreased to sustain the target 95% metallization and allow for greater plant production without exceeding equipment limitations.

The clustering index of the coated sample was the most difficult to evaluate in early operation. Issues with consistent external coating and early plant upsets resulted in frequent clusters during operation. With increased operating knowledge and competency, control over furnace clustering has improved, allowing for operation to 895˚C Bustle Gas temperature with an oxide coating (dolomitic limestone slurry) application of 1.6 kg/ton of oxide on 100% NSM DR-grade with minimal cluster generation.

The Toledo HBI plant is set up with oxide yard management to supply a singular feed stock to the plant. It was a small challenge in early operation to consistently manage feed to the furnace and ensure a consistent feedstock with the first in/first out ideology. Feed to the furnace was able to be sustained evenly through three day bins, which were designed to support the offload period of cargo vessels to the oxide yard.

Prior to the plant entering operation, the preparation for maintenance regarding briquetter roll wear was established, assuming a lifetime of 100,000 tons per roll tyre, with one possible refurbishment per tyre set and a lifetime between 50,000-80,000 tons per briquetter feed screw. However, upon reaching the recommended 100,000 tons on the roll tyres, the wear did not justify refurbishing the rolls. As a result, roll tonnage for the tyres was increased to approximately 150,000 tons prior to the need to refurbish/replace, with some sets exceeding 200,000 tons prior to removal from operation. A similar extension of equipment life was experienced with the briquetter feed screws, with roll sets reaching 200,000 tons and more.

Product quality was varied during commissioning. When appropriate, material was utilized within Cliffs' blast furnace operations. Once optimized, material was produced and utilized by Cliffs internally and in various external EAFs. Use of HBI in blast furnaces across Cliffs has provided verification of the benefits of using HBI as a key burden component, which include:

- reduced fuel rate
- reduced carbon emission rates
- increased production capacity
- increased operating stability
- improved chemistry control compared to other metallic feedstocks.[3]

As the Toledo HBI plant reached operating stability, opportunities for optimization turned to the pellet feedstock. With the customer demand for HBI within Cliffs shifting from solely EAFs to including BFs, the need for a low gangue, high metallic iron content feedstock was decreased. This began the internal evaluation of pellet availability, pellet requirements for the direct reduction furnace, and determination of flexibility for chemistry of the HBI product.

EVALUATION OF ALTERNATE PELLET FEEDS

Pellet Characteristic Testing

One of the primary issues with the NSM DR-grade pellet was fines generation in the reduction furnace, attributed empirically low pellet compression strength. Therefore, a BF pellet source with high compression strength was preferred. Hibbing High Compression (HHC) pellets, typically with an average compression of 245 kg were identified as a pellet type that might improve the condition in the material handling system and the reduction furnace. The Hibbing Standard Compression (HSC) pellet was also tested. ***Table III*** shows comparison data of the HHC and HSC pellets. Similar lab-scale testing was performed on the BF-grade pellets, as with the NSM DR grade ***(see Table III, following page)***.

Cliff's Toledo HBI plant

	Total Iron (%)	SiO_2 (%)	Compression (kg)	Linder (760°C) Metallization (%)	Linder (760°C) Degradation (%)	Clustering Index* (%)
Preferred	67.0 (min)	2.0 (max)	250 (min)	93 (min)	2 (max)	20
Practical	66.0 (min)	3.5 (max) 150 (min)	91 (min)	5 (max)	-	-
Hibbing High Compression	65.9	2.0	245	96.3	0.8	27.5
Hibbing Standard Compression	66.2	4.45	225	96.1	3.9	15.2

TABLE III. *DR-Grade Pellet Characteristics*

** No coating applied*

Chemically, the HHC pellets were slightly below the total iron content recommended by Midrex. However, as previously stated, this minimum is expressed more as the ability to reduce to a suitable metallic iron content for EAF use. When producing HBI for BF use this was not a concern, as the primary focus for the blast furnace is metallization.

The 4.5% silica content of the HHC material was much higher than the Midrex preferred or practical maximums. With the understanding that the silica content would mainly affect the customer of the HBI, and with the HBI being used internally, the higher silica content was acceptable in the trial. The Linder testing of the HHC pellet for reducibility showed favorable reduction results, with a % metallization comparable to the NSM DR-grade pellets. Linder degradation data showed improvement over the NSM DR-grade pellets, which correlated with the desired outcome for testing of the higher compression pellet. Cluster index testing of the HHC pellet was lower than that of the NSM DR grade, with no applied coating on either sample. The lower clustering index provided some assurance the material would not cluster the furnace during the trial.

As with the HHC pellets, the HSC pellets had a lower total iron content and a greater silica content (4.45%) than the Midrex preferred or practical maximum. The Linder reducibility test showed favorable results for the HSC pellet compared to the Midrex specifications and to the data obtained from the NSM DR-grade pellets with respect to their operation in the direct reduction process. However, with the HSC pellets, the degradation of the material during Linder testing was elevated from the NSM material, causing concern for additional fines generation within the furnace. The clustering index of the HSC pellets without coating was even lower than that of the HHC pellets, causing less concern for clustering/continued operation in the direct reduction furnace.

PELLET TRIALS

The first BF pellet trial was performed with HHC pellets in November 2021. One vessel (~35,000 tons) of material was received onsite in Toledo. The plant has two main pellet storage areas from which material can be easily accessed and reclaimed for the feeding system. The two pellet storage areas are separated into east and west piles, with a total pile capacity of approximately 547,000 tons. Material is stacked/reclaimed from each pile by a single bucket wheel stacker reclaimer (BWSR). The BWSR can stack material from north to south (or inversely) but is only capable of reclaiming moving north to south.

This was the first time in operation when segregation of pellet feeds in the oxide yard became critical for feeding the furnace and classification of the HBI product. Material was segregated in the north end of one oxide pile that was most easily accessible for reclaiming, with the intent to mix it with NSM DR-grade material from the other pile for the trial.

Information for developing the test procedure for pellet trials in a direct reduction furnace was not available in the public domain. However, we were aware that other direct reduction plants have used high silica, BF-grade pellets for DRI/HBI production. While creating the testing procedure, the biggest risk to operation was identified as the possibility of clustering the furnace when changing the feedstock. Oxide coating and bustle gas temperature were determined to be the most effective control measures to limit this risk.

Prior to starting to feed the HHC material to the system, conservative system conditions were set to ensure plant upset caused by the material would be recoverable and not incur plant downtime. Although clustering of the material in the furnace was less of a concern than with the NSM DR-grade material, precautions were taken to ensure a smooth transition. The bustle gas temperature was limited, and the oxide coating application was increased to 1.90kg/ton. Operator monitoring of burden feeder hydraulic pressure was stressed, with cluster checks performed every two hours to monitor for any upsets. Production was limited to 215 tons/hour to hold process conditions constant for pellet evaluation.

To transition from 100% NSM DR-grade operation to 40% HHC/60% NSM DR-grade, a test plan was developed to step-up in 10% increments of HHC pellets. Each feed increase would be sustained for a period of two hours then returned to the previous feed mix (i.e., if the feed transitioned from 100% NSM DR to 10% HHC/90% NSM DR, it would return to 100% NSM DR after two hours of feeding). Feed would then be held at the previous rate for approximately 10 hours. This test would allow for monitoring the clustering behavior of the material as it exits the furnace and as it passes the burden feeders in the furnace without risking an upset of the entire furnace. The 10-hour return to previous feed time would allow the furnace to return to a known stable condition prior to making the full transition to unknown operation with the new feed mix. Once this hold period at the previous feed mix elapsed, the feed would transition to the two-hour mix rate for another 10 hours to allow for a full furnace turnover and taking approximately three samples to better understand how the process condition was affected by the feed mix. This process would be repeated through 40% HHC in the feed mix.

With the beginning of the 2023 shipping season, HHC material became a normal feedstock to the Toledo HBI plant and was run in varying 10% increments from 0-100% feed to the furnace, completing the first 100% HHC operation in May of 2022. With normalization of the HHC pellet feed to the plant, the oxide yard was segregated into a pile for each pellet grade (east & west) to ensure no mixing of higher silica pellets with the DR-grade. A day bin was permanently designated for the blast furnace pellet feed to assist with material segregation.

With the increase in wear from the HHC pellets, HSC pellets, a similar feedstock to the high compression pellet was trialed at the plant. The goal of trialing the HSC pellets was to determine if the wear on the briquetting equipment was caused by the compression increase of the HHC material or some other factor of the pellet. The HSC material was handled in the yard with HHC but remained accessible for reclaiming to the blast furnace pellet day bin and was tracked throughout the system. The HSC material was trialed under similar operating restrictions as for the HHC pellets, and performance was comparable to that of the HHC material. Minimal issues with fines in the material handling system were seen, similar to that of the NSM DR-grade pellets, and no major change to the slurry collection in the water system was observed. The change from HHC to HSC showed no noticeable change in the briquetting equipment wear and has since been accepted as a substitute for the HHC feed based on pellet availability.

RESULTS AND DISCUSSION

Core Process Operating Parameters

The first operating parameter evaluated in determining BF pellet operation in the system was changes necessary to process gas flow per ton (PGF/t). During the initial HHC trials in Q4 2021 and Q1 2022, the need to increase above the operating point for the NSM DR-grade (5% lower than recommended) was not observed. However, moving into 2022 operation, it proved necessary to increase to originally recommended PGF/t to sufficiently achieve 95% metallization with the BF pellet feed (primarily at 100%). This PGF/t matches with the initial operating recommendation for the plant but varies from the IU operating envelope developed with 100% NSM DR-grade feed. The changes in PGF/t to achieve a metallization of 95% (as collected from 2022 operating data) are shown in ***Figure 2.a., (following page)***.

The need for elevated PGF/t to achieve the targeted metallization places additional strain on the system. The increased PGF/t requires harder firing of the reformer combustion system to achieve complete reaction and sufficient exiting gas temperature. This increased firing leads to an increased reformer temperature and reaches the operating limitation for equipment protection of the catalyst tubes at a lower tonnage than operation with the DR-grade pellet.

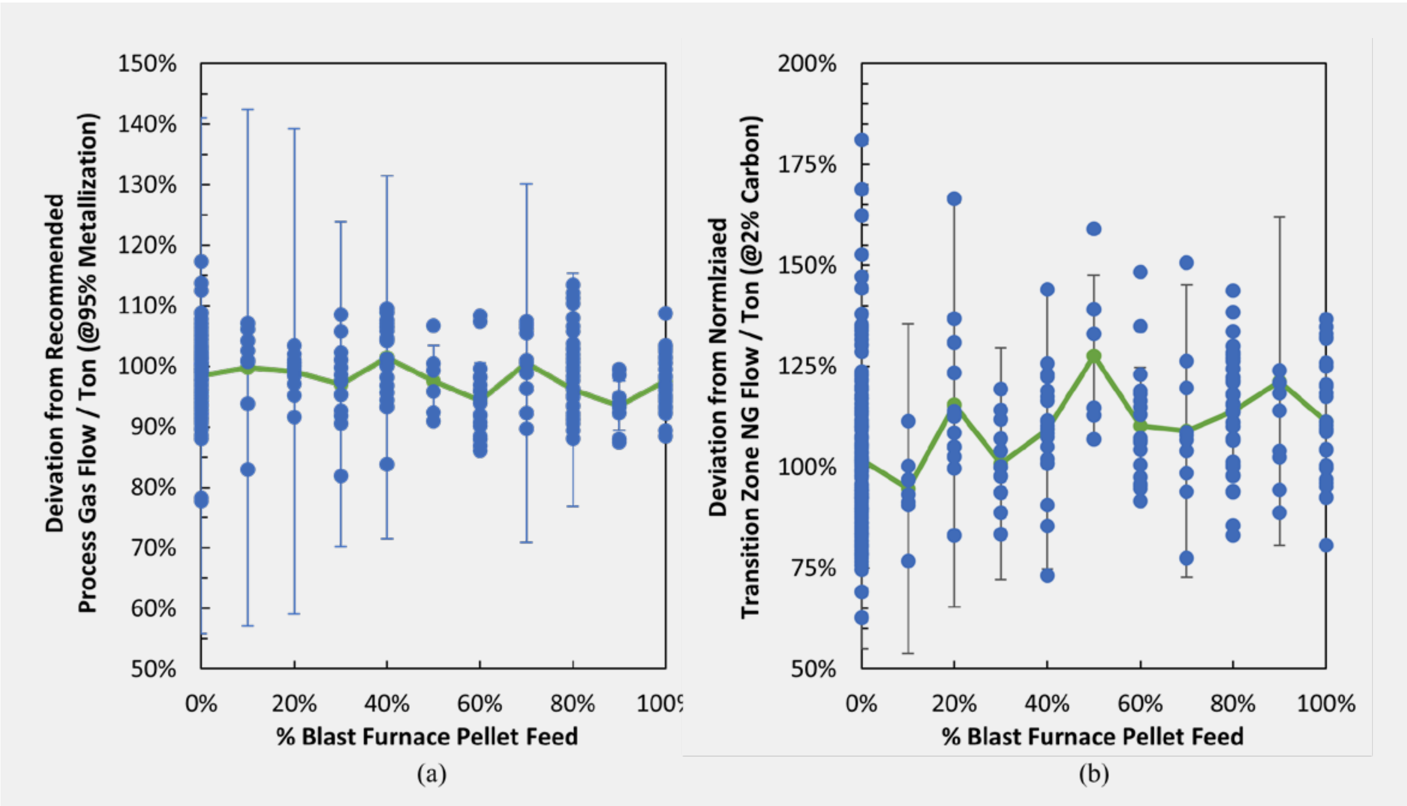

FIGURE 2. *(a) Process Gas Flow (Nm^3) Per Ton Necessary to Achieve 95% Metallization with Feed Mix Varied from 0 – 100% Blast Furnace Pellet Feed, (b) Transition Zone Natural Gas Flow (Nm^3) Necessary to Achieve 2% Carbon With Feed Mix Varied from 0-100% Blast Furnace Pellet Feed*

Carbon content for BF pellet material was slightly more difficult to achieve and required a slightly higher transition zone natural gas flow per ton (TZNG/t) to reach the 2% carbon target. Issues with increased TZNG to reach carbon target were emphasized by the decrease in lower bed temperatures (at similar bustle gas temperature) from operating on 100% NSM DR-grade pellets. With no clustering issues observed from the BF material, the bustle gas temperature was gradually increased 10°C. This temperature was the highest sustainable bustle gas temperature without oxygen injection, accounting for enrichment natural gas addition and sustaining production above that of plant design to reach production targets. With the realization that the increased bed temperature increased the product quality, the bustle gas temperature was sustained at the higher temperature and we were able to resolve the initial issues of achieving % metallization at the above mentioned PGF/t and increased product carbon content. The changes in TZNG/t to achieve a carbon content of 2%, as collected from 2022 operating data, are shown in ***Figure 2b***.

With the increased PGF/t necessary to achieve the desired % metallization, it was also expected that the natural gas consumption would increase per ton. The natural gas consumption (process natural gas and combustion gas) remained constant per ton regardless of BF pellet feed mix. However, the necessary TZNG consumption increased with BF pellet feed mix.

The fines generation internal to the system was expected to decrease following the Linder degradation testing data for the HHC pellets. The first shipment of HHC showed a decreased count of necessary filter press cycles for fines removal from the process water system. However, over time the filter press counts by material grade showed an increase, with BF pellet feed mixes leading to the conclusion that the fines generation/solids loading to the water system increased with the BF feed mix. This data is presented in ***Figure 3 (following page)***. The increased solids loading was unexpected with the lab-scale testing and is thought to be a result of pellet breakage. Possible sources of error are that the data is likely skewed to show fewer on 100% NSM due to issues with system operation early in 2022.

Ultimately, the determination of feed mix when consuming BF pellets was not a decision made by the core process operability. Instead, this decision was driven by operation of the briquetting machines (see “Briquetting: Increased Maintenance Activity” later in this article) and the desired chemical content of HBI for the customers.

The largest chemical difference of the HBI produced with 100% NSM DR-grade pellets and a mix with BF pellets is the increased gangue content. With this being an undesirable trait in HBI for EAF use, the low silica material (produced with 100% NSM DR-grade pellets) will be referred to and classified as “E-Grade.” HBI with a higher gangue content and thus lower total iron is produced for BF customers and classified as “B-Grade.”

Knowing the MIDREX Process is capable of producing HBI with a BF pellet, the production targets for % metallization (driving the metallic iron content and based on total iron) and % carbon were set with input from EAF and blast furnace customers). ***Table IV*** defines the typical product specification of E-Grade vs B-Grade HBI. E-Grade material typically is produced with 95% metallization, providing an 86.3% metallic iron content. The typical E-Grade carbon content is 2.1%. The silica content for the E-Grade material is typically 2.7%, with minor variance in the DR pellet feed stock. B-Grade material has typical metallization of 94% with metallic iron content of 83.9%. The carbon content of B-Grade is typically controlled at 2.0%. Typical Cliffs HBI specifications can be found in ***Table V***.

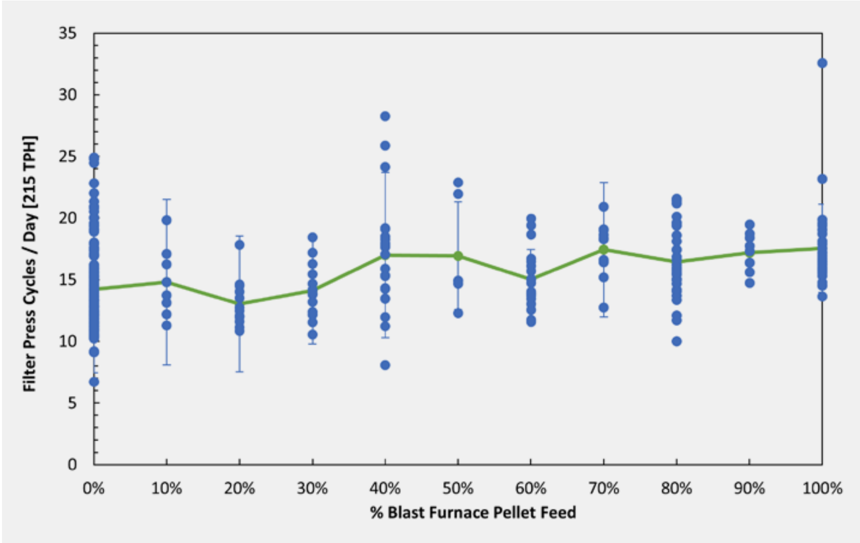

FIGURE 3. *Filter Press Cycles Per Day (Normalized To A Production Of 215 TPH) Varied Across Different Blast Furnace Feed Mixes*

	E Grade / Low Silica HBI			B Grade / High Silica HBI		
	Low Range	Typical	Upper Range	Low Range	Typical	Upper Range
Total Iron	89.0	90.6	92.3	86.7	89.0	91.3
Metallic Iron	82.5	86.3	90.1	78.5	83.9	89.3
Metallization	93%	95%	98%	91%	94%	98%
Carbon	1.3	2.1	2.9	1.3	2.0	2.6
SiO_2	2.2	2.7	3.2	3.0	5.6	6.5

TABLE IV. *HBI Product Ranges for Different Product Grades*

	E Grade / Low Silica HBI			B Grade / High Silica HBI		
	Low Range	Typical	Upper Range	Low Range	Typical	Upper Range
Total Iron	89.0	90.6	92.3	86.7	89.0	91.3
Metallic Iron	82.5	86.3	90.1	78.5	83.9	89.3
Metallization	93%	95%	98%	91%	94%	98%
Carbon	1.3	2.1	2.9	1.3	2.0	2.6
SiO_2	2.2	2.7	3.2	3.0	5.6	6.5
Al_2O_3	0.28	0.37	0.46	0.19	0.26	0.32
CaO	1.32	1.56	1.80	0.56	1.10	1.64
MgO	0.23	0.30	0.37	0.27	0.43	0.60
P	0.014	0.020	0.026	0.009	0.013	0.017

TABLE V. *Typical HBI Specification by Grade*

BRIQUETTING: INCREASED MAINTENANCE ACTIVITY

The largest impact on plant operation when adding BF pellets was the increased wear on the briquetting system. Slight wear on the briquetter feed screws was noticed during the first trial run of BF pellets. The baseline for wear, as stated previously, was understood to be 100,000 tons per tyre, with two uses of each tyre set (a new tyre and post refurbishment). After initial operation on 100% NSM DR-grade pellets, the wear life for the rolls was extended to 150,000 tons per tyre set (exceeding 200,000 tons at times). This tonnage was determined by setting the maximum land depth for refurbishment at 6 mm, with precautions for roll change taken around 4.5 mm, as recommended by the OEM. With the addition of BF pellets to the plant feed mix, the wear on the machines accelerated to approximately 85,000 tons per use. A visual comparison of the briquetting tyre wear ***(see Figure 4)*** shows the greatest wear at the lower tonnage with a mixed feedstock.

The operability of the briquetter roll drives when producing B-Grade HBI is also significant. With increased wear of the tyre, the material "sticks" in the pocket of the fixed roll instead of entering the string chute as a compact briquette and splits the string in half, causing issues with back-up at the roll drive. This issue is far more prevalent when operating with BF-grade pellet feed.

The feed screw wear also increased with the addition of a BF-grade pellet feed ***(see Figure 5)***. The intended feed screw wear was expected to be 50,000-80,000 tons. The wear on screw feeders prior to the addition of BF-grade pellets was minimal and the life of the feed screw shafts was approximately 200,000 tons. However, with the addition of BF-grade pellet feed, the life of the feed screws decreased to the originally predicted 50,000-80,000 tons.

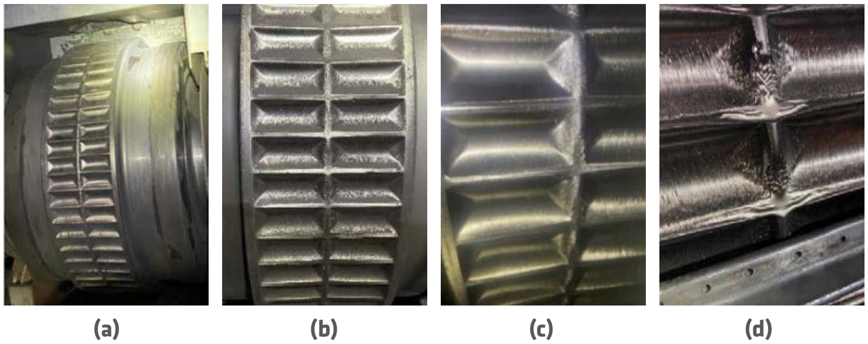

FIGURE 4. *(a) New Briquetting Tyre, (b) Briquetting Tyre After ~252,000 Tons With 100% DR-Grade Feed, (c) Briquetting Tyre After ~181,000 Tons With 100% DR Feed, And (d) Briquetting Tyre After ~165,000 Tons With Mixed DR/BF-Grade Feed*

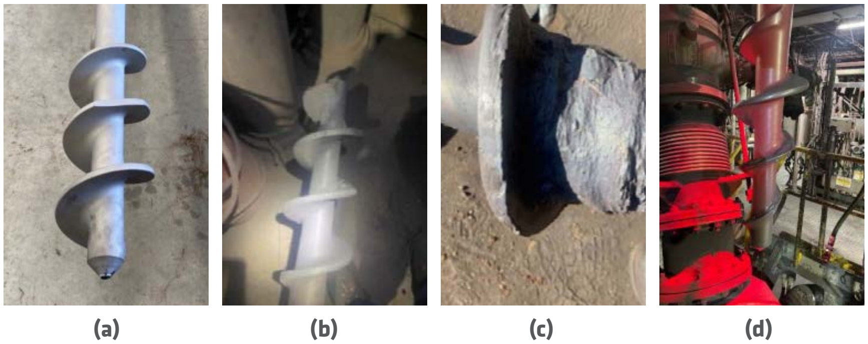

FIGURE 5. *(a) New Briquetter Feed Screw, (b Briquetter Feed Screw After ~181,334 Tons With 100% DR Feed, (c) Briquetter Feed Screw After ~120,000 Tons With 100% DR Feed, And (d) Briquetter Feed Screw After~48,900 Tons With Mixed DR/BF Feed*

Other operational issues when using BF-grade pellets were observed at the feed screws. On feed mixes of DR/BF-grade pellets, the torque on the feed screws was elevated and erratic while attempting to meet roll torque targets to form briquettes. While performing the 100% BF-grade pellet feed trial with HHC, it was observed that the operating torque of the briquetter feed screws was much more stable than when operating with any of the other feed mixes.

FUTURE WORK

With the wear identified on the briquetting equipment during initial operation with the BF-grade pellet feed, the wear rate of the equipment per ton of each pellet grade was examined. However, due to the customer demand between E-Grade and B-Grade, the time frame to evaluate wear has not been long enough to develop wear rates at different feed mixes of DR/BF-grade feed and at 100% blast furnace mix. The maintenance benefit of tracking the wear rates for predictive maintenance changes with feed stock changes would be beneficial to plant operation, pending production planning to extend production time frames.

The physical quality of E-Grade and B-Grade briquettes is also a topic under consideration. It is known that the total iron content and apparent density of the low silica B-Grade briquettes tends to be lower. However, the briquette strength and fines generation is currently not well understood. The need for varied operating roll torque to form briquettes at different feed mixes of DR/BF-grade pellets is a topic that should be investigated once the strength and fines generation of the two types at current operating parameters is known.

Options for pellet feedstock to Cliffs Toledo HBI plant vary; therefore, the evaluation of the effects of different feed stocks on plant operation and briquetting maintenance will continue as the plant is optimized and feed options are diversified.

CONCLUSIONS

Operation of the Cliffs Toledo HBI plant with BF-grade pellet feed mix has been successful in meeting quality and production targets. The HBI produced from the plant is classified in two product grades: E-Grade is a low silica HBI produced with 100% DR-grade pellets targeted for use in electric arc furnaces due to their gangue content sensitivity; B-Grade is a higher silica material made with a mix of BF-grade pellets targeted for use in blast furnaces to provide productivity benefit with its high metallization.

The operating baseline developed with the NSM DR-grade pellet proved the ability to achieve a higher product metallization at a PGF/ton lower than that achievable with the trialed BF-grade pellet feeds. This allowed for higher production rates while operating with NSM DR-grade. Operation with HHC/HSC pellets still allowed for plant production rates to be met but reached the core process limit when attempting to reach the necessary PGF/ton at similar production rates. Achieving the targeted carbon content with NSM DR-grade pellets was more easily achievable with a lower bustle gas temperature, which is ideal for a pellet with a higher clustering index. Reaching a similar carbon content with HHC and HSC material proved more difficult until the bustle gas temperature was increased. The increased temperature achieved the target carbon content; however, due to customer need for the HBI, the carbon content for B-Grade HBI was lower than that of E-Grade.

The largest impact on plant operation from the use of BF-grade pellets was the decrease in equipment life in the briquetting system compared with 100% NSM DR-grade operation. The increased system maintenance activities have challenged maintenance practices and repair cycles and increased equipment costs.

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This article is based on a paper titled "Impact of Direct Reduced and Blast Furnace Grade Pellet Feedstock on Direct-Reduced Iron Plants," which was presented by the author at *AISTech 2023,* 8–11 May 2023, in Detroit, Mich., USA. Any views or opinions presented in this article do not necessarily represent those of Cleveland-Cliffs, Inc., and Cleveland-Cliffs accepts no liability for the content of this article and for consequences of any action taken based on information contained therein.

Pictured: Hadeed, Module E, in Saudi Arabia

MIDREX® Plants produced 76 million metric tons (Mt) of direct reduced iron (DRI) in 2023, which is 3.3% more than the 73.56 Mt produced in 2022. The production total for 2023 was calculated from the 41.64 Mt confirmed by MIDREX Plants located outside of Iran and Russia (LGOK) and the estimated 34.36 Mt for MIDREX Plants in Iran and Russia (LGOK), which is based on data reported by the World Steel Association (WSA). Over 11 Mt of hot DRI (HDRI) were produced by MIDREX Plants, which were consumed in nearby steel shops to assist in reducing energy consumption per ton of steel produced and to increase productivity.

MIDREX Plants have produced a cumulative total of more than 1.39 billion tons of all forms of DRI (cold DRI, CDRI; hot DRI, HDRI; and hot briquetted iron, HBI) through the end of 2023.

MIDREX Technology continued to account for ~80% of worldwide production of DRI by shaft furnaces in 2023. At least nine MIDREX Modules* established new annual production records and at least nine established new monthly production records. Eleven additional modules came within 10% of their record annual production and 17 operated more than 8000 hours.

The Venezuelan plants (COMSIGUA, Ferrominera Orinoco, Sidor, and Venprecar) operated during 2023 at reduced capacities, but most of their production details were not available. No detailed production information has been received from the plants in Iran and LGOK from Russia. The following plants did not operate in 2023 due to commercial or market conditions: ArcelorMittal Point Lisas in Trinidad, ArcelorMittal South Africa, Delta Steel in Nigeria, ESISCO in Egypt, Lion DRI in Malaysia, and NSCL National Steel Complex Ltd (formerly Tuwairqi Steel Mills) in Pakistan.

** A MIDREX Plant can include one or more modules*

2023 PLANT HIGHLIGHTS

ALGERIAN QATARI STEEL (AQS)

In its second full year of operation, after starting up in March 2021 during the pandemic, AQS continued ramping up production to meet its steel shop's requirements. AQS set new annual production, electricity consumption, and operational time records in 2023, as well as a new monthly production record in December.

ANTARA STEEL MILLS

The first MIDREX HBI Module that started up in August 1984 operated 9% over its annual rated capacity. Total iron in its HBI was the highest of all MIDREX Plants, averaging 92.63% for the year. All production was shipped by water to third parties.

ARCELORMITTAL ACINDAR

In its 45th year of operation, the AM ACINDAR module operated the whole year below maximum capacity due to local market conditions in Argentina. AM ACINDAR has achieved the most production from a 5.5-meter MIDREX Shaft Furnace to date, with over 34 Mt of CDRI produced. AM ACINDAR set a new annual metallization record in 2023.

ARCELORMITTAL CANADA

In its 50th anniversary year, Module 1 operated a record 8542 hours, with a 99.6% plant availability. Module 2 surpassed the 30-Mt mark since start of production and operated with a 99.4% plant availability in 2023. The Module 2 average DRI total iron percentage for the year was the second highest of all MIDREX Plants at 92.04%.

ARCELORMITTAL HAMBURG

The longest-serving MIDREX Module operated at reduced capacity during the warmer months of the year due to the limited natural gas (NG) availability and high NG prices in Europe and remained shut down during the colder months of the year.

ARCELORMITTAL LÁZARO CARDENAS

AMLC produced 24% over its annual rated capacity of 1.2 Mt using almost exclusively oxide pellets made in its adjacent pellet plant. Its 6.5-meter reduction furnace has produced a total of 39.0 Mt of CDRI, the most by a single module to date.

Algerian Qatari Steel (AQS)

Antara Steel Mills

ArcelorMittal Acindar

ArcelorMittal Canada

ArcelorMittal Lazaro Cardenas

ArcelorMittal Hamburg

ARCELORMITTAL POINT LISAS

All three MIDREX Modules remained shut down throughout the year.

ARCELORMITTAL SOUTH AFRICA (SALDANHA WORKS)

This COREX® export gas-based MxCol® Plant was idled in January 2020 and remained shut down throughout 2023.

ARCELORMITTAL TEXAS HBI

The ArcelorMittal Texas 2.0 Mt/y HBI module located near Corpus Christi, Texas, USA, established new annual production, NG and electricity consumption, and operational time records in 2023, as well as a new monthly production record in May. In July 2022, ArcelorMittal completed the acquisition of an 80% stake in the HBI plant from voestalpine AG (Austria).

ARCELORMITTAL/NIPPON STEEL INDIA

All six modules combined have produced over 91 Mt of HDRI, HBI, and CDRI since start-up of the first two modules in 1990. All modules combined fell 0.4% short of equaling their multi-module production record established in 2021. AM/NS India's Modules I, III, V, and VI operated above rated capacity and Modules III and VI surpassed the 15-Mt milestone. Approximately 96% of the output from the four HDRI/HBI modules was in the form of HDRI. Modules I and VI produce CDRI exclusively. Modules V and VI operated using top gas fuel-to-VPSA for CO_2 removal, and COREX gas was used to fuel the reformer burners. COREX gas represented 19-22% of the energy input. Mod IV established new annual productivity and electricity consumption records in 2023, as well as a new monthly production record in May. Modules V and VI operated over 8000 hours. Mod V established a new annual operational time record in 2023. Module VI established new annual production and productivity records in 2023, as well as a new monthly production record in June.

CLEVELAND-CLIFFS

In its third full year of operation, Cliffs operated 6% over its annual rated capacity and produced just 0.3% less than its annual production record set in 2022. Cliffs set new annual productivity, NG, and electricity consumption records in 2023, as well as a new monthly production record in August. The 1.6 Mt/y plant located in Toledo, Ohio, USA, produces HBI, mainly for consumption by internal Cleveland-Cliffs steel companies in the region.

ArcelorMittal Texas HBI

ArcelorMittal/Nippon Steel India

Cleveland-Cliffs

COMSIGUA

In their 25th anniversary year, COMSIGUA's production of HBI fell to an all-time low of ~35,000 metric tons (t), distributed over 5 months of the year.

DELTA STEEL

The two modules in Nigeria did not operate in 2023.

DRIC

Both of DRIC's modules in Dammam, Saudi Arabia, operated well above rated capacity and set a new combined module annual production record of 1.19 Mt. Module 1 set new annual production, productivity, and electricity consumption records in 2023, and broke monthly production records twice in 2023. Module 2 set a new annual electricity consumption record in 2023.

ESISCO

After shutting down in early March of 2020, Beshay Steel's MIDREX Plant remained shut down throughout 2023.

EZDK

Production was above rated capacity in all three modules, and with over 3 Mt of total production, the three modules exceeded their multi-module production record set in 2004. Module 1 surpassed the 30-Mt milestone and the three modules combined have produced over 74 Mt to date. Modules 1 and 2 set new annual electricity consumption records in 2023. Module 2 set a new annual production and productivity record in 2023.

FERROMINERA ORINOCO

Ferrominera Orinoco's HBI module in Puerto Ordaz, Venezuela, is reported to have produced small amounts of HBI (not exceeding 20,000 t per month) over a 6-month period for a total production of ~62,000 t in the year.

HADEED

In the 40th anniversary year from the start-up of Module A, the four MIDREX Modules at Hadeed in Saudi Arabia, surpassed the 109-Mt production milestone in 2023, and were within 2.4% of their total, multi-module annual production record set in 2013. Modules A and B were shut down for major maintenance in the months of May and June. Module B averaged 2.64% carbon in its DRI for the year, which was the second highest of all MIDREX Plants. Module B surpassed the 25-Mt mark, and Module C operated over 8200 hours to surpass the 30-Mt production milestone in 2023. Module E set a new annual operational time record in 2023, and was within 0.5% of its annual production record. With over 27.5 Mt produced to date, Module E has attained the most production from a 7.0-meter MIDREX Shaft Furnace. Hadeed also owns an HYL plant (Module D).

DRIC

EZDK

Hadeed Module E

JINDAL SHADEED

After establishing a new annual production record of 1.82 Mt in 2022, Jindal Shadeed's HOTLINK® Plant operated over its rated capacity of 1.5 Mt in 2023, and surpassed the 20-Mt milestone. Thanks to added HDRI bin capacity at the MIDREX Plant, 98.3% of production was consumed as HDRI in the steel shop that is physically attached to the DR Plant. The single module plant, located in Sohar, Oman, is designed to produce mostly HDRI, with HBI as a secondary product stream.

Jindal Shadeed

JSPL (ANGUL)

This is the first MxCol Plant using synthesis gas from coal gasifiers to produce both HDRI and CDRI for the adjacent steel shop. HDRI production was 54% of total production. Coke oven gas (COG) use in the DR plant continued throughout the year, averaging ~15% of the plant's energy requirements.

JSPL (Angul)

JSW STEEL (DOLVI)

JSW Steel's module producing CDRI handily exceeded its rated capacity and operated 8198 hours. Approximately 10% of the plant's energy input is COG injected to the shaft furnace to reduce NG consumption. JSW Steel (Dolvi) has averaged 8044 hours of operation per year since its initial start-up in 1994, and 8149 hours per year in the last 8 years.

JSW Steel (Dolvi)

JSW Steel (Toranagallu)

JSW STEEL (TORANAGALLU)

JSW Steel's HDRI/CDRI module in Toranagallu, Karnataka State, India, using COREX export gas as energy input, operated over 8000 hours and increased its production compared to 2022, although limited by the availability of COREX export gas. Fifty five percent of production went to the steel shop as HDRI, with the balance being CDRI. This is the second plant of its kind, the first being ArcelorMittal's COREX/MIDREX plant at Saldanha, South Africa, which is presently shut down.

LEBEDINSKY GOK

The production for 2023 was estimated, based on data for Russia reported by the World Steel Association (WSA) and the annual average from 2019-2022.

LGOK HBI-2

LGOK HBI-3

LION DRI

The Lion DRI module, located near Kuala Lumpur, Malaysia, remained shut down throughout 2023 due to competition from foreign steel products.

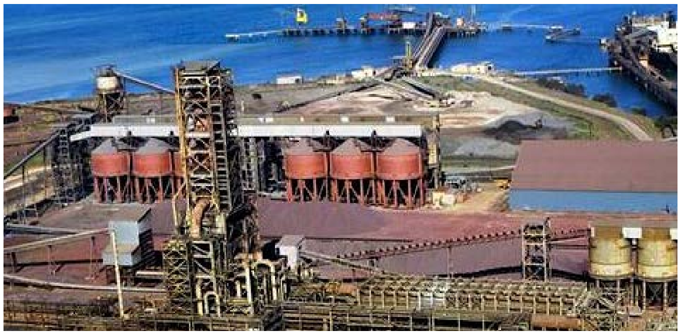
LISCO

Production by LISCO's two DRI modules and one HBI module in Misurata, Libya, showed a marked improvement in 2023 compared to previous years. Module 3, producing HBI mainly for export, ramped up production to 7.8% over rated capacity. Module 3 set new annual production and electricity consumption records and a new monthly production record in October. Modules 1 and 2 also ramped up production of CDRI to feed the LISCO steel shop. The three modules combined surpassed the 35-Mt milestone and set a new multi-module production record that was standing since 2005.

LISCO

NSCL (FORMERLY TUWAIRQI STEEL MILLS, LTD)

The 1.28 Mt/y combination plant, located near Karachi, Pakistan, did not operate in 2023 due to market conditions, 10 years after initial plant start-up. Ciena Group acquired the plant in April 2022, renaming it National Steel Complex Limited (NSCL).



Nu-Iron Unlimited

NU-IRON

Nucor's module in Trinidad and Tobago reported a production of 1.4 Mt of CDRI in 2023, despite a shutdown for routine major maintenance in September and October and downtime caused mainly by outside sources. Average DRI metallization and carbon for the year was the highest of all MIDREX Plants at over 96.2% and 2.72%, respectively.

OEMK

OEMK

In the 40th anniversary year from the start-up of Module I, the four MIDREX Modules in Stary Oskol, Russia, surpassed the 85-Mt production milestone in 2023. Module I set new annual production, productivity, and electricity consumption records in 2023, as well as a new monthly production record in July. Module II set new annual productivity and electricity consumption records in 2023, and broke its monthly production record twice in 2023. Module IV surpassed the 20-Mt milestone, as well set new annual production and electricity consumption records in 2023.

Qatar Steel Module 2

QATAR STEEL

In its 45th anniversary year, Module 1 remained shut down most of the year due to limited market demand. Module 2 operated 8048 hours in the year and produced over its annual rated capacity, supplying the adjacent steel mill in addition to producing over 500,000 t of CDRI and HBI for export. The complex surpassed the 50-Mt milestone in February 2023. Qatar Steel's Module 1 has produced over 28.3 Mt of DRI since its start-up in 1978, the most for a 5.0-meter shaft furnace.

SIDOR

Only Sidor's Module 2B has been reported to have produced DRI in 2023. The other three modules remained shut down.

SULB

In its 10th anniversary year, SULB's 1.5 Mt/y combination plant (simultaneous HDRI/CDRI production) in Bahrain broke its previous annual production record established in 2018. SULB also set a new annual operational time record in 2023, with 8468 hours. Of the total production, 83% was consumed by the adjacent steel shop as HDRI (98.5% of the DRI received by the steel shop) and 93% of more than 250,000 t of CDRI produced was exported by sea.

TENARISSIDERCA

TenarisSiderca's CDRI module in Argentina operated the entire year to satisfy the DRI demand from its steel shop, with the customary shutdown in the cold months of June, July, and August due to NG price. The module's average DRI metallization percentage for the year was the second highest of all MIDREX Plants at 95.37%.

TOSYALI ALGERIE

In its 5th anniversary year, Tosyali Holding's 2.5 Mt/year combination HDRI/CDRI module, located in Bethioua, near Oran, Algeria, produced just 0.4% less than its annual production record set in 2021, and surpassed the 10-Mt milestone since start-up in 2018. Tosyali has achieved the most production from a 7.5-meter MIDREX Shaft Furnace to date and set a new annual electricity consumption record in 2023. Over 76% of production went to the adjacent steel shop as HDRI. Together with Algerian Qatari Steel (AQS), this is the largest capacity MIDREX Module built to date.

VENPRECAR

VENPRECAR operated at minimum capacity as best possible due to a lack of raw materials and NG shutoffs.

SULB

TenarisSiderca

Tosyali Algérie

Midrex News & Views

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

K.C. Woody Named Midrex President and CEO, Stephen Montague Continues on Board, Dempsey and Boyle Promoted

K.C. Woody, Midrex President and CEO

"PEOPLE, GROWTH, AND TECHNOLOGY – HAVE BEEN OUR WATCHWORDS SINCE DAY ONE AND ARE POWERING US INTO OUR SECOND 50 YEARS OF TOTAL COMMITMENT TO BRINGING VALUE TO OUR CUSTOMERS."

- K.C. WOODY

Stephen Montague

Will Dempsey

Sean Boyle

K.C Woody has been named President & CEO of Midrex Technologies, Inc. effective immediately and Stephen Montague, former Midrex CEO will continue to serve on the Board of Directors.

Concurrently, Will Dempsey was appointed Chief Operating Officer (COO) and Sean Boyle was promoted to Vice President – Commercial.

Woody, a graduate of the U.S. Military Academy at West Point who served on active duty as an officer in the US Army, joined Midrex in 2010 and has held a variety of commercial roles including the first Managing Director of Midrex India Private Limited. He was named Director–Plant Sales in 2014, and was promoted to Vice President–Sales & Marketing in 2016. Woody became Chief Operating Officer (COO) in 2020, responsible for leading all the commercial and operations activities for the company, and in 2023, he was promoted to President of Midrex.

"Our industry has a key role to play in reducing global CO_2 emissions, and we are dedicated to creating a sustainable future for iron and steelmaking," Woody said. "We are continually evaluating our capabilities and adding resources that accentuate our culture of innovation, improvement, teamwork, and service."

Midrex News & Views

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Midrex Recommended for Continuation of ISO 9001:2015 Certification

Kobe Steel Ltd, parent company of MTI, requires its subsidiaries to have a Quality Management System, and certain clients require ISO 9001 certification.

Auditors from DQS Inc., a member of the IQNet network of 35 international certification organizations, have recommended Midrex for continuation of its certification under the 9001 ISO Standard following a recent three-day recertification audit. There were no nonconformities cited during the audit, and two strengths were noted in their report:

- Project Execution: "incorporation of lessons learned in this process provide continual improvements at all levels of operation exceedingly well."
- Quality System Auditing: "great care in planning and executing their internal audits. Internal auditors ... are rewarded for their training and hard work with pellet rewards ($$) which can be used for travel or gifts."

Midrex Headquarters was originally certified on June 17, 1998, for the "provision of contracted engineering services, technical staffing services, and equipment packages for industrial plants" including "procurement of original plant equipment and the supply of replacement parts." Midrex Technologies Gulf Services FZCO was added to the certification for "provision of contracted engineering services" and the Midrex Research & Development Technology Center for "I/T backup storage and new product and technology development."

Cleveland-Cliffs Selected to Receive $575 Million in US Department of Energy Investments for Two Projects to Accelerate Industrial Decarbonization Technologies

Congratulations to Cleveland-Cliffs for being selected! If awarded, the Company would replace its existing blast furnace at its Middletown Works Facility in Middletown, Ohio with a 2.5mtpa hydrogen-ready MIDREX Flex® Plant and two 120 MW Electric Melting Furnaces (EMF) to feed molten iron to the existing infrastructure already on site.

The process will dramatically reduce carbon emissions intensity and will consolidate Middletown Works as the most advanced, lowest GHG emitting integrated iron and steel facility in the world. The facility will have the flexibility to be fueled by natural gas, which would reduce current ironmaking carbon intensity by over 50%; a mix of natural gas and clean hydrogen; or clean hydrogen, which would reduce current ironmaking carbon intensity by over 90%.

Midrex News & Views

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

SNIM and CWP Global Agree to Explore Decarbonizing Mauritania's Iron Ore Production - Midrex Participates in Associated Workshop

Related to CWP Global's ultra-large-scale green hydrogen project, AMAN, sited in Mauritania's north-west corner, a new Direct Reduced Iron (DRI) hub project could host multiple green hydrogen based DRI plants capable of converting Mauritanian raw iron ore into millions of tonnes of green Hot Briquetted Iron (HBI) per year, predominantly for export to the European steel industry.

The MOU was signed last week at a meeting between SNIM and CWP Global in Nouakchott. A workshop was also attended by representatives from the Government of Mauritania, as well as senior representatives from leading technology provider Primetals Technologies, and Midrex Technologies, Inc., the industry leader for DRI technology.

Lauren Lorraine: Editor

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