Advancing Electric Smelting for Sustainable Iron Production: Pilot-Scale Validation of Controlled Open-Arc DC Technology



The steel industry is undergoing a fundamental shift toward decarbonization, with direct reduced iron (DRI) smelting emerging as a critical component in achieving sustainable steelmaking. To support this transition, Metix Pty Ltd. has developed the Controlled Open-Arc (SOAC™) smelting process, designed for efficient and flexible processing of DRI in an electric furnace. This article outlines the structured development of SOAC, following the Technology Readiness Level (TRL) framework from initial concept (TRL 1) to pilot-scale validation (TRL 8). Two smelting campaigns were completed at pyrometallurgical pilot facilities: 200-kW test furnace processing 10 tons of DRI and nominally 1,000-kW demonstration test processing 370 tons of DRI. The results confirmed the high efficiency, metal recovery and adaptability of the SOAC process, with key benefits attributed to controlled arc length, optimized feed distribution and enhanced furnace stability. This work contributes to the broader green steel initiative, demonstrating the potential of open-arc smelting in a sustainable and scalable electric smelting process.

Authors

Isabel Geldenhuys (top left), Metix Pty Ltd. (SMS group), Sandton, South Africa; and Isabel Geldenhuys Consulting, Johannesburg, South Africa
isabel@pyroconsult.co.za

Gerhard Terblanche (top right), Metix Pty Ltd. (SMS group), Sandton, South Africa

Stephan Louw (bottom), Metix Pty Ltd. (SMS group), Sandton, South Africa

Introduction

The global steel industry is undergoing a transformative shift toward decarbonization, with direct reduced iron (DRI) processes playing a crucial role in reducing carbon emissions. Electric smelting technologies are emerging as viable solutions within the green steel value chain, providing efficiency and flexibility through the utilization of sustainable energy and low-carbon DRI.

Metix Pty Ltd., as part of the SMS group, has been developing furnace technology to support this transition. As part of the green steel value chain, Metix supplied open-bath furnaces (OBFs) (2 x 100 MW units) to process pelletized DRI from a MIDREX® Direct Reduction Plant (DRP). The successful completion of this project is expected to contribute to a 3.5-million-metric-ton reduction in CO_2 emissions.[1]

The transition to low-carbon ironmaking requires robust and adaptable smelting technologies that can integrate seamlessly into existing steelmaking infrastructure. Open-arc smelting presents a unique advantage due to its inherent flexibility, intensity and process control capabilities. This presentation outlines the methodology adopted by Metix for the development of the Controlled Open-Arc (SOAC™) process, aimed at achieving sustainable iron production through effective electric smelting. The process aims to advance the state of the art for DRI smelting through intensification and efficiency benefits.

A structured technology road map, based on the Technology Readiness Level (TRL) framework, was developed to systematically advance the SOAC process.[2,3] This road map tracks via specific milestones the SOAC process from concept development (TRL 1–3), through pilot-scale validation (TRL 4–6), to large-scale demonstration (TRL 7–8), forming the basis of this case study. A summary of this progression is provided in Table 1.

Pilot-scale validation, to confirm and demonstrate the process benefits, was a critical step in this development, involving dedicated test units designed to evaluate key performance characteristics of controlled open-arc

Table 1

Summary of Controlled Open-Arc (SOAC™) Technology Development Across Technology Readiness Levels (TRLs)

TRL	Description	SOAC development milestone	Key outcomes
TRL 1–3	Concept development	Process feasibility assessment, theoretical modelling, initial furnace design studies	Established baseline smelting conditions, identified criteria for success, identified DC arc advantages
TRL 4–6	Pilot-scale validation	200-kW pilot test (10 tons of DRI) tested at MINTEK	Confirmed stable and accurate arc control, evaluated metallurgical behavior, tested feed distribution concept
TRL 7–8	Demonstration	1000-kW test (370 tons of DRI) operated under near-industrial conditions	Demonstrated scalability, process stability and benefits, confirmed high recovery efficiencies and energy requirements
TRL 9	Commercial implementation	Future: Full-scale industrial deployment of SOAC process technology	Ongoing planning for TRL 9 transition with commercial partners

smelting. These trials, conducted at MINTEK's pyrometallurgical pilot facilities in South Africa, provided essential data on furnace operation, process efficiency and scale-up feasibility. The findings contribute to the broader dialogue on decarbonizing ironmaking and advancing the electrification road map for the steel industry.

Background

The transformation of the steel industry is driving the adoption of new furnace technologies to replace traditional blast furnaces (BFs) in the BF-basic oxygen furnace (BOF) process route for producing molten pig iron (hot metal). Given that many of these new furnaces will be implemented in brownfield site installations — where the downstream steel process value chain, including hot metal (HM) desulfurization, remains unchanged — it is critical that any replacement technology meets stringent performance benchmarks. When an electric smelting furnace replaces existing smelting infrastructure (e.g., a blast furnace), the technology must satisfy the following key criteria:

1. Throughput and maintenance: The new furnace must match the productivity and reliability of blast furnaces.
2. Hot metal quality: Must maintain chemical energy for BOF steelmaking and ensure proper superheat for transport.
3. Slag compatibility: The slag should meet cementitious additive standards.
4. Energy efficiency: The process specific energy consumption (SEC) must align with economic and sustainability goals.
5. Feedstock flexibility: The furnace and process must be able to accommodate various low-carbon DRI feedstocks, including hydrogen-based DRI.

It is well established that direct reduction (DR) technologies are diverse within the steel industry,[4] and the choice of furnace technology will be closely linked with the selected DR process to ensure optimum processing. To maximize the value of the reduction step, the smelting process must efficiently utilize the direct reduction plant's output, whether the product is pellets, briquettes, lumpy feed or fines. In many cases, the optimal approach is to process the metallized product directly at elevated temperatures, thereby reducing the electrical energy required for smelting.

Smelting various DR products, typically referred to as direct reduced iron, with different degrees of metallization, metal content, gangue composition, particle size and temperature demands a furnace that is both flexible and robust. Open-arc smelting technology provides this flexibility and control due to the nature of the smelting mode, allowing for precise process adjustments and efficient smelting. For a smelting technology to integrate successfully into existing value chains, it must meet the listed performance criteria, while also being capable of processing low-carbon DRI, such as hydrogen-based reduced iron.

This background establishes the critical criteria that a smelting technology must satisfy to replace traditional blast furnaces without compromising production quality or throughput, while also offering the capability to process a variety of direct reduced iron feedstocks. While there is a shift toward green steel production, long-term success depends on ensuring that the process remains both economically viable and operationally sustainable.

Given these requirements, the SOAC process was developed to systematically address the technical and operational challenges of DRI smelting. To validate its feasibility, a structured testing program was designed, following a staged development approach from laboratory-scale feasibility studies to large-scale demonstration campaigns. The following section details the methodology and experimental framework adopted to evaluate SOAC technology at progressively increasing scales.

Methodology

Technology Development Road Map

A structured technology development road map was followed to advance the SOAC smelting principle for processing DRI from concept to pilot-scale validation. The TRL framework is widely used to assess the maturity of technological developments. This article details the SOAC process progression from concept to pilot-scale validation and demonstration, structured within the TRL framework.

1. Concept Development (TRL 1–3): Early-stage feasibility assessments, evaluation of process feasibility, furnace design principles, theoretical performance assessments, and modeling to establish the foundation and develop the concept for pilot readiness.
2. Pilot-Scale Validation (TRL 4–6): Experimental test work conducted to evaluate key performance characteristics including initial experimental work in a smaller-scale smelting furnace, processing about 10 tons of DRI to evaluate key performance parameters and confirm process viability.
3. Demonstration (TRL 7–8): A large-scale demonstration test, processing 370 tons of DRI under near-commercial conditions to assess scalability, energy efficiency and operational robustness.

Building upon the TRL framework, the next phase focused on concept development, where existing smelting processes were analyzed and engineering principles were applied to refine the SOAC approach.

Concept Development: SOAC technology stems from evaluating existing processes and applying fundamental engineering principles to DRI smelting in an electric furnace. The objective is to achieve a step change in understanding the fundamental mechanisms of smelting DRI in an open-arc mode, enabling the development of robust, well-understood engineering solutions for industrial deployment.

It is well established that both alternating current (AC) and direct current (DC) furnace configurations can be applied in various metallurgical process value chains, with the choice of technology depending on project-specific criteria and operational constraints. The most common distinction between AC and DC furnaces is the association of DC furnaces with the direct smelting of fines. However, when a furnace is operated without a burden (submerged-arc furnace configuration), direct smelting of fines can be achieved in both AC and DC furnaces — either through arc smelting or resistance heating (immersed electrode operation). Potential advantages of AC over DC arc smelting arise primarily from differences in arc properties and the mechanical design and geometry differences. Minor benefits associated with DC furnaces such as lower electrode consumption and the ability to process fines directly would not necessarily factor into the evaluation, although it may contribute to the overall efficiency of the process.

A relevant industrial example where both AC and DC smelting technologies have been successfully applied is the processing of titaniferous-rich feedstocks to produce titania-rich slag and pig iron. Different furnace configurations have been selected based on geographical conditions, historical factors and specific operational needs.[5] The following operations exemplify this:

1. Richards Bay Minerals (RBM), a subsidiary of Rio Tinto, operates four large-capacity rectangular AC furnaces (six in-line electrodes), processing beach sand–derived titaniferous materials, with titania-rich slag as the primary product.[6]
2. Tronox Namakwa Sands operates two circular DC furnaces with power inputs of 25 MW and 35 MW, processing ilmenite from beach sand deposits to produce titania-rich slag and pig iron.[7]
3. New Zealand Steel operates two rectangular AC furnaces (six-electrode configuration) to process prereduced ironsands (~80% metallization) for iron and vanadium recovery. These ironsands contain up to 70% titaniferous magnetite. Unlike ilmenite smelting, where slag is a valuable product, New Zealand Steel optimizes slag composition for iron and vanadium recovery, making slag a secondary byproduct rather than a primary product.[8]

Smelting of titaniferous feedstocks is characterized by the electrically conductive nature of the slag (due to the titania content) with the most extreme example being case studies for ilmenite smelting. The impact of smelting highly metallized feed on the effective electrical properties of the slag is an important furnace design consideration to ensure the power supply is specified correctly. In addition, all the referenced operations produce a pig iron product with post-taphole processing of the iron to meet specific product composition targets.

A similar approach is envisioned for the DC SOAC process. While many other examples exist, these industrial cases provide a high-level overview of how both AC and DC furnaces can be applied to smelting the same commodity type. The titaniferous feedstock processing example is particularly relevant to the SOAC technology because several aspects of these processes align with the objective of electric smelting of DRI feedstocks, particularly in terms of slag-metal interactions, arc stability and furnace operation strategies.

Conceptual assessments identified DC smelting, specifically controlling arc length and feed distribution, as a promising approach to advancing electric smelting of DRI. The technology aims to leverage the inherent DC arc stability, heat transfer efficiency and smelting intensity potential to optimize DRI smelting in the context of the sustainability objective.[9]

The ability to precisely control arc length is crucial in achieving optimal metallurgical performance and efficiency, a key benefit of DC arc smelting, as well as an upside to the smelting intensity potential.[10] The SOAC principle, namely stable and controlled arc smelting with balance power-to-feed control, applies to both AC and DC arc smelting. Due to the inherent benefits of DC, however, the validation and demonstration phases focused on assessing controlled open-arc smelting in a DC furnace configuration. The DC SOAC integrated in a typical steelmaking chain is presented in Fig. 1 to illustrate the envisioned integration.

Pilot-Scale Validation and Demonstration: The validation and demonstration phase followed conceptual development, with test parameters and furnace design tailored to assess the benefits of controlled open-arc smelting in a DC furnace.

Pilot-scale test work consisted of two dedicated smelting campaigns designed to evaluate the SOAC process under controlled conditions. The phased approach aligned with the evolution of the technology maturity, as defined through the TRLs. These campaigns were conducted at MINTEK's pyrometallurgical pilot facilities in South Africa, leveraging the existing infrastructure and operational experience for efficient execution. For each test, a bespoke test furnace was designed, fabricated and integrated into MINTEK's facilities to facilitate key test objectives, in particular the ability to distribute feed evenly around the arc attachment zone, the engine room of the controlled smelting process. The ability to balance the feed and power ratio is a key metric for any open-arc smelting process and is fundamental to the SOAC approach.

The two smelting projects are as follows:

Pilot Test Campaign 1 (OB1)

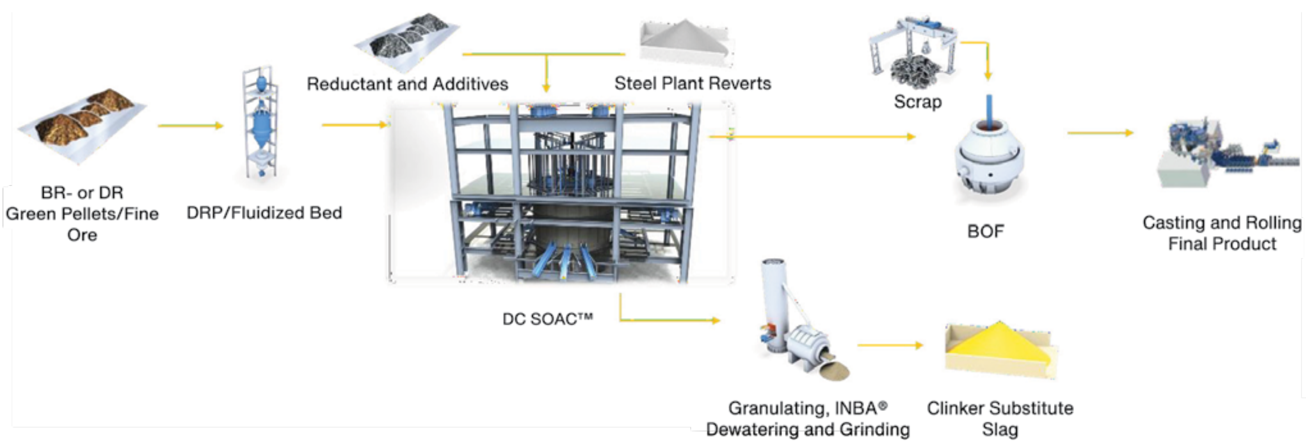
- Duration: 10 days (26 June–7 July 2023).
- Furnace specifications: 100 to 210 kW operating power (nominally 200 kW), single 150-mm graphite electrode (cathode) with embedded pin anode design, DC furnace, 1-m shell diameter, 760-mm working diameter (bath area).
- Material processed: ~10 metric tons of DRI.
- Objective: Initial assessment of arc and smelting behavior, metal-slag interactions, and process stability in a controlled open-arc environment.

Pilot Test Campaign 2 (OB2)

- Duration: 34 days (2 April–5 May 2024, 2–5 April commissioning and start-up), 29 days of smelting.
- Furnace specifications: 900 to 1,400 kW operating power (nominally 1,000 kW), 3.4-m shell diameter, DC test furnace, 2.4-m working diameter (bath area), centrally located 200-mm graphite electrode (cathode), embedded pin anode design.
- Material processed: ~370 metric tons of DRI.

Figure 1

Illustrative value chain with direct current (DC) as the primary processing unit for the direct reduced iron (DRI).



- Objective: Extended operation to assess scalability, energy efficiency and process consistency at higher throughputs.

The pilot test furnaces were integrated into the existing MINTEK facilities, leveraging available infrastructure to support efficient operation and reduce the development timeline. These facilities included the existing DC power supply and control systems, ensuring stable power delivery and precise furnace control; offgas handling and water-cooling systems, which maintained safe operating conditions; and feed and product handling logistics, enabling continuous feedstock input and effective metal/slag tapping. MINTEK's well-established pyrometallurgical pilot plant capacity enabled a fast-tracked approach to technology development, accelerating validation while minimizing capital investment in new infrastructure. The pilot campaigns were executed by MINTEK's operating teams, supported by round-the-clock engineering and metallurgical expertise from Metix.

Key parameters assessed during the campaigns included arc stability, energy efficiency, feed distribution effectiveness and slag-metal interactions. These factors were critical in evaluating the scalability and feasibility of the SOAC process.

Equipment and Operational Overview

The first test unit, with a nominal 1-m-diameter water-cooled shell, included integrating a feed distribution system with four feed ports positioned around the central electrode. Approximately 10 tons of DRI were smelted. The arc length was controlled using an existing hoist and electrode clamp system to achieve a short, stable open arc while balancing the smelting zone in terms of feed and energy input. The feed was distributed equally around the arc attachment zone via four feed ports and demonstrated the benefits of controlled, metered feed when operating in open-arc mode. Key outcomes from the test included validation of the concept of controlled open-arc smelting for highly metallized DRI feed. The test demonstrated stable furnace operation could be achieved and provided valuable operational experience. In accordance with the principles of technology readiness, the test successfully passed the stage-gate for TRL 6.

For the demonstration test campaign, the furnace consisted of a 3.4-m shell. The furnace was designed with a feed arrangement that could distribute the feed around the electrode, as for the first test, as well as selectively toward the sidewalls. Approximately 370 tons of DRI was smelted together with fluxes and anthracite as reductant. The furnace was operated continuously to emulate an industrial operation as closely as practical. Additional equipment, a taphole drilling and plugging system for the metal taphole, temperature measurements, intensive sidewall cooling (plate coolers), and an on-line furnace camera, amongst others, completed the complex and integrate setup of the demonstration furnace.

Different operating regimes and test parameters were assessed during the demonstration test to determine the impact of variables such as the degree of reduction, smelting intensity, smelting mode (arc length) and recipes on the product quality, and the operability of the furnace. The demonstration-scale furnace was highly instrumented and included a dedicated carbon lance to inject carbon directly into the molten metal in the furnace to achieve in situ carburization during operation. The furnace offers the unique opportunity to operate the process as close as possible to industrial conditions while still being able to evaluate and measure the impact of changes to test parameters at a significant scale, which is not typically practical on an industrial operation.

The general arrangement and setup for the two test furnaces are presented in Fig. 2 while the controlled and targeted feed arrangements for the furnaces are illustrated via the roof designs presented in Fig. 3.

The primary objective of this article is to demonstrate the successful progression of the

Figure 2

Controlled open-arc pilot furnace setup at MINTEK during pilot testing, 1-m furnace (left) and 3.4-m furnace (right) used for validation and demonstration test phases respectively. Photos by I.J. Geldenhuys (2023, 2024).

Figure 3

The pilot furnace roof designs illustrate the intended distribution of feed through strategically located feed ports for two pilot furnaces (feed ports highlighted in blue, diagrams not to scale, 1-m furnace roof (a), 3.4-m furnace roof (b)).

View of the 1-m-diameter pilot furnace roof with four feed ports around the centrally located electrode.

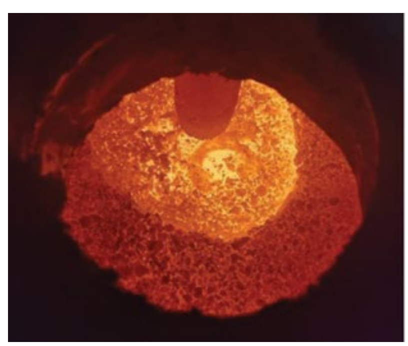
(a)

View of the 3.4-m-diameter pilot furnace roof with four centrally located and eight peripheral feed ports.

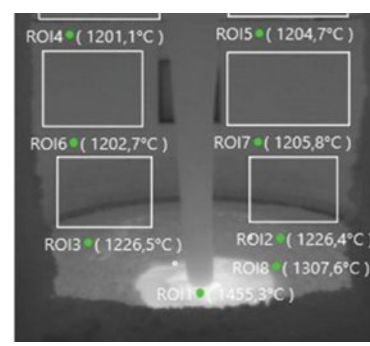
(b)

Figure 4

View of feed distribution achieved with the controlled feed and arc length. 1-m furnace (a), 3.4-m furnace (b). Photographs of the operating condition the 3.4-m campaign captured with an AMETEK LAND thermal imaging camera.



(a)



(b)

process through the TRLs, validating the controlled open-arc smelting approach. While key findings are discussed, detailed analyses of specific test aspects will be presented in future publications.

Each furnace was specifically designed to enable testing the benefits of controlled feed and controlled arc length smelting with strategically located feed ports and dedicated feed distribution systems. It is unique for pilot-scale furnaces to be designed with multiple-feed ports, as typically, space constraints are associated with a small furnace, and the complexities seldom justify the additional cost and complexity for a short-term test. However, as a keystone of the technology, Metix designed both test furnaces with the capacity to distribute feed evenly around the electrode, which enhances the test outcomes when assessing the maturity of the technology.

Considering the roof designs presented in Fig. 3, Fig. 4 presents a view of the feed distribution and internal view of the furnace during the two campaigns. Fig. 4a shows the even fed distribution achieved in the small furnace. The feed cover is clearly visible (with power off), while an active zone is visible in the center underneath the electrode tip. The view of the internal condition of the furnace during the second campaign (with power off) is presented in Fig. 4b demonstrating the transferred concept to the scaled-up operation. The arc attachment zone is key to successful management of an open-arc furnace, as described elsewhere,[11] and the test work configuration demonstrated that this aspect of the open-arc smelting can be well managed with distributed feed for highly metallized DRI.

Results

The smelting results from the two test campaigns provide a high-density data set covering all aspects of the smelting process. Pilot-scale tests typically generate a large volume of interconnected data, encompassing feed materials, process conditions, product compositions, energy consumption and refractory performance.

The test program demonstrated that key success criteria and performance objectives were met for DRI smelting in open-arc mode. Other aspects included evaluations of the performance of the mechanical design of the furnace, the refractory performance, energy efficiency, and finally slag and metal properties and quality of the product. The following sections present an overview of the technological advancements achieved during the tests, rather than focusing on specific technical aspects in detail. Additional technical information is included for context to illustrate the progression from validation to demonstration scale.

Feed Materials

The DRI compositions for the two test phases are presented in Table 2, providing a comparative overview of the total iron content, average degree of metallization, and general appearance of the DRI from both tests is provided for reference.

The material tested during the first campaign consisted of DRI produced directly from crushed ore, while the second campaign processed DRI in pellet form. Due to the shape of the pelletized DRI, the overall behavior of the bath cover was a key aspect evaluated in the open-arc, open-bath operating mode.

The gangue composition and iron content influence the fluxing ratios required to produce a targeted slag. This is important if the slag is used downstream as a cementitious additive. The total Fe and C content, as well as the degree of metallization, are key factors in determining the metal product composition, Fe recovery and the required reductant to achieve the targeted outcome.

Table 2

General DRI Composition During the Two Smelting Campaigns (mass %)

Component	Campaign 1	Campaign 2
Quantity	10 tons	370 tons
General appearance of the DRI processed during the pilot tests		
Al_2O_3	0.20	0.96
CaO	5.49	1.07
Cr_2O_3	0.19	0.01
Fe (total)	88.5	87.0
MgO	2.63	1.87
MnO	0.73	0.09
SiO_2	1.41	5.03
C	<1.21	2.32
P	0.08	0.06
S	0.06	0.01
Fe (metallization)	~80%	~90%

Reductants and fluxes were selected for their primary role in the process recipe and were not test variables under evaluation. The reductants, South African anthracite, had fixed carbon contents of 82% in campaign 1 and 78% in campaign 2, respectively. To adjust the silica concentration in the slag, silica sand and quartzite were used. In the second campaign, bauxite was added to regulate alumina levels. Limestone and dolomite were used as fluxes in the first test, while in the larger test, burnt lime and calcined dolomite were used to avoid the additional energy consumption associated with the decomposition of limestone and dolomite during smelting.

Operating Results

Throughout both test campaigns, metal and slag compositions varied due to upset or start-up conditions, transitions in recipes or operating parameters, normal operating variations, or intentional changes. However, periods of operational stability and consistency were achieved in both campaigns.

The large-scale test provided the opportunity to assess a broader range of variables compared to the smaller validation test. Metal and slag were extracted from separate tapholes, with successful slag and metal tapping serving as a key outcome in validating and demonstrating the process. The separate tapholes ensured that the slag inventory in the furnace remained reasonably consistent. A dedicated feed system integrated into the control system ensured that the power-to-feed ratio is managed aligned with the targeted operating regime. While the two campaigns were run on different facilities, the control methodology is the same. The power supply was common to both tests, although for the first campaign the power is supplied by one half of the DC power supply.

A summary of the overall operational results, and the results for stable operation at a set operating regime, is presented in Table 4. For cases where inventory effects may skew the result, the data is only reported for the overall campaign; this is particularly relevant for the small-scale test. Operating results from the two campaigns are included and discussed in the following sections referencing the results presented in Table 4 where applicable, while additional information is presented to provide context.

Campaign 1: The first pilot campaign processed about 10 tons of DRI, with an average Fe content of 88.5% and 80% metallization. A total of 1,104 kg of anthracite was charged as the reductant during the test. As part of the slag modification strategy, 321 kg of silica sand and 1,616 kg of a limestone-dolomite blend (mixed in a ratio of ~2:1) were added to the recipe.[12]

The furnace was operated with a power input of about 160 to 210 kW, depending on the test condition. At this scale, the thermal efficiency of the furnace is lower due to the higher relative rate of energy loss. The average rate of energy loss from the small-scale furnace was about 96 kWh/hour (also referred to as “heat losses”). The lower thermal efficiency at this scale means that the furnace was operated with high total bath power (kW/m^2), which is typical for smaller furnaces, and for this reason the smelting intensities are preferentially expressed as kg/hour/m^2 to show the progressive nature of the tests. For campaign 1, the smelting intensity when operating at 210 kW, based on the installed bath diameter, was about 216 kg/hour total feed per m^2. The equivalent smelting intensity, due to the lower thermal efficiency would be about 424 kW/m^2, which is high for a small furnace but typical for the DC open-arc smelting regime.

The feed mixture was introduced through four individual hoppers located above the furnace. Due to system limitations that allowed for only four feed streams, the dolomite and limestone were preblended before being added in the desired ratios. The four feed streams combined in a final feed bin, from where the mixture was evenly distributed around the electrode. For the smaller furnace, a 150-mm-diameter electrode is the standard size used by MINTEK. The existing electrode clamp and hoist system was used, and the hoist system controls the voltage at a specific target. The arc length in turn is correlated to a voltage range for a given operating regime and through the control of the power and voltage, a specific arc length (voltage) is maintained through the automation of the control loop in the control system. With the DC power supply, this is easy to manage due to the inherent stability of the DC arc. As presented in Fig. 4, even for the smaller test the controlled arc length and feed distribution was well managed using this basic principle.

Following the initial validation in campaign 1, the second smelting campaign (campaign 2) was conducted at a larger scale to assess process scalability and efficiency under near-commercial conditions.

Campaign 2: During the second smelting campaign, about 370 tons of DRI were successfully smelted. The furnace was operated with a range of power inputs, starting from 900 to 1,400 kW, depending on the test condition. At this scale, the thermal efficiency of the furnace improves significantly, especially as the furnace operating power increases. The rate of energy loss for the demonstration test was about 280–380 kWh/hour, depending on the operating conditions and operational stability. The overall average rate of energy loss was about 350 kWh/hour. In comparison, the smelting intensity for the larger furnace is lower, because the thermal efficiency is higher as the scale increases. However, the smelting intensities expressed as kg/hour/m^2, is comparable and demonstrates the value of the scaled test methodology, but also that the outcomes from campaign 1 were good predictors of the smelting behavior. During campaign 2, the smelting intensity was increased systematically, demonstrating that the process is robust and significant intensification is likely feasible.

The overall material consumption and process ratios are presented in Table 3, which also includes the typical batch size. The batches are linked to the tapping sequence followed during the test. Operationally, the process was managed in batches. That is, for each batch, the recipe, energy input requirement and feeding rate determine when the furnace is tapped. The furnace is periodically tapped to manage the inventory in a systematic manner. A batch typically consisted of about 2.5 tons of DRI, mixed with reductant and fluxes according to targeted ratios. The overall mass accountability and inventory management was good, with an average metal mass per tap of 2.3 tons of metal, which is well aligned with the batch size and the expected conversion ratio to metal.

The mixture was fed through a metered feed system, with the feeding rate carefully controlled to balance the power-to-feed ratio. The power-to-feed ratio is optimized to achieve the desired operating temperature and metallurgical outcomes. Its management is crucial for maintaining process stability, alongside arc length control and feed distribution.

Comparative Results

The results summarized in Table 2 compare key process outcomes of the two test campaigns, including subperiods where operating targets and conditions remained stable.

Overall, both test campaigns demonstrated high Fe recovery rates. Campaign 1 recorded a residual FeO

Table 3

Quantities of Raw Materials Consumed During Campaign 2 (3.4-m Furnace)

Material type	Total mass processed (metric tons)	Average ratio (% of DRI)	Average batch size (kg/batch)
DRI pellets	371	—	2,539
Anthracite	22.7	6.1	156
Total flux	60.4	16.3	414
Limestone	34.9	9.4	239
Dolomite	2.4	0.6	16
Quartz	18.4	5.0	126
Bauxite	4.7	1.3	32
Total feed	454	—	3,108

Table 4

General Operational Results From the Pilot-Scale Tests, Overall and Stable Subperiods at Targeted Power Level

Aspect	Overall test1	SOAC 210 kW	Overall test 2	SOAC 1,000 kW	SOAC 1,200 kW	SOAC 1,400 kW
Duration (hours)	221.9	55.3	699.0	116.5	35.8	52.5
DRI processed (kg)	10,764	3,134	370,632	59,160	25,966	37,513
Anthracite consumed (t)	1,104	283	22,736	5,297	1,530	1,547
Anthracite addition (%)	10.2	9.0	6.1	9.0	5.9	4.1
C addition (kg/t DRI)	84	74	48	71	46	33
Total flux consumed (t)	1,938	572	60,370	9,311	4,135	6,059
Metal product (t)	9997	3134	334.5	51,482	24,110	32,142
Slag product (t)	1,606	598	82.2	12,655	5,800	9,074
Dust from offgas system (t)	439	—	5,762	1,271	332	517
Electrode consumption (kg/MWh)	2.55	—	2.29	—	—	—
Slag-to-DRI ratio (kg/t)	140	—	222	231	223	226
Metal-to-DRI ratio (kg/t)	920	—	902	870	929	887
Energy consumption (kWh)	31,288	7,970	481,726	82,662	28,980	23,351
Average power target and power target range (kW)	186 160–210	210	1,072 900–1,400	1,000	1,200	1,400
Average voltage target (V)	90	105	190	188	197	233
Average slag tap temperature (°C)	1,673	1,649	1,612	1,698	1,625	1,545
Average metal tap temperature (°C)	1,432	1,434	1,425	1,364	1,410	1,461
Average smelting intensity (bath area, total feed rate) (kg/h/m^2)	189	216	182	181	215	248
Metal composition (mass %)						
Fe (%)	94.0	94.0	95.3	94.2	95.1	95.9
C (%)	2.60	3.01	3.32	4.0	3.3	3.10
Si (%)	1.25	1.45	0.83	1.19	0.98	0.53
Slag composition (mass %)						
Al_2O_3 (%)	13.6	16.7	10.1	11.6	10.4	9.0
CaO (%)	34.8	43.5	43.3	46.9	43.3	43.1
FeO (%)	1.69	0.98	0.39	0.26	0.23	0.60
MgO (%)	7.51	4.32	8.4	7.4	8.1	8.1
SiO_2 (%)	31.2	30.3	34.6	31.7	34.8	35.7
TiO_2 (%)	0.38	0.23	1.02	0.57	0.89	1.67

content of ~1.5%, corresponding to 99.2% Fe recovery, while campaign 2 achieved FeO levels below 0.5%, equating to 99.7% Fe recovery. The improved Fe recovery in campaign 2 is attributed to scale effects, enhanced process stability and optimized slag inventory management. These findings confirm that controlled open-arc smelting effectively maximizes Fe recovery across different feed conditions.

For both tests, the furnace behavior during high carbon additions (anthracite) exhibited similar trends. Under highly reducing conditions, increased Si deportment to the metal phase was observed, along with higher energy consumption. During these conditions, metal with Si content of greater than 1% was produced, as illustrated by the results summarized in Table 4. This outcome also underscores the importance of carburization to meet BOF requirements, as increased reductant addition provided little carbon benefit while impacting the overall energy and operational efficiency of the process.

The DRI processed in campaign 1 contained approximately 1.2% C, while in campaign 2, the carbon content was 2.3% C. The objective of maximizing the metal C content through smelting, though constrained by the high metallization degree of the feed, resulted in highly reducing conditions. This, in turn, favored Si deportment to the metal phase, an endothermic reaction that increased energy demand. The test work provided an opportunity to assess the deportment of C to the metal phase as a function of reductant (carbon) addition and energy consumption. The test work confirmed that the metallurgical trends observed in the small-scale test (campaign 1) were reliable predictors of outcomes in the larger-scale test (campaign 2).

At the larger scale, more consistent metal and slag tapping was achieved due to the higher processing volumes and the ability to closely replicate industrial operating conditions. This also allowed for more consistent measurement of tapping temperatures. The process benefited from higher throughput operations (higher power input) and appeared to be most stable at elevated power levels. Despite differences in raw material composition and process scale, the results from both test campaigns aligned well in most respects. This consistency validates the SOAC process methodology, demonstrating its scalability and effectiveness for smelting highly metallized DRI feed in an electric furnace. The operational experience gained from these trials provides a strong foundation for further optimization and industrial deployment.

Conclusion

The TRL framework was successfully applied in the development of a smelting technology for the sustainable processing of DRI in an electric furnace. The controlled open-arc smelting process was systematically advanced from TRL 1 to TRL 8 following a structured approach to development and testing. The final stages of validation and demonstration testing were completed at MINTEK's facilities, utilizing Metix's bespoke-designed furnaces at an appropriate scale.

Pilot-scale tests confirmed the technical and operational advantages of open-arc smelting in a DC furnace. The expected metallurgical consumptions and requirements were defined and measured, and critical engineering parameters such as slag and metal properties could be assessed hands-on during the trials. The process was demonstrated to enable high metal recovery and process efficiency. The results highlighted the benefits of controlled arc length and balanced feed distribution, which contributed to stable operation and improved metallurgical performance.

The technology presents a compelling opportunity for the implementation of a highly efficient, flexible and compact smelting unit, particularly when employing a DC furnace configuration. The process has proven to be robust, with operational outcomes benefiting from higher throughput and greater adaptability to feed variations.

The insights gained from the pilot-scale campaigns form a critical foundation for the next stage of development — the transition from TRL 8 to TRL 9. Extensive test results, covering key aspects of furnace operation, feed behavior, process stability and product quality, provide the necessary data to support the future commercial implementation of the SOAC process. This marks a significant step toward scaling up sustainable ironmaking technologies, paving the way for a cleaner, more efficient and commercially viable pathway for green iron production.

Acknowledgments

The authors and Metix's management team express their sincere appreciation to MINTEK for their invaluable support and contributions during the installation and operation of the test furnaces. The collaboration between Metix and MINTEK played a crucial role in accelerating the progression from concept to demonstration within a highly accelerated schedule.

The authors would like to extend their gratitude to the MINTEK employees for their dedicated efforts in data collection and verification, data processing, 24-hour operational management, and day-to-day oversight of the test campaigns. Their commitment and expertise were instrumental to the successful execution of these trials. The commitment, expertise and contributions of the Metix team are acknowledged. The design, fabrication, installation, commissioning and operation of two technically advanced furnaces were successfully completed with less than 12 months — an achievement that would not be possible without the contributions of the entire team.

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AISTech This paper was presented at AISTech 2025 — The Iron & Steel Technology Conference and Exposition, Nashville, Tenn., USA, and published in the AISTech 2025 Conference Proceedings.