

Nitrogen dynamics in steels produced in electric arc furnace and the challenges for the future

Rubia Teodoro Silva ^{1*} 
Ismael Vemdrame Flores ¹ 

Abstract

The control of nitrogen content in steels produced via electric arc furnace (EAF) is one of the main metallurgical challenges faced by modern steelmaking, particularly considering the advancement of more sustainable and flexible production routes. This paper presents a technical review of the thermodynamic and kinetic mechanisms involved in nitrogen absorption in liquid steel, detailing the factors that influence its solubility, the incorporation pathways of the element, and the main methods used for its industrial control. The challenges of decarbonization are also discussed, with an emphasis on the implications of the transition to low-carbon technologies, such as hydrogen-based direct reduced iron (H-DRI), and their impact on the dynamics of nitrogen removal. By integrating fundamental knowledge with current operational approaches, this study aims to contribute to the improvement of EAF-based steelmaking processes focused on the production of high-quality steels.

Keywords: Electric Arc Furnace (EAF); Nitrogen control; Thermodynamics and kinetics; Decarbonization.

1. Introduction

Since its invention by Paul Héroult in 1889 [1], the electric arc furnace (EAF) has evolved into one of the main steelmaking processes, standing out for its flexibility in using different metallic charges. It can operate with different proportions of scrap, pig iron, and direct reduced iron (DRI) and/or hot briquetted iron (HBI). Electrical energy, supplied through the arc generated between the electrodes and the metallic charge, is directly applied inside the furnace, allowing for the melting of solid materials and the subsequent heating of the metal bath. In 2022, this route accounted for over 531 million tons of steel, representing 28.2% of global steel production [2]. In addition to its current relevance in terms of production volume, the EAF also plays a key role in the steel industry's energy transition, particularly due to its potential for lower specific CO₂ emissions compared to the integrated BF-BOF route, when operated with renewable electricity and low-impact metallic charges. While BF-BOF production can emit between 1.9 and 2.3 tons of CO₂ per ton of crude steel, the EAF operated with DRI/HBI and clean energy can significantly reduce this value to around 0.6 [3,4]. This emission gap has driven the development of new routes for producing low-carbon sponge iron, including the use of hydrogen or methane as reducing agents. In this context, the EAF emerges as a strategic route to support the

growth of sustainable steel production as a substitute for the blast furnace, especially in regions with a high share of renewable energy sources. However, the process still presents metallurgical challenges, such as high nitrogen absorption. Unlike the integrated BOF route, where the contact between steel and the atmosphere is limited, the EAF widely exposes the metal bath to air, resulting in significantly higher nitrogen contents—ranging from 70 to 120 ppm—compared to the typical 30–40 ppm observed in BOF operations [5].

Given the metallurgical challenges associated with the production of high-quality steels in electric arc furnaces, it is important to review and systematize the main mechanisms related to nitrogen absorption and control in liquid steel. Therefore, the objective of this review is to consolidate the fundamental thermodynamic and kinetic aspects governing nitrogen solubility and absorption, as well as the main strategies currently adopted in industrial practice. Initially, it is essential to understand the thermodynamic fundamentals governing nitrogen solubility in the metal bath, as described by Turkdogan [6], with emphasis on the influence of parameters such as temperature, carbon content, chemical activity, and slag composition, based on the models presented by Zhang et al. [7] and Zhan et al. [8]. The kinetic approach is also relevant, as it details the rate-limiting mechanisms

¹Universidade Federal do Rio de Janeiro, Programa de Engenharia Metalúrgica e de Materiais, Rio de Janeiro, RJ, Brasil.

*Corresponding author: rubiateodorosilva@gmail.com
E-mails: ismael@metalmat.ufrrj.br



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of absorption, highlighting the importance of the gas-metal interface, the presence of surface-active elements, and bath dynamics, as proposed by Irons et al. [9] and Zhang et al. [7]. Additionally, it is also crucial to understand the main nitrogen incorporation routes, via metallic charge, furnace atmosphere, and metal-slag interaction, as well as the operational conditions that enhance or mitigate absorption [10]. Currently, there are industrial strategies to control nitrogen content, such as the use of high-carbon DRI, injection of reducing gases (Ar, CO, CO₂), and slag modification, supported by studies from Pal [11], Wei et al. [12-14] and Zhan et al. [8]. Altogether, these aspects provide the basis for discussing nitrogen control in EAF steels and for improving practices associated with high-quality steel production.

2. Development

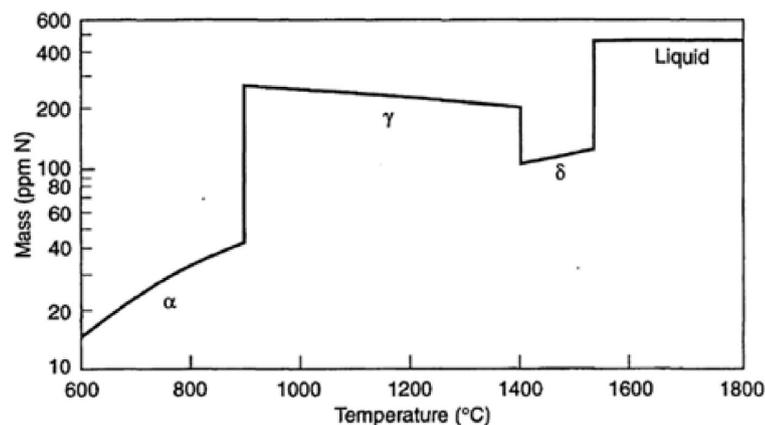
2.1 Thermodynamics of nitrogen incorporation

The control of nitrogen content during steel production in electric arc furnaces is a fundamental concern in the pursuit of high-quality steels. The dissolution of nitrogen in liquid steel within EAFs is governed by fundamental thermodynamic principles, which determine the equilibrium limit of the element in the metallic phase.

These conditions create a highly favorable environment for nitrogen absorption, with the process commonly described by Equation 1, which represents the dissociation of N₂ gas at the gas-metal interface. The equilibrium constant (K) associated with this reaction, which relates the concentration of dissolved nitrogen in the steel to the partial pressure of N₂, is expressed in Equation 2, both described in the book by Turkdogan [6]:



$$K = \frac{[ppm N]}{(pN_2)^{1/2}} \quad (2)$$



The thermodynamics of this process is largely governed by three main variables: temperature, the partial pressure of nitrogen, and the activity of dissolved nitrogen. The solubility of nitrogen in pure iron, as shown in Figure 1, is strongly influenced by temperature and by the allotropic phase of the metallic matrix. The element exhibits higher solubility in the liquid phase, especially at elevated temperatures, which is directly related to the increase in the equilibrium constant with temperature. The empirical equations used to describe this behavior in each phase of iron (α , γ , and liquid) are presented in the figure itself. Under these conditions, the maximum solubility of dissolved nitrogen in steel can reach values on the order of 450 ppm at a partial pressure of 1 atm.

At the beginning of EAF operation, particularly during the melting stage of the metallic charge, the furnace atmosphere is predominantly composed of air, which creates an environment with a high partial pressure of N₂ over the metal bath, favoring nitrogen absorption by the steel. At this stage, nitrogen dissolution is strongly influenced by variables such as carbon content, temperature, and nitrogen partial pressure. Figure 2 presents results from thermodynamic simulations representing the melting phase of a steel containing 0.2% Si, 0.75% Mn, and 0.03% S, evaluating nitrogen solubility as a function of these three operational variables. It can be observed that increasing the carbon content from 0.45% to 2.2% leads to a reduction in nitrogen solubility from 0.0320% to 0.0198%, while raising the temperature from 1550 °C to 1620 °C results in higher solubility, increasing from 0.0318% to 0.0332%. Finally, as the nitrogen partial pressure is increased from 0.2 P⁰ to 0.8 P⁰, solubility rises from 0.0178% to 0.0320%. The graphs compare the calculated values obtained from thermodynamic equilibrium of the dissolution reaction and the constants presented in the work by Zhang [7] with experimentally measured data. The difference between the results is due to the difficulty in achieving full equilibrium during experiments, which leads to slightly lower experimental values compared to the calculated ones.

SOLUBILITY OF NITROGEN IN PURE IRON IN DIFFERENT ALLOTROPIC PHASES OF THE METAL MATRIX (α , γ and liquid)

$$\log K_{\alpha,\delta} = -\frac{1570}{T} + 2.98$$

$$\log K_{\gamma} = -\frac{450}{T} + 2.05$$

$$\log K_l = -\frac{188}{T} + 2.76$$

Figure 1. Solubility of nitrogen in pure iron (or low-alloy steels) under a nitrogen partial pressure of 1 atm. The equations describe the variation of the equilibrium constant with temperature for the α , γ , and liquid phases [6].

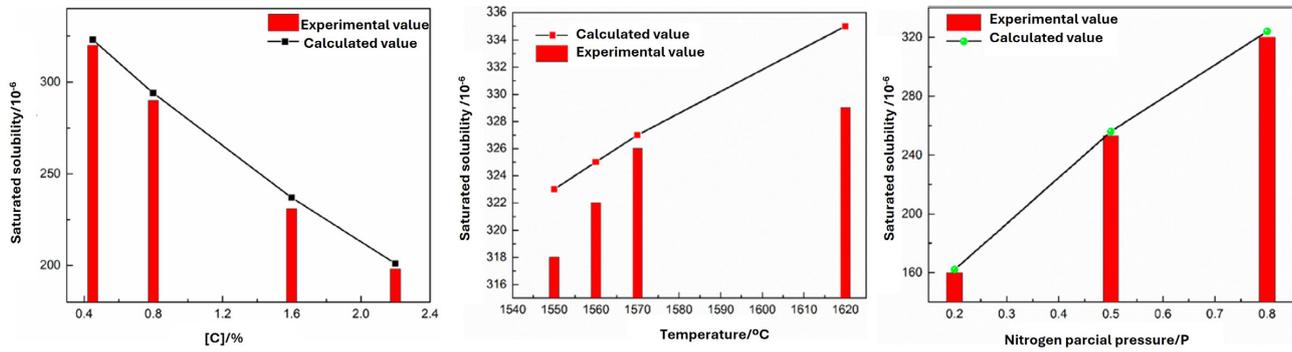


Figure 2. Nitrogen solubility in liquid steel as a function of carbon content, temperature and N_2 partial pressure during scrap melting [7].

An increase in carbon content in the bath reduces nitrogen activity and its solubility, while higher temperatures or nitrogen partial pressures promote its absorption. The curves used to illustrate these effects correspond to specific conditions during the initial melting of scrap, under an air-rich atmosphere. In these early stages, the partial pressure of N_2 exerts a strong influence; however, its relevance diminishes in the subsequent phases of the process, such as the oxygen-blowing and refining stages, where the presence of CO bubbles and foaming slag reduces gas exchange. Under these conditions, nitrogen absorption is effectively inhibited due to slag formation and the intense generation of CO bubbles, which lower the partial pressure of N_2 at the interface and isolate the metal bath from the atmosphere. As a result, in the later stages of the process, such as the oxygen-blowing stage, the dominant reaction becomes nitrogen removal from the steel, as demonstrated by Zhang et al. [7].

In addition to the effect of carbon content on nitrogen solubility, as shown in Figure 2, other elements present in the steel composition also influence the activity of dissolved nitrogen, altering its thermodynamic behavior. The electric arc during melting further contributes to the intensification of nitrogen absorption, particularly in the initial stages of the process. According to Zhang et al. [7], localized heating in the arc zone generates temperatures close to 10,000 °C, promoting the excitation and ionization of nitrogen molecules present in the air. In addition to temperature and nitrogen partial pressure, the activity of the element in the metallic solution is a key factor in the thermodynamic description of the dissolution reaction. Under ideal conditions, nitrogen activity is assumed to be proportional to its mole fraction in the bath. However, in real systems such as liquid steel, the presence of dissolved elements can significantly affect this activity by altering the activity coefficient f_N . These effects are particularly relevant in multicomponent alloys, as described by Turkdogan [6], where the interaction between atoms is quantified using binary interaction coefficients. The general equation describing the activity is by the Equation 3 below:

$$a_N = f_N \cdot [N] \quad (3)$$

Where a_N is the activity of nitrogen in the metal bath, f_N is the activity coefficient, and $[N]$ is the nitrogen concentration in ppm or %. The value of f_N can be estimated based on the alloy composition using the interaction coefficients e_i^j and e_j^i , according to the Equation 4:

$$\log f_i = e_i^j [\%i] + \sum e_i^j [\%j] \quad (4)$$

According to Turkdogan [6], elements such as aluminum, titanium, and silicon—due to their strong affinity for oxygen and nitride-forming tendencies—reduce the activity of dissolved nitrogen in liquid steel, thereby decreasing its solubility.

Carbon, although not forming stable nitrides, also contributes to a reduction in dissolved nitrogen content by lowering nitrogen activity and promoting nitrogen removal through kinetic mechanisms associated with CO formation. As discussed by Costa e Silva [15], both thermodynamic interactions in the Fe–N system and process-related effects lead to a decrease in nitrogen solubility with increasing carbon content. This behavior explains the similar decreasing trends observed for carbon and silicon in Figure 3, despite the different metallurgical mechanisms involved.

The relationship between the concentration of dissolved nitrogen and the partial pressure of nitrogen in the atmosphere can also be described by Henry's Law in Equation 5, adapted for metallurgical systems [10]:

$$[N] = K_N \cdot p_{N_2}^{1/2} \quad (5)$$

where K_N is Henry's constant, which is temperature dependent. In ferrous systems, K_H increases with temperature, indicating that nitrogen solubility is favored under high thermal conditions.

The concept of nitrogen partial pressure (p_{N_2}) is fundamental for understanding the incorporation of nitrogen into liquid steel. In atmospheres dominated by air or without protective coverage over the metal surface, (p_{N_2}) remains high, favoring nitrogen dissolution. In contrast, atmospheres modified with CO, CO_2 , or inert gases such as Ar reduce (p_{N_2}) and shift

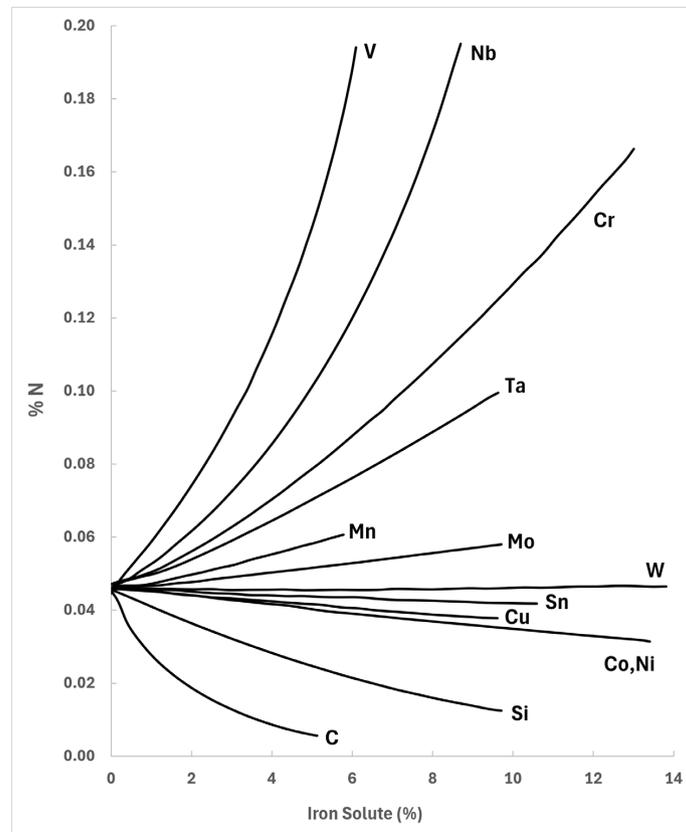


Figure 3. Effect of different solutes in steel on the solubility of nitrogen in steel at 1600°C and 1 atm. Adapted from Costa e Silva [15].

the equilibrium toward lower dissolved nitrogen concentrations. In EAF operations, this modification may occur naturally, for example, during decarburization with CO and CO₂ bubble formation, or be deliberately promoted through the injection of inert gases via lances or bottom stirring, thereby reducing the potential for nitrogen absorption.

The natural formation of slag during furnace operation primarily acts as a chemical barrier between the atmosphere and the metal surface, limiting the direct contact of gaseous nitrogen with the molten bath. This chemical isolation significantly reduces N₂ absorption, especially in the initial melting stages, even before the formation of a foaming slag layer. Studies also indicate that slag has the capacity to absorb nitride ions (N³⁻), which can combine with SiO₂ or Al₂O₃ networks within the slag structure, leading to a reduction in nitrogen solubility as the optical basicity increases [8]. This behavior can be described using the metal/slag partition coefficient (L_N), as shown in the Equation 6 below:

$$L_N = \frac{(N)_{slag}}{[N]_{metal}} \quad (6)$$

As the slag develops, through the injection of pulverized carbon and reactions with FeO, there is not only an enhancement of surface protection, but also the generation of CO bubbles, whose nitrogen partial pressure is nearly zero. These bubbles rise through the molten bath and create microenvironments that promote the removal of dissolved

nitrogen, provided that the residence time and concentration gradient are sufficient. Thus, foaming slag plays a dual role: physical protection and the indirect promotion of nitrogen removal via CO flushing [8].

A recent study [8] show that the chemical composition of slag significantly affects nitrogen transfer between the liquid steel and the slag phase. According to Zhan et al. [8], the partition coefficient L_N , which expresses the equilibrium ratio of nitrogen between the slag and the metal, decreases with increasing optical basicity and MgO content in the slag, indicating a lower capacity of the slag to retain nitrogen under such conditions, as illustrated in Figure 4. On the other hand, higher concentrations of Al₂O₃ result in a significant increase in L_N , suggesting that this oxide favors the dissolution and stabilization of nitride ions (N³⁻) within the slag matrix, particularly through interactions with SiO₂ and Al₂O₃ networks. This behavior indicates that slag functions not only as a physical barrier to gaseous nitrogen but also as an active thermodynamic agent in the fixation of the element. In this regard, the authors suggest that slag compositions with higher Al₂O₃ content and lower MgO content and optical basicity tend to be more effective in removing or retaining nitrogen in the slag phase, reinforcing its protective role in steel metallurgy.

Although the L_N value for basic systems (high CaO content) is typically varying between 15 and 50, knowledge of this parameter is useful for advanced thermodynamic modeling and may be relevant in specific experimental contexts.

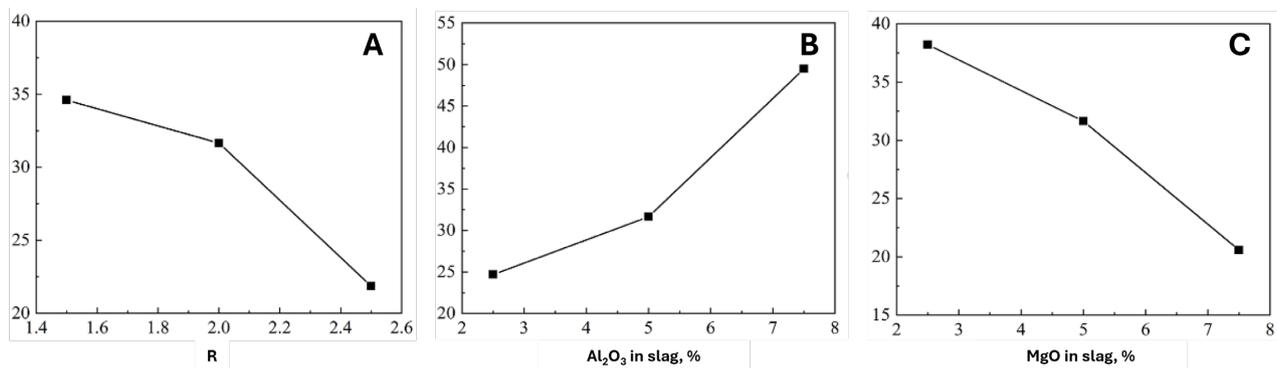


Figure 4. Influence of slag composition on the partition coefficient L_n : (a) correlation with basicity R ; (b) variation with Al_2O_3 content; (c) variation with MgO content [8].

2.2 Kinetics of nitrogen incorporation

Final composition, particularly in processes carried out in electric arc furnaces, is strongly influenced by the furnace atmosphere and the dynamic behavior of the metal bath, which vary significantly throughout the operation. Nitrogen uptake is governed by kinetic mechanisms that impose resistance to its absorption, even when thermodynamic conditions are favorable.

The mechanism of nitrogen absorption from the atmosphere, illustrated in Figure 5, involves a sequence of steps: the transport of molecular nitrogen (N_2) from the atmosphere to the surface of the metal bath, followed by molecular dissociation at the gas–metal–slag interface, and the subsequent diffusion of dissolved nitrogen atoms into the bulk of the liquid metal [7,9]. Each of these steps may represent an individual resistance to the process, potentially acting as the rate-limiting factor depending on the system conditions. It is important to emphasize that this mechanism specifically applies to nitrogen originating from the atmosphere. Nitrogen input from raw materials, such as DRI or pig iron with residual nitrogen content, follows distinct mechanisms associated with thermal decomposition and the release of the element during melting.

Classically, three main regimes are recognized as potential controllers of the overall nitrogen absorption rate: diffusion of N_2 in the gas phase, interfacial dissociation reaction, and diffusion of dissolved nitrogen within the liquid bath [6]. In general, under typical steelmaking operating conditions with the presence of slag, the interfacial dissociation of N_2 at the metal–gas or metal–slag interface tends to be the rate-limiting step, especially when the interface is not fully renewed by stirring [7]. This behavior is thermodynamically described by the equilibrium constant presented in Equation 2.

The trajectory of nitrogen to the metal bath surface may involve an equilibrium distribution at the interface between the slag and the molten steel, particularly in the presence of foaming slag. Under such conditions, nitrogen mass transfer is influenced by concentration gradients between the phases. As described by Zhan [8], the ratio between

the nitrogen concentration in the slag (C_s) and in the liquid steel (C_m) defines the partition coefficient (h), as shown in Equation 7. Both concentrations refer to nitrogen content expressed in mass units (g/cm^3). This approach considers that mass transport occurs due to concentration differences across the interface, with C_s and C_m being bulk concentrations, while C_s^i and C_m^i represent interfacial concentrations on the slag and molten steel sides, respectively.

This distinction is essential for properly modeling nitrogen fluxes and understanding the mechanisms that either limit or enhance nitrogen absorption during the refining process.

$$h = \frac{C_s^i}{C_m^i} \quad (7)$$

Once nitrogen reaches the metal surface, molecular nitrogen must dissociate so that its atoms can be absorbed. This dissociation, which is endothermic in nature, requires high activation energy and depends directly on the interfacial temperature and the availability of reactive sites. It is at this rate-limiting step that the presence of surface-active elements becomes particularly relevant. Elements such as oxygen and sulfur have a high affinity for the metal surface and tend to accumulate at the interface, occupying active sites and hindering the dissociation of N_2 molecules [6]. This competition reduces the fraction of the metal surface available for the reaction and consequently slows down the absorption process [9].

Irons et al. [9] highlights that, in EAF operating conditions, stirring caused by oxygen blowing, electrode movement, or CO evolution in the bath contributes to renewing the gas–metal interface, increasing the absorption rate during the initial stages of the process. According to the author, this constant renewal reduces bubble residence time and facilitates the replenishment of N_2 at the interface, which can sustain a high absorption rate even under conditions of lower nitrogen partial pressure. Additionally, Zhang [7] present modeling results that reinforce the role of turbulence in the arc zone as a key factor in intensifying the flux of

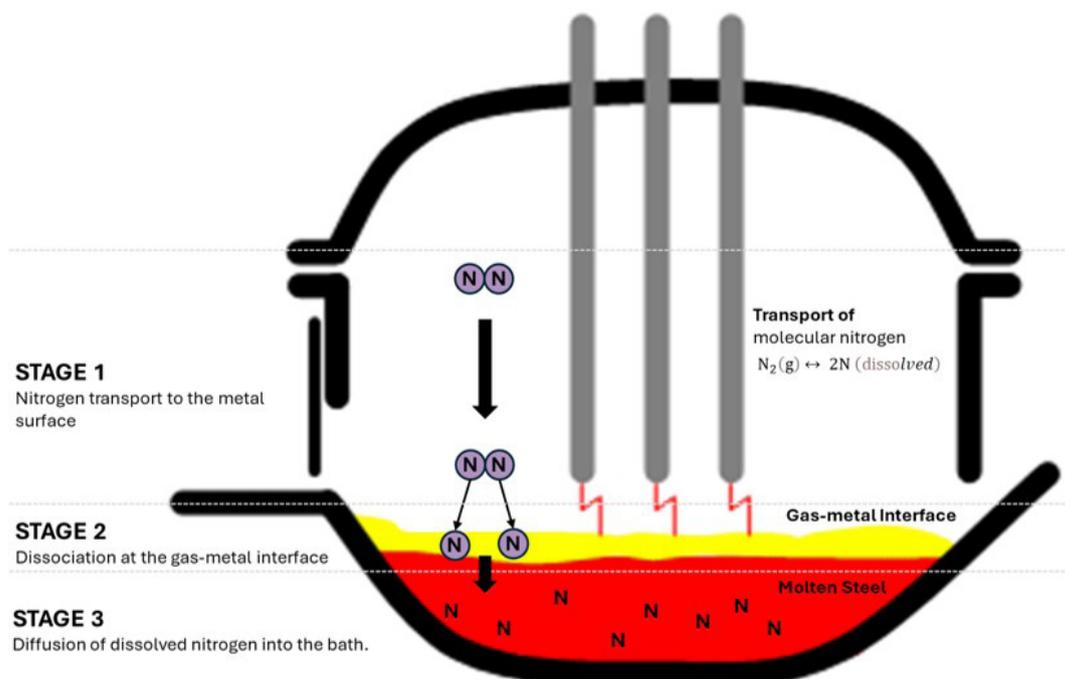


Figure 5. Schematic drawing of the kinetic steps of nitrogen incorporation into liquid steel in electric arc furnaces.

molecular nitrogen to the metal surface. Nitrogen movement at this stage is driven by partial pressure gradients but is facilitated by convective dynamics generated by heat transfer and rising CO bubbles.

Zhang et al. [7] analyzed the kinetic trends by tracking the evolution of nitrogen content in liquid steel as a function of different operational parameters, as shown in Figure 6. It was observed that increasing the carbon content in the bath significantly reduces the nitrogen content in the liquid steel, especially during the initial stages of the reaction (Figure 6-A). With respect to temperature, variations between 1550 °C and 1620 °C led to a moderate increase in the initial absorption rate, although the effect tends to stabilize over the course of the reaction time (Figure 6-B). In contrast, an increase in nitrogen partial pressure showed a strong impact on both the absorption rate and the final nitrogen saturation level, demonstrating that under nitrogen-rich atmospheres, incorporation is favored throughout the process (Figure 6-C). These results reinforce the interdependence between thermodynamic conditions and kinetic barriers in the nitrogen absorption process.

As the process progresses, the presence of foaming slag, particularly slags with higher FeO or MnO content, affects the exchange rate at the interface by altering the local oxygen activity and, consequently, impacting the kinetics of the nitrogen reaction [8].

These slags form a partial barrier to gas renewal, reducing the contribution of nitrogen partial pressure and shifting the rate control toward diffusion within the metal bath or chemical limitations. Although the diffusion of

atomic nitrogen in the bath is generally not the rate-limiting step, it may become significant in cases of low stirring, greater bath depth, or systems with more viscous metallic compositions [6]. In such cases, the concentration gradient between the interface and the bulk of the bath becomes the governing factor for the transport rate of dissolved nitrogen.

2.3 Behavior of incorporating nitrogen into EAF

Nitrogen incorporation in steel produced via electric arc furnaces (EAF) occurs through different physical and chemical pathways, depending on operational conditions, the composition of the metallic charge, and the characteristics of the gaseous atmosphere. The variation in nitrogen content throughout the different stages of the EAF process reveals the influence of distinct incorporation mechanisms. According to data presented by Pilliod [16] and illustrated in Figure 7, nitrogen levels increase significantly during the initial melting stages due to the exposure of the bath to a nitrogen-rich atmosphere and tend to stabilize or decrease during the refining stage, when foaming slag is formed and CO generation becomes intense [16]. These results illustrate how different nitrogen sources contribute at specific moments of the process.

In steels produced via electric arc furnaces, nitrogen may originate from the following sources: the presence of nitrogen in the metallic charge, particularly in scrap and materials derived from direct reduction (HBI/DRI); and the exposure of liquid steel to atmospheric nitrogen, which may be ionized by the electric arc. The solid charge materials, such

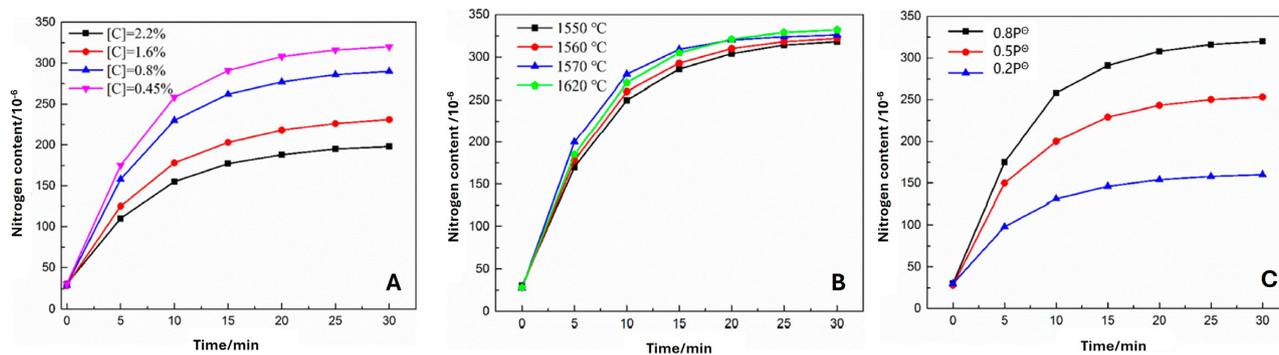
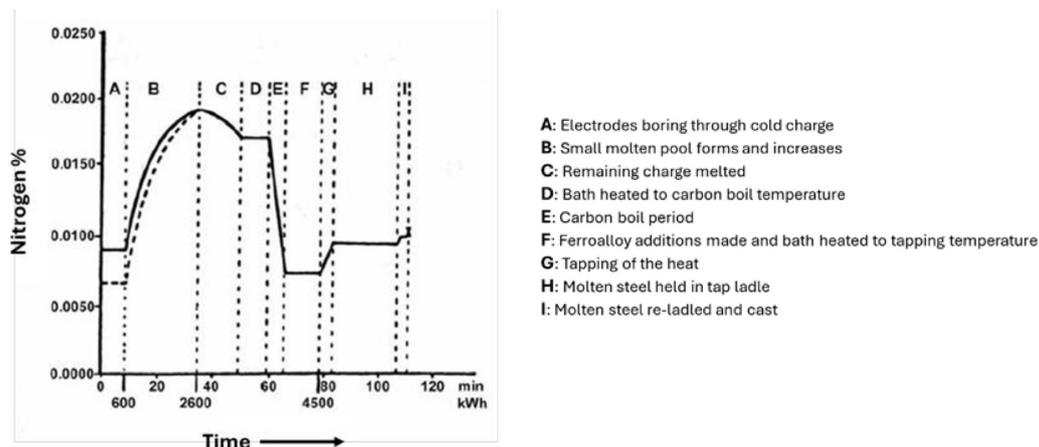


Figure 6. Variation of nitrogen content in liquid steel as a function of (a) different carbon contents, (b) bath temperature, and (c) nitrogen partial pressure [7].



- A: Electrodes boring through cold charge
- B: Small molten pool forms and increases
- C: Remaining charge melted
- D: Bath heated to carbon boil temperature
- E: Carbon boil period
- F: Ferroalloy additions made and bath heated to tapping temperature
- G: Tapping of the heat
- H: Molten steel held in tap ladle
- I: Molten steel re-ladled and cast

Figure 7. Nitrogen content in steel during EAF smelting and refining. Adapted from Trotter et al. [10].

as steel scrap, DRI, and HBI, can significantly contribute to nitrogen enrichment of the metal bath. Table 1 presents the nitrogen content of the different raw materials commonly used in EAF steel production.

Another nitrogen absorption mechanism in EAF operations is dissolution from the furnace atmosphere, which is rich in air, particularly during the initial melting stage of the metallic charge. During this period, the partial pressure of nitrogen (pN_2) is high, and the surface of the metal bath is largely exposed, favoring the dissociation of N_2 molecules at the gas–metal interface and their diffusion into the molten metal. The behavior and magnitude of nitrogen uptake from the atmosphere are directly linked to the thermodynamic and kinetic factors previously discussed. Thermodynamically, nitrogen partial pressure, temperature, and bath composition define the driving force for dissolution, while the kinetics of the process depend on the dissociation rate, transport to the metal surface, and diffusion of the dissolved element.

In addition to the gas–metal and metallic charge pathways, nitrogen may also be incorporated into the bath through the slag. Although slag often acts as a physical barrier to nitrogen absorption, its chemical composition can promote nitrogen transfer reactions under specific conditions. The presence of metal oxides such as FeO , MnO , and SiO_2 ,

Table 1. Nitrogen content in raw materials used in EAF steel production. [10,17]

Materials	Nitrogen Content (ppm)
Shredded	100
HBI/DRI	20-30
Internal scrap	50
BF Liquid Pig Iron	60
Coke	5000-10000
Graphite for Injection	13000
Oxygen	30-200
Fluxes	450

combined with low basicity, may alter surface tension and locally reduce the chemical potential of nitrogen, favoring its absorption [8]. Slags with high oxidation and low viscosity have a greater ability to interact with the metal interface, increasing the potential for bath contamination.

Another factor of practical relevance is gas injection during the process. The use of N_2 as a purge gas, for bottom stirring, or for electrode cooling, even in controlled volumes, can lead to unintentional absorption, especially under conditions of high liquid surface exposure. Furthermore, leaks in pipelines or false air ingress through the exhaust

system or injection nozzles represent critical sources of nitrogen incorporation [7,9].

Finally, part of the dissolved nitrogen may originate from residual steel in the furnace from previous heats. This contribution can be significant in plants operating with large heel volumes or when remelting steel from previous charges rich in nitrogen. This incorporation must be considered, as it represents nitrogen that is already dissolved in the liquid steel.

2.4 Methods to control nitrogen in EAF

Nitrogen control in steels produced via electric arc furnaces is particularly challenging due to the composition of the metallic charge, the intense exposure of the bath to a nitrogen-rich atmosphere, and the dynamic conditions of the process. In the case of scrap, in particular, uncertainties regarding its elemental composition and previously absorbed nitrogen content make reactive control during melting more difficult. Effective strategies combine three fundamental principles: the use of raw materials with low nitrogen content, the prevention of atmospheric absorption during smelting and refining, and the active removal of dissolved nitrogen throughout the process.

The composition of the metallic charge, especially the carbon content present in direct reduced iron (DRI), significantly influences nitrogen removal in EAF operations. Operational practices involving high-carbon DRI promote the intense formation of CO bubbles during melting, creating a reducing atmosphere that contributes to the removal of dissolved nitrogen [18]. Comparative trials have shown that the use of DRI with increasing carbon content (between 2.0% and 2.9%) results in lower final nitrogen concentrations in steel, reaching values between 7 and 12 ppm when using DRI with 2.9% carbon [17]. On the other hand, results reported by Erwee and Pistorius [18] suggest that low-carbon DRI, such as that produced via the SL/RN process, may not provide the same reducing effect on nitrogen especially when top-charged into the furnace. Additionally, significantly high nitrogen levels were observed in DRI (up to 250 ppm), with a direct impact on the final nitrogen content in the steel.

One of the strategies for nitrogen removal from liquid steel involves the injection of gases such as argon, CO, or CO₂ through the furnace bottom. The formation of gas bubbles reduces the local partial pressure of N₂ at the gas-metal interface, thereby promoting its removal and transfer to the gas phase. Studies indicate that this practice can reduce nitrogen concentrations by up to 30% of the original value, with experimental removals in the range of 10 to 20 ppm [11,19]. However, the use of CO or CO₂ requires caution, as their decomposition may lead to undesired absorption of oxygen and carbon into the bath.

The injection of DRI fines (sponge iron) using argon as a carrier gas has proven to be an efficient technique for nitrogen removal from liquid steel. Once dispersed in the bath, the fines react with dissolved carbon to form multiple fine CO bubbles. These bubbles have a high surface area and

act as nuclei for the removal of dissolved nitrogen, promoting its extraction as they rise to the surface [11]. The efficiency of the process can also depend on operational factors such as bath depth with greater depths enhancing the effectiveness of the fines and carbon content, since nitrogen removal is favored at high carbon concentrations due to the increased activity coefficient of nitrogen in steel.

Gas injection in electric arc furnaces is a key strategy in nitrogen control. The use of side lances, particularly in the form of coherent jets, has been widely employed for impurity oxidation, although it presents limitations regarding bath agitation efficiency and gas penetration. As an alternative, submerged injection of oxygen mixed with CO₂, installed on the sidewall of the furnace as shown in Figure 8, has demonstrated significant improvements in both nitrogen removal and operational stability, in addition to reducing energy consumption and refractory wear [13].

Complementary studies have shown that bottom blowing with CO₂ outperforms the use of Ar or N₂, generating finer bubbles that are more effective in nitrogen removal, particularly in baths with higher carbon content and pig iron [12]. Comparatively, while oxygen injection through the lance tends to be more effective during the initial stages for direct oxidation, bottom blowing with CO₂ has proven more advantageous during refining phases, promoting better bath homogenization and higher nitrogen removal efficiency [14].

The chemical composition of slag can also be adjusted to mitigate nitrogen absorption. As demonstrated by Zhan [8], slags with lower basicity ratios (R), higher Al₂O₃ contents, and lower MgO levels result in higher nitrogen partition coefficients (L_n), indicating greater retention of nitrogen in the slag phase and thus reduced reincorporation into the metal. Additionally, the presence of foaming slag contributes to isolating the bath, creating microenvironments with reduced nitrogen partial pressure. This leads to the formation of vacuum-like microbubbles, with virtually zero pN₂, which promote denitrification reactions within the molten metal [7].

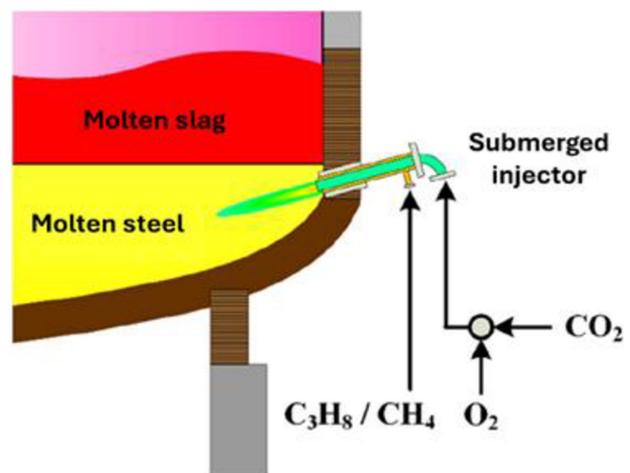


Figure 8. Submerged injection of O₂ with CO₂ in EAF steelmaking. Adapted Wei et al. [14].

2.5 Future trends and decarbonization

The advancement toward decarbonizing the steel industry imposes new demands on the control of steel chemical composition, including nitrogen content. Studies highlight that the higher nitrogen concentration typically observed in steels produced via EAF, when compared to the BOF process, presents a challenge to produce high-quality steels, requiring more effective strategies for nitrogen removal and prevention [7]. In this context, the use of hydrogen-based direct reduced iron (H-DRI) emerges as a promising technology. Pfeiffer [20] showed that the addition of carbon rich DRI not only enhances the energy efficiency of the process but also improves melting behavior and slag formation, creating favorable conditions for the removal of dissolved nitrogen from the bath [21].

On the other hand, Pistorius [22] emphasize that the growing use of alternative carbon sources and green hydrogen, as in the HYBRIT project, for direct reduction introduces operational challenges in EAFs, such as thermal control, oxidation balance, and slag dynamics. These challenges demand a revision of blowing and stirring models to maintain nitrogen removal efficiency [22]. Although green hydrogen, produced by water electrolysis using renewable energy, represents a sustainable solution, its use remains economically more expensive than conventional DRI production with natural gas.

In this scenario, future innovations must combine nitrogen control strategies with operational practices compatible with low-carbon steelmaking routes, such as

continuous H-DRI charging, optimized injection of reducing gases (such as CO and H₂), and the development of predictive models coupled with real-time monitoring of the metal bath.

2.6 Nitrogen control strategies in EAF steelmaking

A comparative summary of these key influencing factors is presented in Table 2, highlighting the primary conditions that favor nitrogen pickup as well as those that mitigate its absorption and enhance removal.

From a practical standpoint, several nitrogen-control strategies summarized in Table 2 can be implemented with relatively low technological complexity and immediate impact on EAF operation. Among these, the selection of raw materials with lower nitrogen content, particularly scrap and DRI, represents one of the most direct approaches to limit nitrogen input from the early melting stage. In parallel, carbon injection and the use of carbon-bearing materials promote CO generation in the molten bath, leading to nitrogen removal through bubble flushing mechanisms. At the same time, the early formation and stabilization of foaming slag play a critical protective role by acting as an effective physical barrier between the molten steel and the nitrogen-rich furnace atmosphere.

Therefore, nitrogen control during EAF operation results from the combined action of CO bubble formation and slag coverage, which together reduce nitrogen absorption and enhance overall bath homogenization.

Table 2. Summary of Factors Affecting Nitrogen Absorption in EAF Steelmaking

Category	Factors that increase nitrogen absorption	Factors that reduce nitrogen absorption
Furnace atmosphere	<ul style="list-style-type: none"> High nitrogen partial pressure (air-rich atmosphere) Exposure of molten bath to ambient air 	<ul style="list-style-type: none"> Gas injection with CO, CO₂ or Argon Reducing atmosphere generated by CO bubbles
Electric arc and temperature	<ul style="list-style-type: none"> Air ingress through leaks or exhaust system High temperatures in the arc zone promoting N₂ dissociation Ionization of nitrogen by the electric arc 	<ul style="list-style-type: none"> Controlled furnace sealing Temperature control during refining Reduced arc exposure of the molten bath
Metallic charge	<ul style="list-style-type: none"> Scrap or DRI with high nitrogen content Low carbon content in the charge 	<ul style="list-style-type: none"> Use of low-nitrogen raw materials High-carbon DRI (≈2–3% C) promoting CO generation
Carbon content in the bath	<ul style="list-style-type: none"> Low carbon levels, increasing nitrogen activity 	<ul style="list-style-type: none"> High carbon content reducing nitrogen activity and enhancing CO flushing
Slag coverage	<ul style="list-style-type: none"> Absence of slag in early melting stages Thin or unstable slag layer 	<ul style="list-style-type: none"> Early formation of stable foaming slag Thick slag acting as a physical barrier
Slag composition	<ul style="list-style-type: none"> High basicity (CaO/SiO₂) High MgO content Highly oxidizing slag 	<ul style="list-style-type: none"> Higher Al₂O₃ content Optimized basicity Lower MgO content
Slag properties	<ul style="list-style-type: none"> High slag viscosity limiting gas transport control 	<ul style="list-style-type: none"> Lower slag viscosity improving bath homogenization
Gas injection practices	<ul style="list-style-type: none"> Injection or use of N₂ for stirring or cooling 	<ul style="list-style-type: none"> Bottom blowing with CO₂ or Ar
Bath stirring	<ul style="list-style-type: none"> Low bath agitation limiting nitrogen removal 	<ul style="list-style-type: none"> Efficient stirring (bottom blowing, CO evolution) enhancing nitrogen removal

3. Conclusion

Understanding nitrogen absorption in electric arc furnaces requires an integrated analysis of the thermodynamic, kinetic, and operational aspects governing this phenomenon. From a thermodynamic perspective, temperature, nitrogen partial pressure, and alloy composition, particularly the presence of nitride-forming and deoxidizing elements, directly influence the solubility limit of nitrogen in liquid steel. Under typical steelmaking conditions, this limit can reach up to 450 ppm, reinforcing the need for refined control. From a kinetic standpoint, nitrogen incorporation is limited by mechanisms involving gas-phase transport, molecular dissociation at the gas-metal (or gas-slag, when present) interface, and diffusion into the molten bath. The presence of foaming slag plays a dual role, acting as both a physical

barrier to absorption and an active medium for nitrogen transfer, as demonstrated under specific conditions.

Operationally, the selection and composition of the metallic charge, the use of high-carbon DRI, the injection of reducing gases, and the controlled formation of slag are effective strategies to mitigate nitrogen absorption and promote its active removal. However, the transition to more sustainable processes, such as the use of H-DRI and green hydrogen-based technologies, introduces new challenges in terms of process efficiency and operational stability. In this context, the advancement of predictive models, improved stirring control, and real-time monitoring of the furnace atmosphere emerge as promising approaches to reconcile environmental requirements with the desired metallurgical quality.

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André Luiz Vasconcellos da Costa e Silva 