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# Oxygen deficiency hazard in confined spaces in the steel industry: assessment through predictive models

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*Objective.* In the steel industry, performing activities in confined spaces where potential oxygen displacement can occur may expose workers to fatal consequences. To the best of our knowledge, no quantitative exposure assessment of oxygen deficiency in steel industry confined spaces is available in the literature. To overcome this gap, we performed oxygen deficiency hazard (ODH) assessments in real confined spaces using two existing models to identify the most critical parameters responsible for ODH, and suggest controls for mitigating the asphyxiation risk. *Methods.* We applied a well-mixed model and a near field–far field approach to estimate the indoor oxygen level with time during and following release of simple asphyxiants. Model inputs were mainly gathered thanks to audits and instrumental tests in three firms. *Results.* The most severe ODH exposures are posed in spaces with restricted volume and where accidental releases of inert gases can occur. Such exposures can be controlled through early release detections and augmented reality systems. *Conclusions.* ODH assessments in confined spaces of steel firms allow the identification of the most critical parameters from an oxygen depletion perspective, focusing on which data need careful measurement, and help to establish controls compatible with the operations conducted in these areas.

**Keywords:** oxygen depletion; oxygen displacement; asphyxiation risk; inert gas; argon; furnace; welding; steel industry

## 1. Introduction

The iron and steel industry represents a key sector for Europe's economy and competitiveness, and is able to produce considerable quantities of pig iron and its refinements, billets, ingots and bars [1,2]. Activities usually performed in this industry can expose workers to a wide range of hazards and cause injuries and diseases [2]. According to the International Labour Organization (ILO) [2], one of the most common causes of injuries in iron and steel firms is working in confined spaces, where oxygen ($O_2$) displacement is an occupational safety and health (OSH) hazard requiring special vigilance by employers [2].

Confined spaces are industrial places where both fatal and non-fatal accidents occur and where the tolerance for errors or oversights is small [3]. A universal accepted definition of confined spaces is not available [3,4]; however, a common definition is a space which: (a) is large enough and so configured that an employee can bodily enter and perform assigned work; (b) has limited or restricted means for entry or exit; (c) is not designed for continuous occupancy [5,6]. These working environments are frequently characterized by the presence of multiple hazardous conditions, where a risk assessment should be performed prior to entry and work [3,7,8]. Rekus [9] points out that confined space hazards can be divided into physical and atmospheric ones. The former include engulfment, moving mechanical equipment, electrical systems, ionizing and non-ionizing radiation, temperature extremes and thermal conditions [3,9]. The latter comprise $O_2$ deficiency or enrichment, flammable and explosive gases and vapours, and toxic substances [3,9]. Recently, Selman et al. [10] highlighted that atmospheric hazards are a significant mechanism of incident in confined space fatalities, stating that approximately half of all confined space entrant fatalities, and nearly all confined space rescuer fatalities, are as a result of atmospheric hazards.

McManus and Haddad [11] introduce a recent contribution stating that $O_2$ deficiency is a well-recognized cause of death in confined spaces. $O_2$ in confined spaces may be deficient because of displacement through the action of inert gases, adsorption by porous materials and/or surfaces, or consumption due to chemical reactions (e.g., welding, rusting, corrosion) [9]. Other consumption effects can be related to combustion of flammable substances, respiratory and breathing mechanisms [12,13], and/or overcrowding in the workplace [14]. Inert gases are particularly insidious from an OSH point of view because they are odourless, colourless and tasteless, and thus undetectable by people exposed [14].

Steel processes employ large quantities of inert gases that may lead to the displacement and the consequent reduction of $O_2$ in the air. For instance, nitrogen ($N_2$) and

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argon (Ar) are used as purging gases in pipelines and tanks, and as process gases in furnaces, ladles, restricted areas near furnaces, vacuum degasser tanks to remove dissolved gases and non-metallic inclusions in liquid steel. In addition, welding and cutting are typical activities involving inert gas use.

Although confined spaces and oxygen deficiency hazard (ODH) are serious OSH issues in the steel industry, only recently a first list and a characterization of confined spaces did appear in the literature [8]. Particularly, confined spaces in the steel industry that should capture safety managers' attention from an ODH point of view are heating and heat treatment furnaces, inspection chambers, tanks and ladles [8]. To the best of our knowledge, no quantitative exposure assessment of $O_2$ deficiency in steel industry confined spaces is available in the literature. To overcome this gap, we carried out ODH assessments in three real confined spaces: an inspection chamber of a continuous casting machine; a heat treatment furnace; an underground confined area around an electric arc furnace (EAF). These areas are commonly present in steel plants, where workers frequently enter to perform production and/or maintenance operations (e.g., welding tasks, repairs of malfunctions, component replacements). The ODH assessments in such spaces were performed using two existing predictive models in order to achieve the following objectives: (a) identify the most critical parameters responsible for ODH, comprehending which data require careful measurement and which features and conditions of the workplace necessitate regular monitoring; (b) suggest actions and controls for mitigating the ODH exposure and the asphyxiation risk in the analysed steel industry confined spaces.

## 2. Oxygen deficiency hazard

ODH occurs when the indoor $O_2$ content drops to a level that may expose workers to risk of asphyxiation, with even severe and fatal adverse health effects [14]. ODH due to displacement in the air can be caused by simple asphyxiants [15]. Many simple asphyxiants are physiologically inert (e.g., Ar, helium [He], $N_2$); others (e.g., carbon dioxide [$CO_2$], methane [$CH_4$], propane [$C_3H_8$]) have some physiological effects, but the most frequent significant injury happens primarily through $O_2$ deprivation [16]. The European Industrial Gases Association (EIGA) [17] underlines that incidents involving asphyxiating atmospheres are always serious.

Rekus [9] draws attention to the fact that the effects of too little $O_2$ are largely health related, with symptoms ranging from a mild headache to permanent brain damage, depending on the degree of $O_2$ deficiency. These symptoms are also documented by the American Conference of Governmental Industrial Hygienists (ACGIH) [18], which highlights that the tissues most sensitive to $O_2$ deficiency are the brain and myocardium. The different health effects on the body due to occupational exposures to $O_2$ deficient atmospheres are summarized in Table 1. The considerations reported in this table are valid for concentrations at atmospheric pressure and at sea level, and for individuals at rest. Moreover, many of the physiological responses to exposures to low $O_2$ levels can have profound effects on the ability to work safely, to escape from a dangerous situation and/or to make clear judgements about the environmental dangers [13,19,20].

Table 1. Overview of effects and symptoms based on different oxygen concentrations [21,22].

| Oxygen concentration (%) | Physiological effect |
|---|---|
| 18.0–20.9 | No symptoms in healthy adults |
| 15.0–18.0 | Decreased ability to perform tasks (early symptoms and signs in persons with coronary, pulmonary or circulatory problems); night vision reduced; increased breathing volume; accelerated heartbeat; dizziness; time required for novel tasks doubled; loss of muscle control |
| 12.0–15.0 | Respiration deeper, pulse faster; impaired muscular coordination, attention, thinking and judgement; intermittent breathing; rapid fatigue; sudden changes in mood; emotional upsets; tunnel vision |
| 10.0–12.0 | Giddiness; possibility of fainting; very faulty judgement; lips slightly blue; loss of consciousness; permanent brain damage; possible damage to the heart; very poor muscular coordination |
| 8.0–10.0 | Nausea, vomiting, unconsciousness, ashen face, fainting and mental failure; inability to move freely |
| 6.0–8.0 | Spasmodic breathing; convulsive movements; after 6 min, 50% of persons exposed to ODH die and 50% recover with treatment; after 8 min, 100% of persons exposed to ODH die |
| 4.0–6.0 | Coma in 40 s, convulsions, respiration ceases and death |

Note: ODH = oxygen deficiency hazard.

Table 1 presents the correlation between different $O_2$ concentrations and some health effects; however, to the best of our knowledge, in the literature there is no consensus about a safe limit value for the $O_2$ level in workplaces [14,21]. According to the EIGA [17], any atmosphere with an $O_2$ level beneath 19.5% by volume shall be treated with concern. An $O_2$ concentration equal to 19.5% by volume is today used by most jurisdictions [11] and is frequently cited as a sort of limit, as highlighted by the references listed in the following:

- The ACGIH [18] emphasizes that the minimum requirement of 19.5% $O_2$ by volume at sea level gives an adequate $O_2$ amount for most work assignments and includes a margin of safety.

- The National Fire Protection Association (NFPA) [6,p.350–358] defines uncontaminated air with an $O_2$ content between 19.5 and 22 percent as breathing air.
- Selman et al. [4] report that 19.5% by volume is the minimal safe $O_2$ level mostly quoted in confined space legislation, regulations and standards (in Canada, in certain circumstances, works are permitted in atmospheres with $O_2$ concentration as low as 18% by volume).
- Pitt and Gales [22] mention that an $O_2$ concentration of 19.5% by volume is the minimum safe level.
- The Occupational Safety and Health Administration (OSHA) [5] refers to an $O_2$-deficient atmosphere when $O_2$ is less than 19.5% by volume, and points out that an atmospheric $O_2$ concentration below 19.5% represents a hazardous atmosphere.

An $O_2$ concentration less than 17% by volume (assuming dry air conditions) is quoted by the European Committee for Standardization (CEN) [23] to define $O_2$-deficient air, where filtering devices cannot be used and, thus, breathing apparatus should be provided. According to Table 1, at this concentration, individuals (mainly with coronary, pulmonary or circulatory problems) can present the early symptoms and negative health effects related to exposure to an $O_2$-deficient atmosphere.

ODH is normally assessed in any working environment through $O_2$-level measurement [14]. Estimating the $O_2$ content through the application of predictive models is an interesting alternative to measurements [14]. Models are useful in accurately predicting exposure and in supporting better decisions on when air sampling is necessary [24,25]. A systematic review and a critical comparison of predictive models available in the literature estimating the indoor $O_2$ level and assessing ODH related to releases of simple asphyxiants are proposed by Stefana et al. [14]. An enhanced well-mixed model and the first near field–far field (NF–FF) approach for assessing ODH have been recently developed [21,26].

## 3. Methods

In order to achieve the article's objectives, we chose a well-mixed model [21] and an NF–FF approach [26] to estimate the $O_2$ level during and following release of simple asphyxiants in any working area. A well-mixed model is able to predict appropriately the indoor $O_2$ content in workplaces where airflow mixing is created and/or operators stay a distance from inert gas sources. The NF–FF approach takes into account workers' exposure to $O_2$-deficient air close to the sources of simple asphyxiant release.

We preferred these two models to others reviewed in Stefana et al. [14] since they consider a more complete set of parameters and thus appear more advisable for more precise estimations of the indoor $O_2$ level in steel industry confined spaces. Indeed, parameters considered in the mathematical formulations of both models (i.e., inputs for users) regard: (a) geometrical features and configuration of the working environment; (b) indoor and outdoor conditions; (c) types and features of substances and mixtures used and/or potentially released; (d) forced (both supply and return air) and natural ventilation characterizations. In particular, the natural ventilation, infiltration and/or exfiltration in these two models assure the equilibrium between indoor and outdoor air pressure. Flows related to release and ventilation are characterized in terms of rate, composition, temperature and reliability data. A voluntary release depends on the reliability of storage and/or distribution systems of substances and mixtures, and thus occurs when there are no failures preventing the systems themselves from operating properly [21,26]. On the contrary, an accidental release is based on the probability that storage and/or distribution systems of substances and mixtures fail [21,26].

The NF–FF model can be implemented during ODH assessments when more precise estimations near the release point(s) of asphyxiant gases are needed. To apply this model, additional inputs are the limit value for the $O_2$ concentration in the NF and the random airspeed at the boundary between the NF and the FF for estimating the interzonal airflow rate occurring between the two fields. The NF contains and is centred on potential asphyxiant gas sources, whereas the FF includes airflows related to forced and natural ventilation. Stefana et al. [26] assume that the NF volume is completely contained in the workplace volume (irrespective of the NF shape) at any time, and the sum of NF and FF volumes is equal to the overall working environment volume.

The well-mixed model [21] assumes completely mixed conditions and, thus, flows, air and $O_2$ are perfectly mixed in the whole working volume. The NF–FF approach [26] considers the subdivision of the working environment into two boxes, in both of which flows, air and $O_2$ are perfectly mixed.

Application of the models permits the following outputs: the well-mixed model [21] provides the time profile of the indoor $O_2$ level in terms of concentration by volume and partial pressure, while the NF–FF approach [26] estimates the time trend of the NF volume containing a limit value for the $O_2$ concentration defined by users.

We applied these models in the confined spaces identified in three steel companies located in the north of Italy during routine and occasional work activities performed inside them. Particularly, we focused our attention on those areas listed and proposed by Stefana et al. [8], on the zones previously assessed as confined spaces by safety managers and on the working sites where past accidents and near misses have occurred due to the presence of asphyxiating gases. Each confined space was characterized in terms of several aspects, such as spatial configuration, entrance characteristics, presence/absence of simple asphyxiant gases, presence/absence of ventilation, task(s) assigned to entrant(s), duration and frequency of access(es), and work assignments. We undertook audits, site visits, measurements of space and access dimensions, and instrumental tests about atmospheric parameters. Input values were directly measured wherever possible or derived from companies' documentation when available. We obtained site-specific factors from evidence provided by safety managers of the companies. In addition, we collected information about technical features concerning steel plants, rolling mill equipment, furnaces, and industrial and process gases through direct contacts with specialized vendors that equipped the steel companies. Analyses of specific handbooks and reports (e.g., [27,28]) allowed us to acquire detailed information on component failure modes and rates, and reference documents for steel production to complete and integrate missing data (e.g., [1]). When data were not available, experts' opinions and professional judgements were collected. All of these data and information deriving from visits, measurements and literature represented the starting point for selecting and defining scenarios that were then simulated by applying well-mixed and NF–FF models. In particular, the scenarios analysed in this paper are as follows:

- Scenario 1: welding activities performed by one or two workers in an inspection chamber of a continuous casting machine;
- Scenario 2: repair of a valve malfunction in a chamber of a vacuum heat treatment furnace;
- Scenario 3: welding tasks in an underground confined area around an EAF during an accidental Ar release from the gas stirring system.

We have considered the welding processes in Scenario 1 and Scenario 3 only in terms of releases of shielding (inert) gases (we have not examined impacts on $O_2$ depression due to its consumption).

For each scenario we investigated several cases in order to assess how different geometrical issues or operating conditions can impact the resulting $O_2$ level. We performed two simulations for each case, one with the well-mixed model and one with the NF–FF model. Inputs valid for the simulations of all scenarios are presented in Table 2, while specific hypotheses and conditions are presented in the dedicated sections. The pressure, temperature and air composition outside confined spaces, indoor temperature and random airspeed at the boundary between the NF and the FF are assumed constant in time.

In all cases, there are no forced ventilation airflows. The gas release considered in Scenario 1 is voluntary, whereas the leakage in Scenario 2 is accidental. Scenario 3 has two simultaneous releases: one voluntary and one accidental. All of these leaks are not detected by instruments and/or operators during the intervention. For the entire simulation period, each release continues discharging a constant inert gas flow rate into the confined spaces.

Table 2. Inputs common to the studied scenarios.

| Parameter | Value |
|---|---|
| Ideal gas constant ($R$) | $8.314472\,J\,K^{-1}\,mol^{-1}$ |
| Specific gas constant for dry air ($R^*$) | $287.05287\,J\,K^{-1}\,kg^{-1}$ |
| Initial indoor temperature | 298.15 K |
| Initial indoor pressure | 101,325 Pa |
| Outdoor temperature | 298.15 K |
| Outdoor pressure | 101,325 Pa |
| Outdoor air composition | $C_{N_2} = 79\%$, $C_{O_2} = 21\%$, $C_{Ar} = 0\%$ |
| Random airspeed at the boundary of the NF | $0.06\,m\,s^{-1}$ |

Note: $N_2$ = nitrogen; $O_2$ = oxygen; Ar = argon; NF = near field.

For the NF–FF model application, the simulated scenarios assume an NF hemisphere shaped and centred on the release point: the radius of the hemisphere can be considered a safe distance between the worker and the release point when the limit value for the $O_2$ concentration is equal to or higher than values at which adverse health effects can occur. We assumed that the random airspeed at the boundary between the NF and the FF is equal to $0.06\,m\,s^{-1}$ as this is often used as a reference value [29]. In all of the simulations conducted with the NF-FF model we set the two following limit values for the $O_2$ concentration in the NF:

- 17% for all cases since this represents a level requiring attention from the ODH point of view, as identified in the Introduction;
- An $O_2$ concentration value attained by applying the well-mixed model during or at the end of simulation, which differed from case to case.

The simulations were performed for 7200 s (2 h). The results are only reported in terms of $O_2$ concentration by volume to facilitate comparisons among the models' outputs, the readouts provided by $O_2$ detector and the values presented in Table 1.

### *3.1. Scenario 1*

A worker carries out welding activities inside an inspection chamber located in the continuous casting machine. The chamber has the typical shape of a cylindrical tower, whose internal diameter of the base is equal to 4 m and height to 13 m. Within the chamber, there are equipment

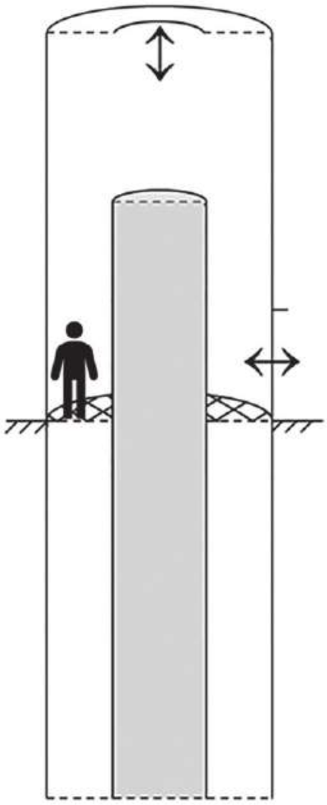

Figure 1. Diagram of the inspection chamber of the continuous casting machine of Scenario 1.

and parts of the machine (e.g., motor, pumps) that reduce the internal volume: the volume that can be occupied by the indoor air and the $O_2$ is equal to 95 $m^3$. There are two access points for entering the chamber. Figure 1 displays the size and shape of the inspection chamber, compared to worker body measurements (assuming a mean stature for the Italian male population equal to 1.72 m [30]).

This simulation was conducted three times: Case 1A, Case 1B and Case 1C. Air sampling highlighted a variable initial indoor air composition; as a consequence, we tested different initial indoor air compositions:

- $C_{N_2}(0) = 80\%$, $C_{O_2}(0) = 20\%$, $C_{Ar}(0) = 0\%$ in Case 1A and Case 1C;
- $C_{N_2}(0) = 79\%$, $C_{O_2}(0) = 21\%$, $C_{Ar}(0) = 0\%$ in Case 1B.

An arc welding operation, in particular tungsten inert gas (TIG) welding on stainless steel components, is performed with an inert gas composed of 100% Ar as the shielding gas [31,32]. The shielding gas flow rate was different depending on the simulated case; in particular, it was equal to:

- 0.0005 $m^3 s^{-1}$ (based on specific nozzle diameter, electrical current and gas frequently employed in operations in steel companies) in Case 1A and Case 1B;

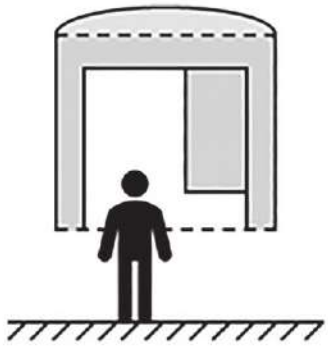

Figure 2. Diagram of the chamber of the vacuum heat treatment furnace of Scenario 2.

- 0.001 $m^3 s^{-1}$ in Case 1C to simulate two operators simultaneously carrying out the same welding operations.

In all cases, the reliability of the welding system is equal to 99% (average value from data provided by suppliers of industrial gases and welding equipment manufacturers), the temperature of the gas flow is equal to 293.15 K and the welding activities last 2 h.

### 3.2. Scenario 2

Personnel frequently enter furnaces to perform maintenance operations and repairs. Scenario 2 considers the hot chamber of a vertical vacuum heat treatment furnace, whose volume is equal to 5 $m^3$ (considering the vessel and the hot chamber) and the net volume is about 70% (i.e., 3.5 $m^3$). Figure 2 outlines the size and shape of this confined space.

The furnace should be opened prior to entering the hot chamber; consequently, the internal pressure equals the atmospheric pressure. We measured the initial indoor air composition: $C_{N_2}(0) = 79\%$, $C_{O_2}(0) = 21\%$, $C_{Ar}(0) = 0\%$.

The worker can access the chamber to repair a malfunction of the gas inlet valve located in the duct delivering the $N_2$ to the hot chamber itself during the cooling process. The failure leads to an $N_2$ leakage into the space. The release flow is composed of 99% $N_2$ and 1% $O_2$ impurities, and its temperature is equal to 293.15 K (data acquired by furnace designers and producers). The $N_2$ flow rate was estimated using equations reported in Standard No. IEC 60079-10-1:2015 [33] and in consideration of different opening section values (fractions of the total duct area). The calculated flow rates and their probabilities are presented in Table 3, identifying four different cases. Therefore, the simulation was conducted four times:

- Case 2A, Case 2B and Case 2C are characterized by the same opening section (10% of the duct area) and thus the same flow rate, but are different from each

Table 3. Different simulated cases for Scenario 2, nitrogen flow rates and probabilities of accidental release.

| Case | Opening section ($m^2$) | Flow rate ($m^3\ s^{-1}$) | Probability |
|---|---|---|---|
| 2A | 0.0002027 | 0.00347 | 0.04 |
| 2B | 0.0002027 | 0.00347 | 0.15 |
| 2C | 0.0002027 | 0.00347 | 0.40 |
| 2D | 0.000002027 | 0.00003 | 1.00 |

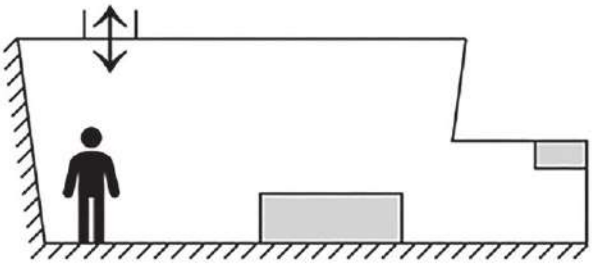

Figure 3. Diagram of the underground confined area around the electric arc furnace of Scenario 3.

other in terms of probability values of accidental release.

- Case 2D assumes a lower opening section (i.e., 0.10% of the duct area) and consequently a lower flow rate than the first three cases, but a maximum value for the accidental release probability.

### *3.3. Scenario 3*

A welding activity can be performed in one of the various underground confined areas around the EAF, and could expose the worker to an unintentional Ar release from the inert gas stirring system. Stirring with inert gas through the bottom of EAF agitates the bath, helps to ensure uniform molten steel composition and temperature, and promotes inclusion removal. The analysed confined space is characterized by a volume, free of equipment, equal to 80 $m^3$, and its configuration is shown in Figure 3.

The initial indoor composition was measured and equal to $C_{N_2}(0) = 79\%$, $C_{O_2}(0) = 19.5\%$, $C_{Ar}(0) = 1.5\%$. This composition can be justified by the persistence of previous releases due to difficulties dispersing Ar and purging the atmosphere inside underground spaces completely (Ar is heavier than air). The accidental Ar release is located in the rigid steel pipe of the EAF stirring system. Assuming the use of a permeable or porous plug and an operating pressure of the stirring element equal to atmospheric pressure, the gas flow rate is estimated equal to 0.00217 $m^3\ s^{-1}$ [33]. This is the maximum design flow rate: according to Augustynowicz [34,p.982], 'in the case of a pipe failure, worst-case leak rates are taken to be equal to the maximum design flow rate'. This gas flow is composed of 99% Ar and 1% $O_2$, and its temperature is equal to 293.15 K (data provided by gas suppliers). In addition, in this area, metal inert gas (MIG) welding on stainless steel components through Ar used as a shielding gas is carried out by an operator. This voluntary release is characterized by a composition of 100% Ar [31], at a temperature equal to 293.15 K. We identified four cases and, consequently, this simulation was conducted four times: Case 3A, Case 3B, Case 3C and Case 3D. Cases 3A–3D are defined in Table 4.

Table 4. Flow rates, probability and reliability values for accidental and voluntary release in Scenario 3.

| | Accidental release (stirring system) | | Voluntary release (welding activity) | |
|---|---|---|---|---|
| Case | Flow rate ($m^3\ s^{-1}$) | Probability | Flow rate ($m^3\ s^{-1}$) | Reliability |
| 3A | 0.00217 | 0.40 | 0.00017 | 0.98 |
| 3B | 0.00217 | 1.00 | 0.00025 | 1.00 |
| 3C | 0.00065 | 0.30 | 0.00017 | 0.98 |
| 3D | 0.00065 | 0.90 | 0.00025 | 0.99 |

The accidental release flow rate was set differently in the cases; specifically, it was equal to:

- the maximum design flow rate in Case 3A and Case 3B;
- 30% of the maximum design flow rate in Case 3C and Case 3D.

The voluntary release flow rate was equal to the following values:

- 0.00025 $m^3\ s^{-1}$ in Case 3B and Case 3D;
- approximately equal to 70% of such value in Case 3A and Case 3C.

We supposed different values for probability and reliability in order to analyse several reasonable situations. Note that a reliability value different from 1 means that there is an uncertainty about the operating conditions of the welding equipment (sometimes, the welding system does not work properly and thus does not release the shielding gas).

## 4. Results

### *4.1. Scenario 1*

The trends obtained simulating Scenario 1 using the well-mixed model are shown in Figure 4.

Figure 4 depicts the effect of the performed activities on the atmosphere during the 2 h of exposure. In Case 1B, the $O_2$ concentration does not drop below the minimum safe level defined in the literature (i.e., 19.5%, as reported in the Introduction) during all simulation time and thus does not cause negative physiological effects. In Case 1A, after 1 h, the $O_2$ concentration is equal to 19.62%, while after 2 h it is 19.25%. After this period,

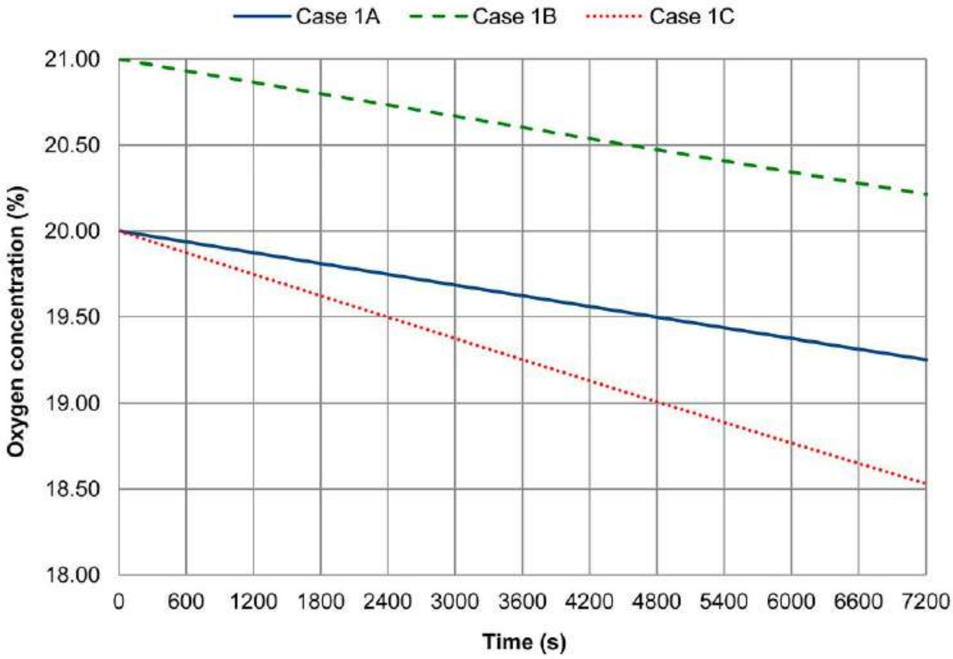


Figure 4. Time trends of oxygen concentration by the well-mixed model in Scenario 1.
Note: The full colour version of this figure is available online.

Table 5. Oxygen concentration in Case 1A, assuming that the welding is carried out throughout the work shift.

| Time (h) | Time (s) | Oxygen concentration (%) |
|---|---|---|
| 0 | 0 | 20.00 |
| 1 | 3600 | 19.62 |
| 2 | 7200 | 19.25 |
| 3 | 10,800 | 18.89 |
| 4 | 14,400 | 18.53 |
| 5 | 18,000 | 18.18 |
| 6 | 21,600 | 17.84 |
| 7 | 25,200 | 17.50 |
| 8 | 28,800 | 17.17 |

the $O_2$ level remains constant at 19.25% because welding activities are no longer undertaken and ventilation airflows are absent. Therefore, according to Table 1, since $O_2$ concentrations remain above 18.0%, no symptoms in healthy adults are suspected and the ODH exposure can be assessed as acceptable. If the worker continues to perform the task beyond 2 h, the $O_2$ concentration continues to decrease linearly. Table 5 presents $O_2$ concentration values reached every hour in a shift, extending the simulation time to 28,800 s (8 h). After 6 h, the $O_2$ concentration is below 18% and can lead to negative physiological effects, but during the whole shift the $O_2$ level does not drop below 17%.

If two operators simultaneously carry out the same welding operations in the same chamber (Case 1C), the $O_2$ concentration decreases and reaches a minimum value equal to 18.53%, which is unlikely to result in negative physiological effects in healthy adults in accordance with Table 1.

In order to more precisely assess the most critical case when only one welder is in the inspection chamber (Case 1A), application of the NF–FF model was used to calculate the size of the volume with a low $O_2$ level (NF), and thus evaluate whether it includes the welder's breathing zones. Figure 5 shows time trends of the NF and FF volumes, setting the limit values for the $O_2$ concentration in the NF to 17 and 19.25%. An $O_2$ concentration of 17% is never reached in the 2 h by the well-mixed model, while a value of 19.25% is achieved at the end of the simulation.

As reported in Figure 5, during the simulation period, the NF and FF volumes with a limit value for the $O_2$ concentration in the NF equal to 17% do not change and thus the working environment is always equal to the FF. The trends of NF and FF volumes with a limit value for the $O_2$ concentration equal to 19.25% are completely different from the previous ones. The choice of a higher limit value for the $O_2$ concentration causes the NF to appear and increase its volume during the last 1200 s (20 min). At the end of this simulation, the radius of the hemisphere representing the NF is equal to 2.92 m.

Figure 6 displays a zoom of Figure 5 related to the trends with a limit value for the $O_2$ concentration equal to 17% during the last 100 s in Case 1A. This graph depicts a high resolution of the NF and FF volume patterns obtained changing the *y*-axis scales. The NF volume increases and comes back to 0 several times: in the instants in which the NF volume is equal to 0, the $O_2$ concentration in the previous instant time, the inert gas flow and the interzonal flow make the $O_2$ concentration within the NF higher than the fixed limit value. When the NF appears, its volume has

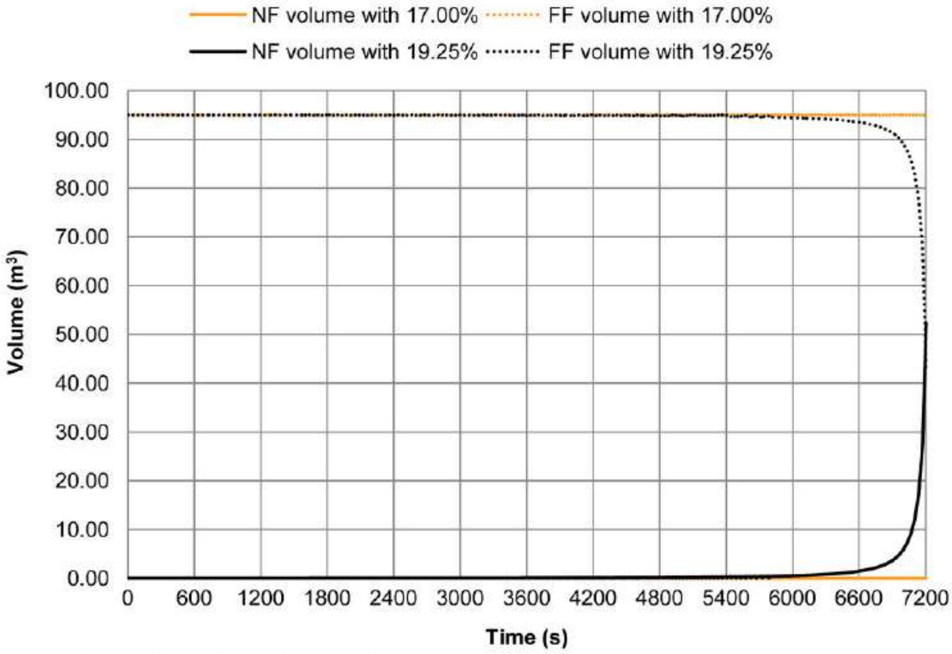


Figure 5. Time trends of NF and FF volumes in Case 1A.
Note: The full colour version of this figure is available online. FF = far field; NF = near field.

negligible dimensions. This particular trend is due to model assumptions and definition, and is also obtained with the simulation of Case 1C. These patterns emphasize the NF absence if the limit value for the $O_2$ concentration is set to 17%, and are in accordance with the well-mixed model results. In both Case 1A and Case 1C, an $O_2$ concentration of 17% is never reached.

### 4.2. *Scenario 2*

The results of the simulations conducted for Scenario 2 by means of the well-mixed model are reported in Figure 7.

Case 2D represents the least alarming situation because the $O_2$ concentration is always higher than 19.5%. The most severe situation in terms of $O_2$ depression is reached in Case 2C, where the probability of accidental release is higher than the assumed values for Case 2A and Case 2B. In Case 2C, the minimum value for $O_2$ concentration at the end of the simulation test is equal to 2.14% by volume, which is an extremely low value. Focusing on this case, Table 6 reports the time instants when the critical $O_2$ levels based on the human effects proposed in Table 1 are achieved.

Figures 8 and 9 depict the NF and FF volume trends for the two most critical cases: Case 2C and Case 2B. For both figures, we set the limit values for the $O_2$ concentration to 17 and 10%. An $O_2$ concentration of 10% is reached by the well-mixed model in Case 2C after about 1990 s (33 min), whereas in Case 2B after 5310 s (1 h 28 min). This concentration represents a hazardous condition in accordance with Table 1: the health effects likely to result from exposure to such atmospheres can be unconsciousness, mental failure and inability to move freely.

Table 6. Time instants when some critical oxygen concentrations are reached in Case 2C.

| Oxygen concentration (%) | Time (s) | Time |
|---|---|---|
| 19.50 | 193 | 3 min |
| 18.00 | 403 | 7 min |
| 15.00 | 886 | 15 min |
| 12.00 | 1487 | 25 min |
| 10.00 | 1989 | 33 min |
| 8.00 | 2618 | 44 min |
| 6.00 | 3461 | 58 min |
| 4.00 | 4743 | 1 h 19 min |

The time trends in Figures 8 and 9 are similar. For instance, with reference to Case 2B in Figure 9, before about 4450 s (1 h 14 min), the NF volume is negligible. After this time period, the NF volume increases, while the FF volume decreases; at $t = 4645$ s (1 h 17 min), the NF is equal to the entire confined space. From this moment onwards, no FF exists anymore and this means that the entire heat treatment furnace has an $O_2$ concentration equal to 10%. Therefore, the NF–FF model reaches the limit prior to the well-mixed model and thus the former approach is more precautionary than the latter. During the simulation test, the distance of the worker from the release point varies, e.g., 0.572 m at $t = 4599$ s (1 h 16 min) and 0.754 m at $t = 4625$ s (1 h 17 min).

### 4.3. *Scenario 3*

The $O_2$ concentration time trends achieved in Scenario 3 assuming a well-mixed atmosphere in the underground

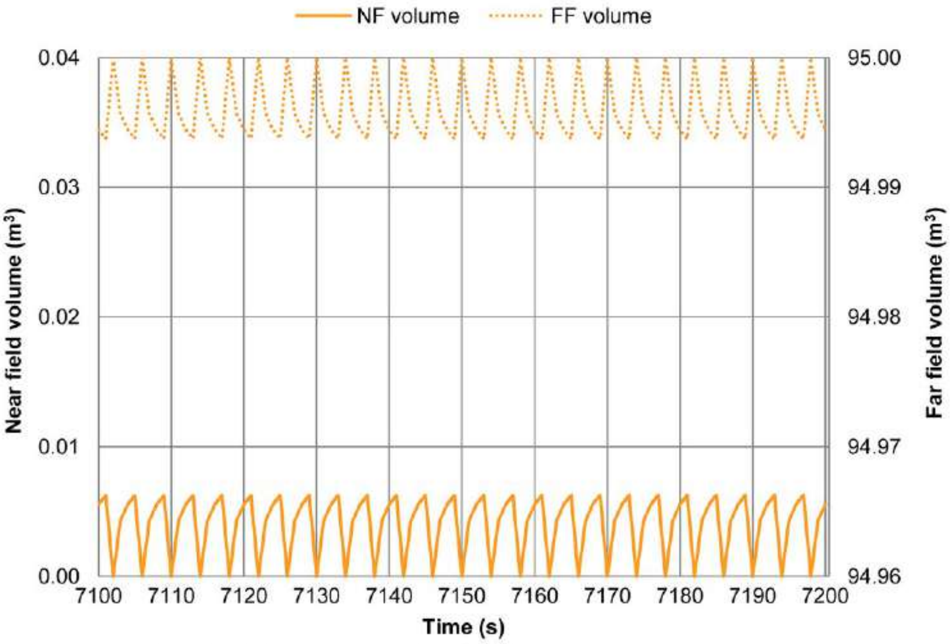


Figure 6. Zoom of the time trend of NF and FF volumes in Case 1A (limit value for the oxygen concentration = 17%).
Note: The full colour version of this figure is available online. FF = far field; NF = near field.

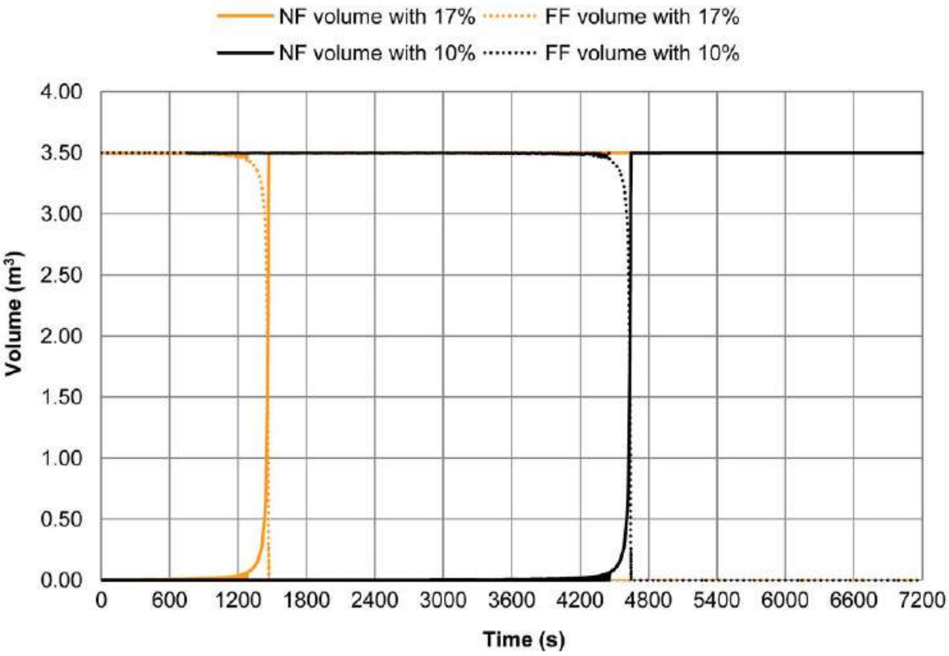


Figure 7. Time trends of oxygen concentration by the well-mixed model in Scenario 2.
Note: The full colour version of this figure is available online. FF = far field; NF = near field.

area surrounding the EAF furnace are depicted in Figure 10. This figure is obtained by varying flow rates, probability and reliability values.

In Case 3C, the minimum $O_2$ level reached after 2 h is equal to 18.88%. In Scenario 3, this represents the least critical case from the point of view of ODH assessment. This result is expected since Case 3C is characterized by the lowest values of flow rate and probability concerning the accidental release, and of the flow rate about the voluntary release. Also, Case 3D produces a final $O_2$ concentration higher than 18% (i.e., 18.12%). As a consequence, in these two cases, no symptoms in healthy adults are suspected and the ODH exposure can be assessed as acceptable.

To the contrary, the ODH exposure is severe in Case 3B that is characterized by a certain accidental release from

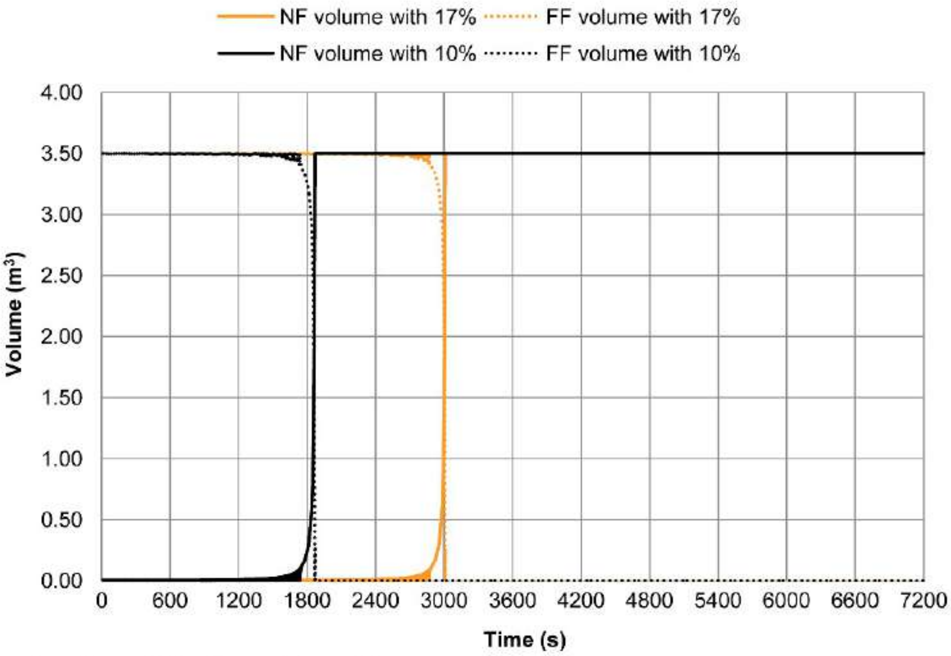


Figure 8. Time trends of NF and FF volumes in Case 2C.
Note: The full colour version of this figure is available online. FF = far field; NF = near field.

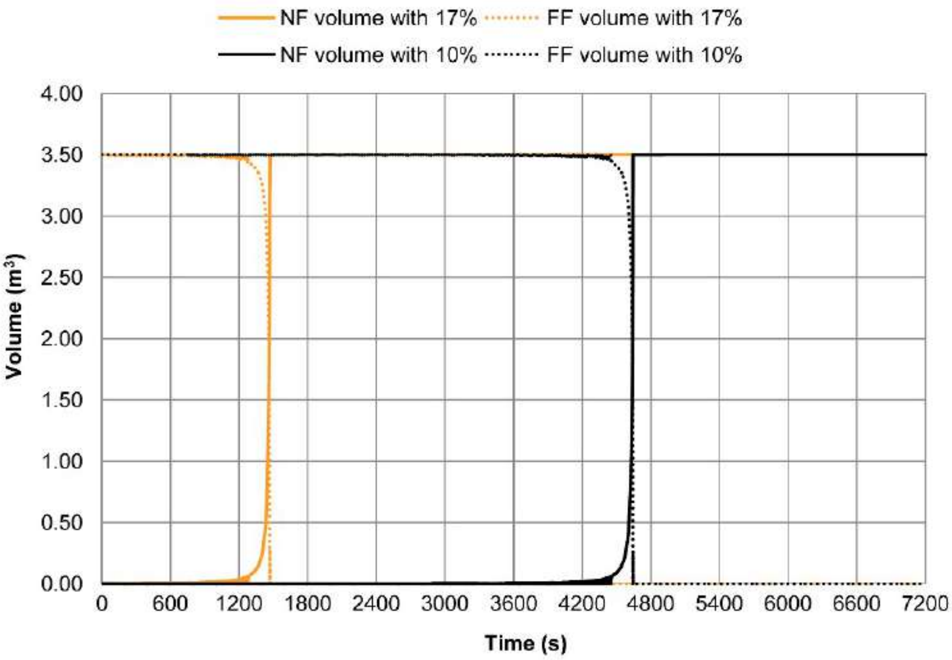


Figure 9. Time trends of NF and FF volumes in Case 2B.
Note: The full colour version of this figure is available online. FF = far field; NF = near field.

the stirring system (the probability is equal to 1). In this case, after 1 h the $O_2$ concentration reaches a value equal to 17.55%, whereas after 2 h it reaches 15.81%.

Figures 11 and 12 illustrate the outcomes achieved through the NF–FF model applied to the most critical cases (Case 3B and Case 3A). The main assumption based on the NF–FF model is the proximity between the two Ar releases. In Figure 11, the limit values for the $O_2$ concentration in the NF are fixed to 17 and 15.8% (the final $O_2$ concentration thanks to the well-mixed model application) in Case 3B. Figure 12 reports different time trends of the NF volume attained varying the limit value for the $O_2$ concentration in the NF in Case 3A. In particular, we tested two $O_2$ concentrations achieved through the application of the well-mixed model (19.0 and 18.5%), and one not reached during the simulation period (17.8%).

The well-mixed model in Case 3B shows that an $O_2$ concentration equal to 17% is reached after about 78 min.

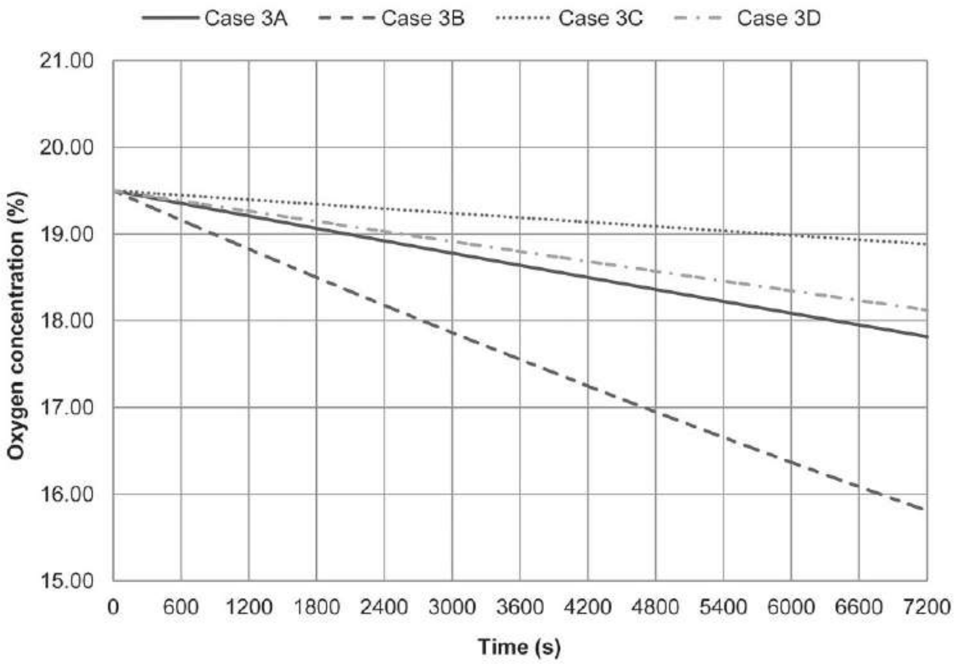


Figure 10. Time trends of oxygen concentration by the well-mixed model in Scenario 3.

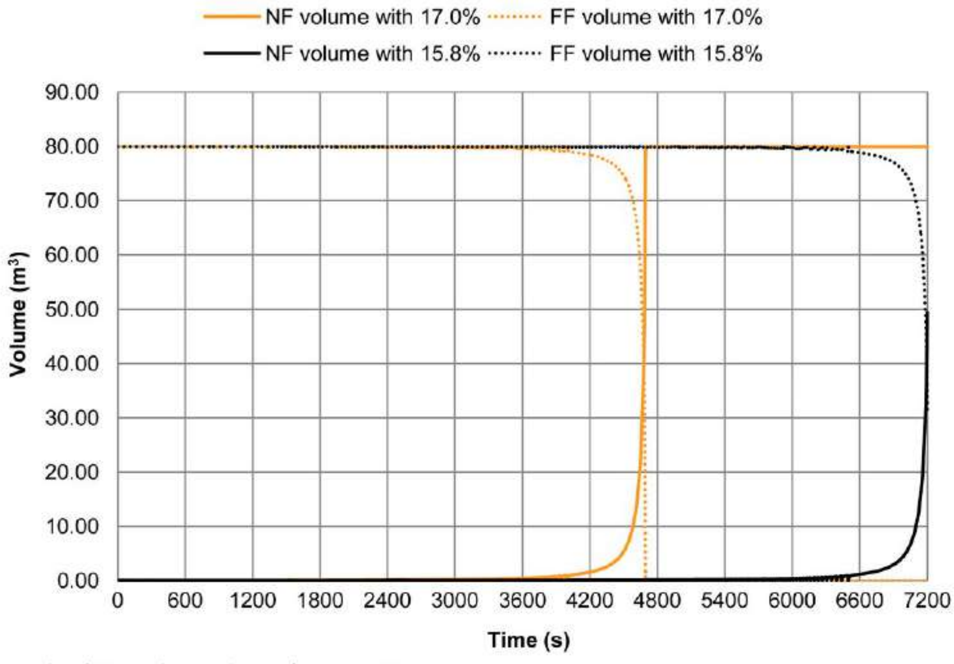


Figure 11. Time trends of NF and FF volumes in Case 3B.
Note: The full colour version of this figure is available online. FF = far field; NF = near field.

This result is confirmed by the NF–FF model (Figure 11). Indeed, the time required to achieve the equality between the NF and the working environment is about 4700 s (1 h 18 min). The NF radius constantly changes during the simulation, e.g., 0.54 m at $t = 3768$ s (1 h 2 min) and 0.80 m at $t = 4049$ s (1 h 7 min).

Taking as an example Case 3A (that has a final $O_2$ concentration equal to 17.82% by volume through the well-mixed model application), Figure 12 highlights that when the limit value for the $O_2$ concentration in the NF decreases, the time necessary for achieving equality between the NF and the working environment increases. This result is expected: a reduction of the limit value for the $O_2$ concentration increases the time to create a working environment with that $O_2$ level because a larger quantity of asphyxiating gases has to be released. The trends obtained with limit values for the $O_2$ concentration equal to 19.0 and 18.5% display that the NF fills the working environment:

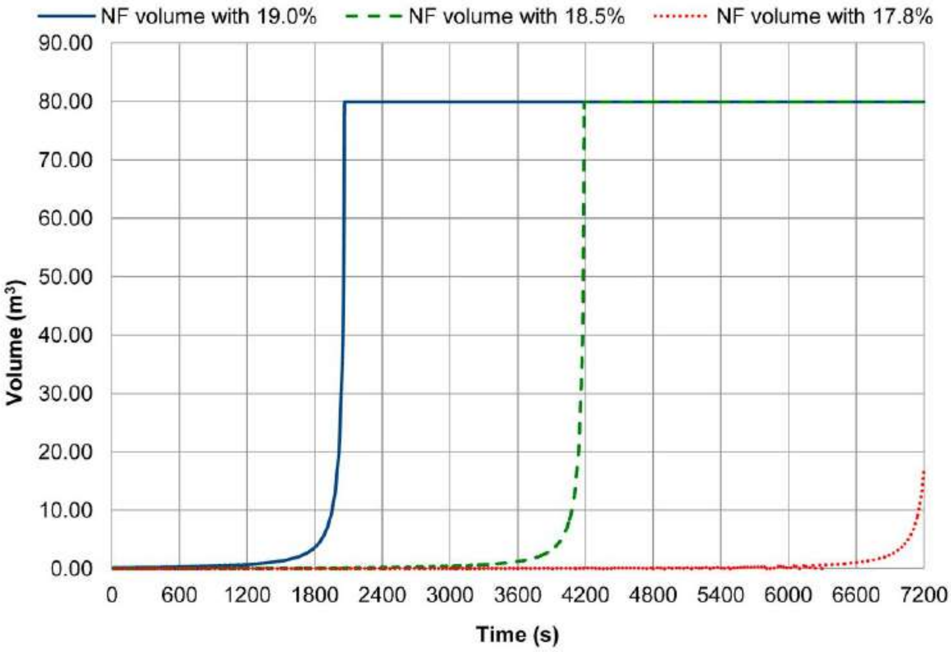


Figure 12. Time trends of NF volume in Case 3A.
Note: The full colour version of this figure is available online. NF = near field.

if the limit value for the $O_2$ concentration is set to 17.8%, the NF does not reach the size of the working environment. These considerations are in accordance with the outcomes provided by the well-mixed model.

## 5. Discussion

The simulations performed in this article highlight that $O_2$ deficiency is an OSH concern that requires careful assessments and analyses of many different parameters. Among the results obtained applying the models in the selected scenarios, the most hazardous situation is represented by accidental $N_2$ release into a vacuum heat treatment furnace (Scenario 2). This event is likely to occur occasionally, but the severity of its consequences is considerable. The severity of this outcome can be mainly justified by the confined space size: the furnace is significantly restricted and its volume is much smaller than the volumes assumed in other scenarios. Consequently, the confined space volume represents a key parameter for $O_2$ deficiency and the related exposures to asphyxiation risk. For instance, considering all parameters and conditions of Scenario 1, if we halve the inspection chamber volume, after 2 h the $O_2$ concentration in Case 1A reaches the value of 18.53% (instead of 19.25%), while in Case 1C it reaches 17.17% (instead of 18.53%).

In addition to the confined space size, another aspect determining the criticality of an $O_2$-deficient atmosphere regards the characterization of different potential releases. Safety managers should focus on their flow rates, duration and occurrence. Higher asphyxiant gas flow rates may result in more severe cases and scenarios. This severity increases mostly if accidental leaks occur in a confined space. Indeed, this type of release is often sudden, inadvertent and uncontrolled, producing a rapid $O_2$ decrease. Moreover, confined spaces typically present in the steel industry often lack ventilation and/or extraction systems, increasing the probability of $O_2$ deficiency and reducing the possibility to restore a safe indoor air composition. The release duration should also be analysed in order to comprehend its nature, i.e., whether it can be instantaneous, temporary or continuous. In this article, we investigated continuous releases and thus the $O_2$ reduction is gradual. In the case of a leak that instantaneously releases a gas volume similar to the total volume released during a continuous leak, ODH can occur rapidly, exposing workers to an immediate asphyxiation risk. For instance, if the flow rate leaked accidentally for 1 h in Scenario 2 was instantly released in 1 s at the beginning of the exposure period (assuming a release volume equal to 12.5 $m^3$ with a probability of 0.15), the operator would be subjected to air containing an $O_2$ level of only 10.20%. Therefore, in all these situations, leak prevention and detection should be matters of priority. In the scenarios presented in this article, undetected releases and leakages are assumed. Their early detection could prevent or interrupt the exposure, and thus modify the simulation results.

The initial indoor air composition is a salient parameter in the determination of an $O_2$ deficiency. Carrying out welding tasks in an underground confined area around an EAF during an accidental Ar release from the gas stirring system (Scenario 3) can lead to a hazardous condition: in Case 3B, after 1 h the $O_2$ concentration by volume is equal to 17.55%, whereas at the end of simulation it is

15.81%. In this scenario, the main assumption with regard to the presence of Ar in the initial air is due to an accumulation and an incomplete purging of previous releases. After a complete purge, the minimum $O_2$ concentration achieved at the end of simulation would be about 17%, while after 1 h the $O_2$ level is about 18.9%. This consideration confirms the expected result underlined in Stefana et al. [21]: a working environment with an initial indoor air composition with less $O_2$ creates ODH faster than a similar space with more $O_2$, assuming the same released inert gas flow rates.

Finally, risky activities should be investigated in terms of physicality of work, psycho-mental burden and duration. The characterization of exposure periods assumes a key point in ODH assessment and recovery with treatment. We refer to the exposure time for indicating the time interval when workers stay within the confined spaces for performing the assigned activities and inhale air with a low $O_2$ content. The combination of the exposure time and the $O_2$ concentration by volume represents crucial information for implementing adequate safety measures and planning breaks outside $O_2$-deficient atmospheres [35].

As a consequence, all of these aspects should be taken into consideration from a multidisciplinary point of view (e.g., the risk management process should also include a medical examination and the participation of occupational physicians) to adequately assess all of the determinants of ODH and workers' exposure. The data representing these models' inputs should be carefully collected and recorded, and the most critical ODH parameters should be properly managed through an identification of proper risk reduction controls to minimize the overall individuals' exposure. For instance, in Scenario 2, since the $O_2$ level of Case 2C rapidly becomes risky and poses a level which is immediately dangerous to life or health (IDLH) [36], the introduction of specific organizational and technical measures including a permit to work system [37], the provision of suitable respiratory protective devices (also in accordance with Standard No. EN 529:2005 [36]) and proper emergency planning should be adopted in order to reduce the risk. In Scenario 3 (mainly in Case 3B), the isolation of piping systems, lockout/tagout of equipment, the provision of safety and specific instructions and actions [38,39], the scheduling of breaks outside this area and the supply of systems allowing communications among workers inside and outside the space appear particularly interesting for managing the unacceptable final $O_2$ concentration (i.e., 15.81%). Furthermore, early release detection appears fundamental in scenarios in which accidental release can happen. Early detection can be obtained using readily available technologies such as electronic gas detectors. Additionally, augmented and virtual reality systems could be adopted in order to acquire information on equipment state and operation (and thus the actual need to enter the space), to increase the space awareness and to improve training effectiveness prior to performing risky activities. The adoption of such technologies could also partially solve compatibility problems between space dimensions/constraints and specific personal protective equipment (PPE) needed to control asphyxiation risks. Indeed, the wearing of some respiratory protection systems (e.g., self-contained breathing apparatus) may be difficult in narrow spaces and/or during activities requiring operator mobility. When possible, as elimination of the need for workers to enter confined spaces is high in the hierarchy of controls, the use of industrial robots is increasing [8]. If the entry of operators into the spaces cannot be avoided, other emerging technologies mentioned by several authors in the literature could be suitable for mitigating risks in confined spaces present in the steel industry [8,40,41]. For example, systems for lone workers should be considered in order to track the operators' location and direct rescuers in the fastest possible time in cases of emergency [8], and/or monitoring and event-detecting systems (e.g., radiofrequency technology-incorporated information technology systems [42]) could be used to check the status of everyone in the space and identify anomalies and/or alarm events. Wearable electronics and Internet of Things (IoT) wearable devices [8,40] could permit the monitoring of the physical activity and health status of workers, the improvement of communication flows among operators, safety managers and rescuers, and the real-time measurement of inside conditions near individuals during activities in confined spaces. The integrated system based on building information modelling (BIM) and wireless sensor technology proposed by Riaz et al. [43] appears to be a possibly valuable option for underground confined areas around an EAF.

These issues and the large number of variations in design and operation for tailor-made plants and equipment, gases, site-specific reliability data and potential confined spaces highlight the existence of a broad range of scenarios and related assessments that should be carried out in terms of ODH. Each situation needs a specific and individual evaluation to properly consider the variables characterizing each steel company. Due to the different designs of an EAF, an individual risk assessment shall be carried out in any case, considering the specific characteristics of the EAF in question and the interface between the EAF and other buildings' equipment (e.g., gas stirring system) [39].

Although such specific and individual ODH assessment is not straightforward, the resources required for the application of both models employed in this article are not prohibitive in terms of costs and time. Consequently, reasonable indoor $O_2$ level estimations and ODH exposure assessments can be obtained relatively quickly. Indeed, by means of our current Excel spreadsheets and Visual Basic for Applications (VBA) codes implementing the models, the simulation of each case takes no more than 2–3 min. The models efficiently perform several simulations starting from different information and data collected through site visits and audits, allowing several evaluations of hazardousness and criticality of scenarios typically encountered in industrial plants.

## 6. Conclusions

This article presents the ODH assessments of real confined spaces typical of the steel industry where inert gases are usually present and used. The simulations performed by means of a well-mixed model and an NF–FF model allow the estimation of time trends of indoor $O_2$ levels in order to assess potential occupational exposures to asphyxiation risk. The outputs of these assessments may assist any steel safety manager to identify the most critical parameters contributing to $O_2$-deficient atmospheres and, consequently, those which require specific attention in terms of data collection and monitoring. In the confined spaces present in the steel industry, it is advisable to take into consideration confined space sizes, different potential releases (e.g., in terms of flow rates and duration), initial indoor air compositions and exposure periods. Inspections and maintenance activities lasting more than 1 h in or near steel furnaces during accidental release may expose personnel to an atmosphere containing an extremely low $O_2$ concentration.

To mitigate the ODH exposure and the asphyxiation risk in steel industry confined spaces, the scheduling of breaks and the provision of any system for communications among individuals inside and outside the space are necessary prevention and/or protection measures compatible with the activities usually carried out in the considered areas. Additionally, the increasing availability of emerging technologies allows the adoption of effective solutions for enhancing OSH in confined spaces.

Future work should continue to analyse confined spaces from an $O_2$ depletion perspective typically present in the steel industry. Finally, more research is needed to further explore other possible emerging technologies for decreasing workers' exposure to ODH.

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No potential conflict of interest was reported by the authors.

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