Environmental issues of formation and utilization of electric arc furnace dust

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The increasing share of steel produced from recycled scrap results in the formation and accumulation of dust generated in the gas cleaning systems of electric arc furnaces (EAF dust). This paper presents statistical data reflecting the dynamics of steel production in electric arc furnaces and the formation of EAF dust at metallurgical enterprises in the Russian Federation from 1992 to 2023. An analysis of the key technological stages of modern electric arc furnace operation is provided, enabling insights into the formation mechanisms of the dust's chemical composition. The study highlights the main challenges associated with EAF dust processing, particularly the zinc content (which determines processing technology and economic feasibility) and the presence of chlorine and non-ferrous metal impurities. The potential sources of chlorine and non-ferrous metal contaminants during smelting were identified. The dual negative impact of chlorine-containing compounds is discussed: on the one hand, they promote the formation of highly toxic organic compounds such as dioxins and furans; on the other, they significantly degrade the quality of the final product obtained during subsequent pyrometallurgical processing into Waelz oxide. Approaches to reducing chlorine content during the steelmaking stage and minimizing its impact on toxic compound formation were examined. The methods for removal of chlorides from EAF dust—pyrometallurgical, hydrometallurgical, and hybrid pyro-hydrometallurgical—were reviewed. The various EAF dust processing technologies depending on zinc content were presented, as well as the options for iron recovery.

Key words: EAF dust, scrap, zinc, chlorides, dioxins and furans, EAF dust recycling methods, roasting, washing.
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Large Volume and Toxicity of EAF Dust

At present, the issue of disposal and processing of metallurgical production waste is particularly serious. One such waste is electric arc furnace (EAF) dust. According to estimates, over 30 million tons of EAF dust are currently stored in the waste dumps at metallurgical plants in the Russian Federation, with additional amount from 600,000 to 700,000 tons annually generated (25–30 kg of dust per ton of steel; in 2023, approximately 24 million tons of steel were produced in the electric arc furnaces in Russia). Most of this dust remains unprocessed in the country [1–3]. The main valuable components in the EAF dust are iron and zinc with contents ranging from 20–50 % and 2–25 % (sometimes up to 40 %), respectively [4–6].

Although zinc is a trace element essential for human health and plant growth, it becomes toxic when its concentration exceeds the permissible exposure limit (PEL). Excess zinc can act as a potent pathogen. Therefore, the storage of such waste as EAF dust poses an environmental hazard. Zinc-containing dust can be dispersed by wind and may enter the eyes, lungs, and mucous membranes of humans and animals causing various health issues. Zinc can also leach into groundwater due to weather conditions, posing significant environmental risks. In humans, excess zinc accumulation is particularly problematic when the excretory system is impaired, affecting immunity and gastrointestinal function. Additionally, excess zinc can interfere with the absorption of other essential trace elements such as manganese, copper and iron. In plants, excess zinc causes leaf chlorosis, brown spotting, and a roughened leaf surface [7].

EAF dust also contains levels of highly toxic and water-soluble cyanides, rhodanides, and other hazardous elements exceeding permissible limits, including Pb, Cd, As, F and Cr (IV). Chlorine-containing compounds are often present in the dust; during subsequent heating (e.g., in the Waelz process) these compounds decompose and chlorine acts as a catalyst for the formation of dioxins and furans. Dioxins (polychlorinated dibenzodioxins) and furans (polychlorinated dibenzofurans) are two structurally related groups of polychlorinated organic compounds with complex isomeric and homologous compositions. These substances are classified as persistent organic pollutants (POPs) [8].

Due to the annual increase in the share of steel produced in electric arc furnaces and the related accumulation of EAF dust, the issue of its disposal is highly relevant. Accordingly, the purpose of this article is to examine the issue of EAF dust recycling, identify the sources of harmful impurities and explore potential methods for the dust utilization.

Formation of EAF Dust and Factors Influencing the Composition

The electric arc furnace (EAF) is one of the primary units in modern metallurgical production. Its main area of application is mini-mills, where a short-cycle steelmaking process is used. **Fig. 1** shows the annual volumes of steel produced in electric arc furnaces in the Russian Federation.

As the graph indicates, there is a general upward trend in the industrial use of electric arc furnaces. The primary input material for these furnaces is scrap metal. Some enterprises also use pig iron and hot briquetted iron (HBI). Alloyed steel scrap is particularly valuable because its alloying elements reduce the need for added ferroalloys. Scrap is typically categorized into three main types: circulating scrap, obsolete scrap, and machine-building plant scrap.

- **Circulating scrap** originates from trimmings and offcuts in rolling, forging, and heat treatment shops. Its main advantage is the well-known and clean chemical composition.
- **Obsolete scrap** is recovered from decommissioned vehicles and dismantled metal structures. Although its volume is substantial, it poses challenges due to unknown composition and contamination with non-ferrous metals.
- **Machine-building scrap** consists mainly of oily metal shavings, limiting its direct application.

Pig iron is used in EAFs at integrated steelworks where the blast furnaces operate. It is relatively inexpensive and chemically stable. Its use is justified as a means to introduce fresh charge and dilute non-ferrous contaminants; although it also adds carbon and harmful impurities such as sulfur and phosphorus. HBI consists of metallic pellets or briquettes with a metallization degree of 90–97 %, containing minimal carbon and harmful impurities. However, its use is constrained by its high cost.

Modern EAF steelmaking is carried out in two main stages—the melting period and the oxidation period:

- During the melting period, arc combustion is intense, leading to local overheating under the arc, which causes the charge to vaporize into the gas phase and settle in the furnace filters. The main elements transferred to EAF dust at this stage include Fe, Zn, Cl, Na, K, Cu, Pb, and Ca. Dephosphorization of the metal is also targeted during melting by adding lime to increase slag basicity and promote foaming.
- The oxidation period in modern high-capacity furnaces lasts about 15–20 min. Its main purpose is to remove excess carbon from the melt via intensive oxygen blowing. Upon completion of this stage, the oxidized semi-product proceeds to subsequent operations, one of which is desulfurization in a ladle furnace (LF). In this process, a special slag is formed, and synthetic slags (SS) may be used to increase basicity [9].

Gross Generation of EAF Dust in Russia, Chemical and Particle Size Composition

On average, about 25–30 kg of dust is generated per ton of steel produced. **Fig. 2** presents the average annual volumes of dust formed during electric arc steelmaking in Russia.

The primary raw material used for steel production in electric arc furnaces is scrap metal. As the number of EAFs at metallurgical enterprises had increased, a challenge arose in obtaining high-quality scrap. Many plants began using scrap with higher levels of impurities such as copper, zinc, lead, cadmium, and chlorine. The use of obsolete scrap has led to an increased concentration of non-ferrous metal impurities in EAF dust, which in turn hinders the recycling of this dust via conventional methods. During steelmaking, metals enter the dust from various sources. For example:

- Zinc, originating from galvanized scrap, ends up in the dust due to its low solubility in molten steel and slag,

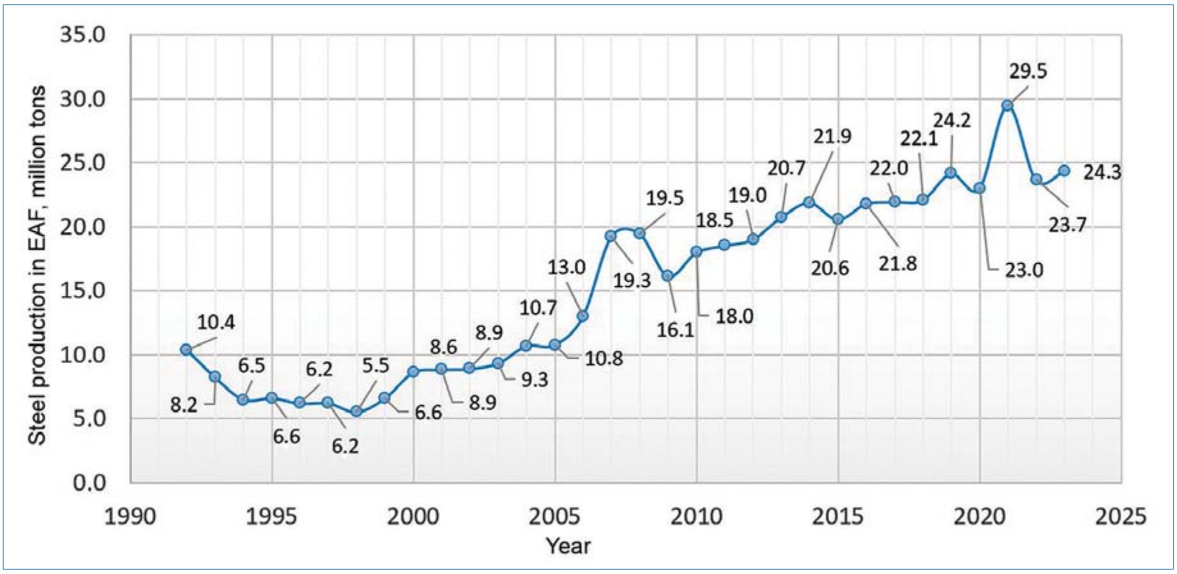

Fig. 1. Volumes of steel produced in electric arc furnaces in the Russian Federation by year (Compiled based on the data from [2])

as well as the fact that its vapor pressure is higher than that of iron at steelmaking temperatures;

- Lead originates from paint coatings on scrap;
- Manganese, chromium, and nickel are often alloying elements in various steel grades [1].

Formation of Chlorides in EAF Dust

In modern steelmaking processes that produce an oxidized semi-product, the main source of chlorine in EAF dust is obsolete scrap which is often contaminated with polyvinyl chloride (PVC) compounds originating from shredded automobile bodies and similar materials.

In earlier steelmaking technologies, where the final steel grade was produced directly in the electric arc furnace, another potential source of chlorine was aluminum used for deoxidation. One of the most widely adopted industrial methods for aluminum production is the Bayer process; a caustic hydrometallurgical method typically applied to high-grade bauxites with a low silica content (those with an alumina-to-silica mass ratio—called the silica module—above 6). After the raw material (bauxite) is crushed and ground, it is treated with an alkaline aluminate solution in a leaching process that extracts aluminum oxide into solution at a concentration of 250–300 g/l Al_2O_3. The insoluble residues precipitate, which are known as red mud. The subsequent stages of production involve separating and purifying the aluminate solution and washing the red mud to extract any remaining aluminum content [10].

Hydrometallurgical methods of aluminum production introduce sodium and potassium salts into the process. As a result, aluminum slag is formed with NaCl and KCl contents reaching up to 50 %. This slag can be recycled to extract aluminum. Low-grade aluminum is sometimes used in slag-forming mixtures (SFM) which may be applied during slag formation in steelmaking. Therefore, chlorine-containing SFM additives used to create a protective slag layer in earlier EAF steelmaking practices could also have been a source of chlorine. Today, such additives are more often used in ladle furnace operations, meaning chlorine may also be present in dust from ladle furnaces (LF) [11].

Dechlorination of EAF Dust

EAF dust with a high chloride content presents several major challenges for processing facilities:

- Low-grade of crude zinc oxide, since further dechlorination is required;
- Risk of dioxin emissions during pyrometallurgical processing (Waelz process);
- High-temperature corrosion of air ducts and related infrastructure.

At zinc production facilities that utilize electrolytic methods, it is necessary to dechlorinate the contaminated Waelz oxide beforehand. During electrolysis, chlorine increases lead content in the zinc deposit due to anode corrosion, degrades aluminum electrodes and causes strong zinc adhesion to electrodes in the presence of elements such as lead, fluorine, and chlorine. These elements result in dense zinc deposits that adhere to electrodes, complicating their removal. Fluorine is especially problematic, as it is considered the main cause of zinc deposit adhesion to aluminum cathodes. In some cases, the adhesion becomes so strong that conventional methods are insufficient for zinc removal [12]. The use of fluorspar (as a flux) has decreased significantly, reducing or eliminating fluoride content in the dust.

Chloride compounds typically found in EAF dust include:

- Sodium chloride (NaCl);
- Potassium chloride (KCl);
- Lead hydroxychloride (PbOHCl) [13, 14].

Metal chlorides that become gaseous at high temperatures act as powerful catalysts [15, 16]. As a result, chlorides are the primary contributors to dioxin emissions during EAF dust processing. Methods for removing chlorides from EAF dust fall into three categories:

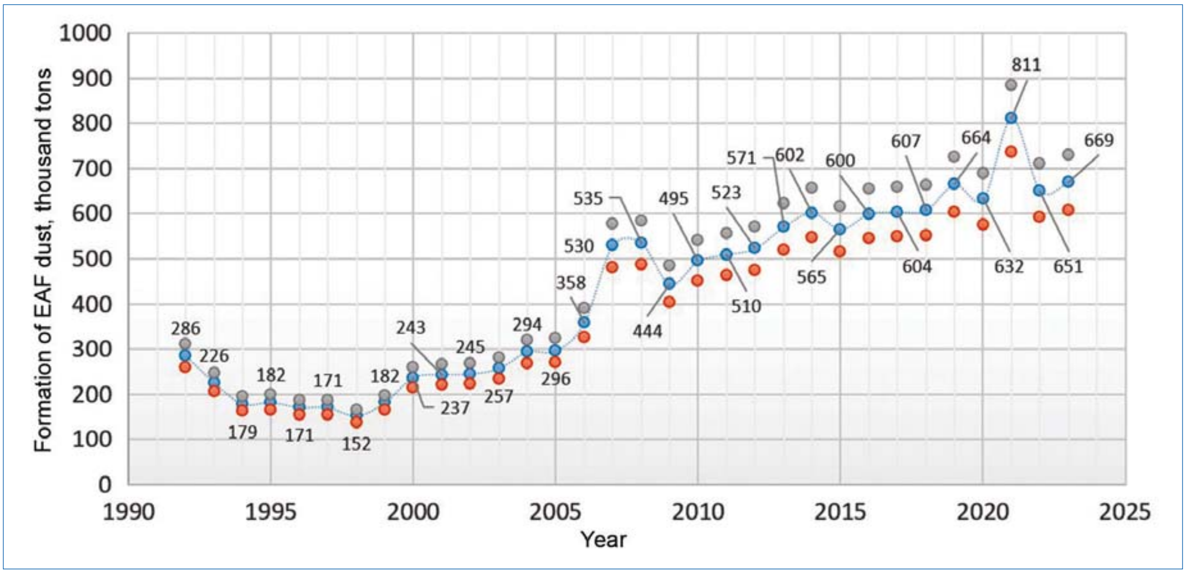

Fig. 2. Gross generation of EAF dust in the Russian Federation by year

- Pyrometallurgical;
- Hydrometallurgical;
- Hybrid pyro-hydrometallurgical.

The literature describes a variety of chloride reduction methods, including:

- Water washing [17, 18];
- Thermal treatment [19–21];
- Electrodialysis [22].

Volatilized chlorides can also be removed by roasting. Washing is commonly applied as a pre-treatment step to remove water-soluble chlorides before dust recycling. However, EAF dust can react with atmospheric moisture and carbon dioxide, triggering natural weathering that converts leachable chlorides into insoluble mineral phases.

Studies on EAF dust from a steelmaking plant in Taiwan [23, 24] recommended a combination of low-temperature roasting and water washing. Roasting was conducted at 200–600 °C for 1–5 hours, and washing was done at a solid-to-liquid ratio of 1:10. The results showed that water washing is effective in removing a broad range of metal chlorides—KCl, $NaCl$, $PbCl_2$, $ZnCl_2$ — from fresh EAF dust. However, weathered or stored dust is more resistant, particularly when zinc and lead form hydroxychloride or carbonate-chloride complexes. Therefore, it is advisable to wash freshly collected dust directly after gas cleaning. Otherwise, roasting above 600 °C followed by water washing is necessary to improve chloride removal efficiency.

Recent domestic research [25] examined the formation of highly toxic organic compounds—dioxins and furans. The findings showed that EAF emissions may contain dioxins and furans in concentrations both below and above permissible limits, necessitating emission control. An increase in chlorine content in the charge leads to higher concentrations of dioxins and furans in flue gases and EAF dust. While only 0.000001–0.001 % of total chlorine contributes to dioxin/furan formation; even small amounts are hazardous. More than 99.99 % of chlorine ends up in non-toxic compounds, but the extreme toxicity of dioxins and furans requires strict control measures. Moreover, dioxins and furans begin to desorb from dust when heated above 300 °C. It is therefore recommended to:

- Control chlorine and organic material content at the scrap preparation stage;
- Apply high-temperature treatment (> 850 °C) to the dust during gas cleaning, followed by lime slurry quenching to neutralize dioxin precursors.

Studies [26] report successful experiments in washing Waelz oxides with added sodium carbonate, achieving over 97 % chloride removal under certain conditions. However, the other work [27] indicates that adding soda or replacing it with lime does not significantly improve dechlorination efficiency — the key factor is increased temperature which enhances chloride solubility and extraction.

Methods of EAF Dust Utilization

Fig. 3 presents the primary methods of EAF dust recycling depending on zinc content. The distribution percentages are approximate and compiled from multiple sources for comparison.

Recycling methods for EAF dust are largely determined by the zinc content. When zinc content is high (≥ 15 %), several processing techniques are available to extract zinc, lead, cadmium and iron. These techniques are generally divided into:

- Hydrometallurgical;
- Pyrometallurgical;
- Combined pyro-hydrometallurgical methods (the most common in practice).

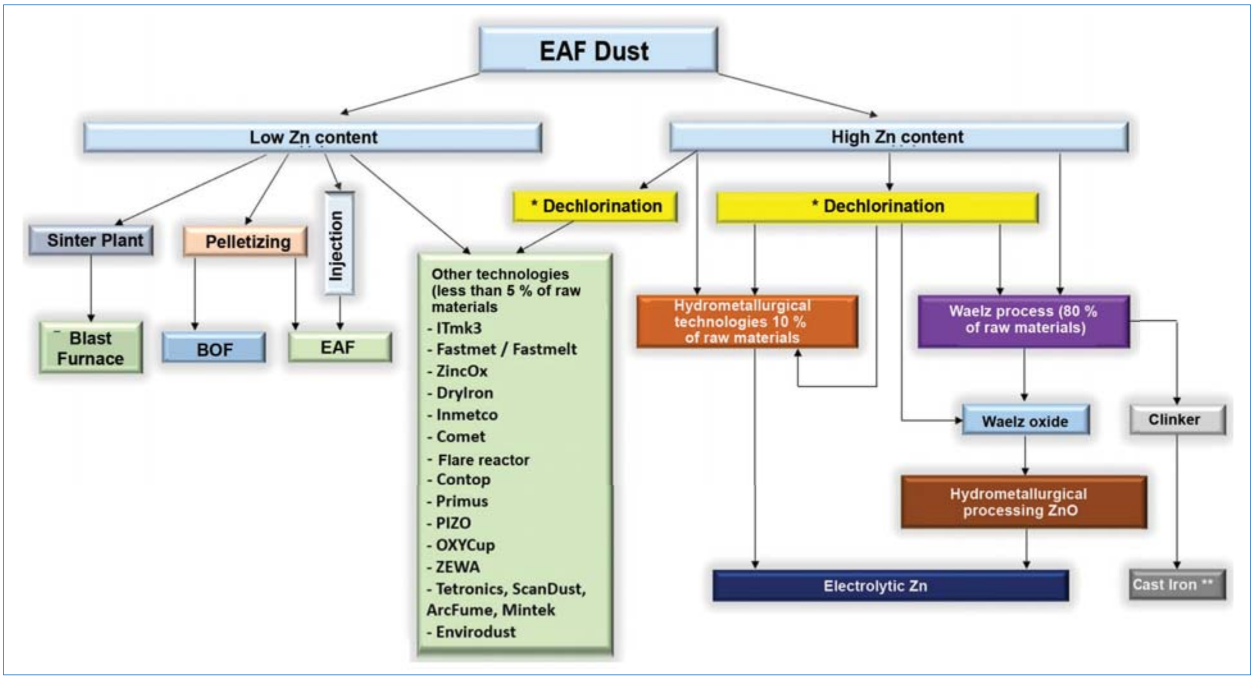

Fig. 3. EAF dust processing options based on zinc content

Approximately 90 % of global zinc-containing EAF dust recycling uses combined pyro-hydrometallurgical methods. This is mainly because the decomposition of zinc ferrite ($ZnFe2O_4$) requires high temperatures. About 80 % of zinc-rich material is first processed by Waelz kiln technology, producing zinc oxide which is then leached. In general, pyrometallurgical processing is mainly conducted via the Waelz process. Compared to purely hydrometallurgical methods, pyrometallurgical routes yield more environmentally stable products (excluding issues related to chlorides).

The essence of pyrometallurgical methods is the reduction of metals at high temperatures, allowing zinc to enter the gas phase due to its high vapor pressure, while metals like iron, with lower vapor pressures, remain in the solid phase. Carbon-containing reductants such as coal or coke fines are used. Zinc is recovered from the gas phase by oxidizing zinc vapor, forming fine zinc oxide powder. If the raw material is sufficiently pure (e.g., zinc dross from cathode zinc remelting), zinc white can be obtained. A by-product of the Waelz process is metallized clinker, which can be remelted to produce pig iron.

Hydrometallurgical techniques include:

- Acid leaching;
- Alkaline leaching;
- Ammoniacal leaching.

Only about 10 % of zinc-containing feedstock worldwide is processed by purely hydrometallurgical methods (i.e., without prior pyrometallurgical treatment). A critical operational issue in any route is *dechlorination which must be applied either to the raw EAF dust or to the zinc oxide obtained after Waelz processing.

Dust with low zinc content is generally not economically viable for full recycling. At some facilities, it is instead sent for internal recycling. For example, steel plants using hot metal in EAFs produce dust with relatively low impurity levels, making it suitable for return to the sintering plant. However, this results in the presence of lead and zinc oxides in the blast furnace lining—a trade-off that is sometimes consciously accepted.

Alternative disposal options for low-zinc EAF dust include:

- Briquetting and limited addition to basic oxygen converters or EAFs;
- Complex briquettes which may contain other wastes (e.g., converter sludges). In converters, such briquettes can serve as coolants and promote early lime dissolution.

Another approach is direct injection of dust into the EAF at the metal-slag interface [28]. However, the literature reports that this significantly reduces melting efficiency, energy performance, environmental compliance and steel quality. EAF dust can also be agglomerated via stiff vacuum extrusion for further reduction smelting, enabling recovery of iron as steel or cast iron**. This can yield products such as:

- Castings;
- Free-cutting steel;
- Hadfield steel;
- Cast iron grinding media [29–31].

Less than 5 % of zinc-containing feedstock worldwide is processed using advanced methods such as:

- ITmk3, Fastmet/Fastmelt, ZincOx, DryIron, Inmetco, Comet;
- Smelting in reactors: Contop, Primus, PIZO, OXYCup, ZEWA, Tetronics, ScanDust, ArcFume, Mintek, Envirodust, etc.

These technologies have limited adoption due to serious drawbacks:

- High capital investment;
- Elevated energy consumption;
- Low capacity.

Moreover, these systems still require dechlorination either of the raw dust or of the zinc oxide produced via pyrometallurgy, along with fluoride removal, if applicable.

Conclusion

The majority of EAF dust generated in the Russian Federation remains unrecycled. The complexity and variability of chemical composition present significant challenges to utilization. A major constraint is the inconsistent zinc content: EAF dust with low zinc levels is not economically viable for processing due to the high cost of technology and the infeasibility of zinc extraction. Such dust is sometimes returned to sinter plants (as it is done in practice) or added in small amounts to BOFs or EAFs. However, each of these approaches comes with own drawbacks.

Even zinc-rich dust has a highly unstable composition, which depends on the raw materials used during furnace operation. Nevertheless, this type of dust is of considerable interest for recycling.

When low-quality scrap is used, EAF dust becomes contaminated with hazardous elements such as lead, copper, chlorine and cadmium. Therefore, it is essential to monitor the quality of feedstock supplied to steelmaking units. Chlorine, in particular, is highly toxic and can lead to poisoning of operating personnel and contamination of the semi-products (e.g., zinc oxide) formed in the gas phase during Waelz processing. Special attention should be given to the removal of plastics from scrap, the purity of deoxidizers and the quality of slag-forming mixtures in order to prevent chlorine contamination from these sources. Thus, specific preventative measures must be implemented on-site at steelmaking facilities.

Chlorine can be removed via pyrometallurgical methods. However, at zinc-producing enterprises roasting must be carefully controlled (aimed at chlorine removal) and performed either below critical temperatures or to be high enough to fully decompose toxic compounds. Otherwise, dioxin and furan desorption may require dedicated gas cleaning systems. Personnel directly handling EAF dust should be equipped with appropriate personal protective equipment (PPE) for skin and respiratory protection.

Finally, the development and industrial application of hydrometallurgical dechlorination technologies for EAF dust remains a highly relevant objective.

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