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Environmental assessment of the use of emulsion explosives in underground iron ore mining

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Abstract:

The article provides a comprehensive analysis of using TNT-free explosives (E) in the iron ore mining sector in Ukraine. It delves into the development and application of a specific type of emulsion explosive known as "Ukrainit," which is free from TNT, with the objective of its adoption in underground iron ore mining operations. Pilot blasting activities were carried out at PJSC "Zaporizhzhia Iron Ore Plant" (PJSC "ZIOP"), selected for its state-of-the-art equipment and advanced ore extraction technology. Through examination of ground-level concentrations of environmentally hazardous substances, the study revealed that the highest levels of carbon monoxide, nitrogen oxide, and dioxide were observed in 2008 when underground mining operations exclusively used 100% TNT-containing E. However, by the year 2020, a situation changed with implementation of a blend comprising 78% "Ukrainit" type EE and 22% TNT-containing explosives, resulting in a notable decrease in the maximum concentrations of environmentally hazardous substances compared to 2008. Specifically, carbon monoxide level decreased by 5.0–5.5 times, while nitrogen oxide and dioxide levels decreased by 1.2–1.3 times. Furthermore, use of "Ukrainit" type EE at PJSC "ZIOP" led to a 1.5 times decrease in the environmental hazard index on average (reduced to 36%) compared to the usage of TNT-containing E. These findings underscore the significant environmental benefits associated with the adoption of TNT-free explosives in iron ore mining operations, particularly in mitigating the release of harmful substances and reducing environmental risks.

Keywords: emission source, ground concentration, environmentally hazardous substances, emulsion explosives, environmental hazard index, environmental assessment

1. Introduction

The Association Agreement between Ukraine and the European Union mandates the adoption of European standards and regulations concerning environmental protection, particularly focusing on safeguarding atmospheric air quality. The mining industry, being the primary source of raw materials for metallurgical enterprises, unfortunately, poses a significant environmental threat to surrounding ecosystems. Prolonged iron ore extraction has resulted in heightened pollution levels in atmospheric air, water bodies, and land, as well as the accumulation of substantial industrial waste, significantly diminishing environmental safety levels in Ukrainian mining regions. Underground iron ore extraction, primarily carried out through drilling and blasting operations using various explosives, contributes to the contamination of mine air with explosion byproducts and iron ore dust. These pollutants are subsequently released into the atmosphere without any purification, posing risks to all components of the surrounding environment, including human health and local biota.

The use of E for extraction different ore sources started at the beginning of the 17th century. The impetus for the development of blasting operations is associated with the appearance in the first half and early second half of the 19th century new E and initiation means (IM). This was due to the rapid development of the mining industry in the world. At the beginning of the 20th century the mining industry received a new E – trinitrotoluene (TNT, tol), which became the most common explosive [1]. TNT is still used by mining enterprises in the form of TNT-containing E. It is known that after blasting operations using these E, harmful substances in the form of nitrogen oxides and carbon monoxide are released into the atmosphere in significant quantities, which causes significant harm to both human health and the environment [2]. Therefore, TNT is banned for industrial use almost all over the world. A direct alternative to replacing TNT-containing E are locally prepared analogues [3], which include TNT-free E and EE [4]. The latter are safe during transportation [5] and storage [6], environmentally friendly [7] and economically beneficial [8].

The Targeted Regional Program, initiated in 1999, aimed at facilitating the transition of mining and processing plants towards environmentally friendly TNT-free explosives. This program, jointly developed by mining enterprises in Kriviy Rig, has witnessed substantial advancements. From 2004 onwards, open-pit ore and non-metallic mines began their shift towards the adoption of new TNT-free explosives. By 2011, usage of these explosives in open-pit mining enterprises had reached an impressive 99% [9]. In recent years this transition has catalyzed significant changes in blasting operations techniques and technology across Ukraine [10], accompanied by a proliferation of explosives and related products.

Expansion of explosives produced directly at the blasting site from non-explosive materials, resulting in a surge in their consumption was a noteworthy development. Furthermore, numerous mining enterprises have established their own production facilities, leveraging both domestic and foreign technologies and equipment. This initiative has substantially bolstered environmental safety measures and enhanced the efficiency of blasting operations across diverse mining and geological conditions.

Despite these advancements, underground ore mining enterprises have predominantly persisted in using TNT-containing explosives. Consequently, the implementation of the Targeted Regional Program for transitioning mining enterprises to TNT-free environmentally friendly explosives for these underground facilities commenced in 2012 [11, 12]. This initiative reflects a concentrated effort towards aligning underground mining practices with environmentally sustainable approaches, ensuring a safer and more sustainable future for the mining industry.

2. Purpose

At underground ore mining enterprises with attempts to replace TNT-containing E with simple mixtures based on granulated ammonium nitrate and hydrocarbon fuel do not solve the problem. Since in these explosives the quality of the explosion depends entirely on the size and structure of the ammonium nitrate particles formed as a result of the destruction of nitrate granules during pneumatic charging of blast-holes or wells. Increasing the strength of ammonium nitrate granules leads to a sharp increase in the critical diameter of the E, as a result of which the performance decreases [13] and charge failures occur. On the contrary, excessive grinding of ammonium nitrate increases dust formation in the working area during pneumatic loading. There have also been attempts to introduce 3-5% water into their composition during pneumatic loading. This prevents the formation and accumulation of static electricity and provides the necessary level of safety, but water, by creating a film on the surface of the granules, prevents their inflammation, reducing the detonation ability and sensitivity of E. As the experience of the world's leading manufacturers of E, such as "Orisa" (Australia), "AEL", "BME" (South Africa), "Dyno Nobil", "Dyno Mainer" (Sweden) shows, the safest and most effective TNT-free E for ore mine conditions are liquid and cartridge EE. But at the same time, the main limiting factor for the transition of ore mines to EE is the high cost and the lack of specialized mixing and charging equipment (CE) [14], which allows mechanized production of E from non-explosive components and the formation of charges, as in blast-holes (up to 5 m long), and in ascending wells with a diameter of up to 110 mm and a length of up to 60 m. In addition, despite the successful experience of using bulk EE (Ukrainit, Emonit, ERA, Anemix) in open-pit mining [15], these types of E require refinement of the recipe component to increase sensitivity, stability and viscosity. No less important is development of regulatory and technical documentation that would ensure the safe and effective introduction of EE to replace standard TNT-containing explosives. This is possible thanks to the preparation of new drilling and blasting (D&B) passports [16] and projects for mass explosions that would take into account the physico-chemical features and detonation characteristics of EE [17], the selection of optimal deceleration intervals, use of non-electric initiation systems, as well as the development of appropriate instructions for blasters and their professional training. Thus, in recent years in Ukraine there has been a constant increase in the use of EE, which are produced at blasting sites, and a reduction in the consumption of explosives containing TNT. This is due to the fact that emulsion explosives do not contain starting materials classified as E [18]. EE acquire explosive properties only at the final stage of preparation and are practically insensitive to accidental initiation from friction, mechanical stress or fire and are safer to manufacture than other explosives [19]. In addition, these substances do not contain highly toxic components. The main representative of EE, widely introduced and used at enterprises with underground iron ore mining in Ukraine, is the domestic EE of the “Ukrainit” type, which was developed exclusively for use in underground conditions and does not contain TNT. PJSC "Zaporizhzhia Iron Ore Plant" (PJSC "ZIOP"), equipped with state-of-the-art machinery and cutting-edge ore mining technology, was selected as the primary facility for experimental blasting operations.

The dynamics of the annual consumption of TNT-free E of the "Ukrainite" type for the needs of PJSC "ZIOP" during 2009–2020 is presented in Fig. 1.

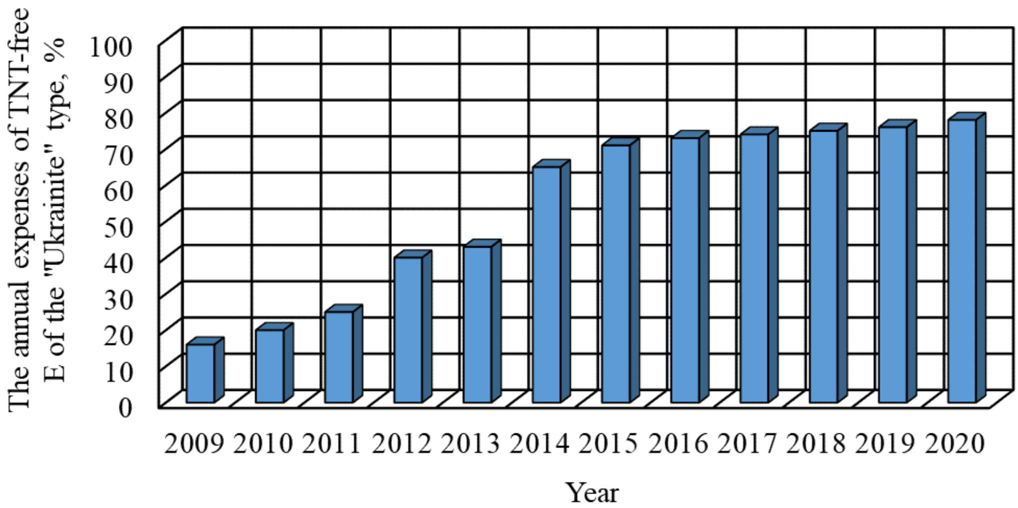

Fig. 1. The dynamics of the annual consumption of TNT-free E of the "Ukrainite" type for the needs of PJSC "ZIOP" during 2009-2020

Hence, there exists scientific interest in conducting an environmental evaluation of utilizing EE like "Ukrainite" in iron ore extraction within the operational environment of PJSC "ZIOP" mines.

Analysis of the results of the introduction of TNT-free E in the underground mining of iron ore has established that the use of EE of the "Ukrainit" type in the mines of PJSC "ZIOP" increased from 16% in 2009 to 78% in 2020 of the total annual expenditures of E.

Therefore, environmental assessment of reducing the technogenic overload on the atmospheric air when using EE for the extraction of iron ore in the mines of PJSC "ZIOP" is the work objective.

In pursuit of the established objectives, the following tasks were addressed:
– calculation of the ground concentration of environmentally hazardous substances and determination of their change depending on the distance from the emission source;
– determination of hazard indices for environmental objects when using TNT-containing and emulsion explosives in the mines of PJSC "ZIOP";
– assessing the environmental hazard of an iron ore mine regarding the technogenic impact on the atmosphere.

3. Methods

The tasks at hand were tackled using a combination of methods. Initially, analytical calculations enabled determination of airborne concentrations of environmentally hazardous substances following explosive operations at different distances from the emission source. This involved a comprehensive analysis of how these concentrations spread in the surrounding environment. Additionally, an environmental analysis enabled evaluating the degree of environmental risk reduction due to adoption of different explosives for drilling and blasting activities in iron ore mining. This involved assessing the potential impact of various explosives on the environment and comparing their effectiveness in mitigating the environmental hazards.

4. Results

To mitigate the adverse environmental impact, especially on atmospheric air quality, and in alignment with the Targeted Regional Program for transitioning mining and processing plants to TNT-free explosives, open-pit mining enterprises began utilizing environmentally friendly explosives (EE). Until 2008, all underground iron ore mines in Ukraine relied on TNT-containing explosives for blasting operations, despite their high cost and associated technological and environmental risks. To enhance environmental safety measures, PJSC "Zaporizhzhia Iron Ore Plant" (PJSC "ZIOP") initiated the adoption of environmentally friendly EE, such as the "Ukrainit" type, and TNT-free explosives since 2009. The annual consumption of TNT-free explosives and "Ukrainit" type EE by PJSC "ZIOP" mines increased from 16% of the total annual consumption in 2009 to 78% in 2020.

Despite these efforts, post-blasting operations associated with underground ore mining continue to release contaminated air into the atmosphere through air shafts without proper purification, as effective equipment for capturing and neutralizing emitted gases in significant volumes is still lacking. Between 2006 and 2010, measurements were conducted to assess the concentration of harmful gases in air samples around the air shafts of PJSC "ZIOP" mines, and the distribution of ground-level concentrations of overall impact was calculated. Additionally, from 2009 to 2011, studies were conducted to evaluate the toxic-mutagenic activity of atmospheric air around emission sources using the "pollen sterility" test. Furthermore, in 2011, investigations were undertaken to assess the technogenic impact on ontogenetic processes of winter wheat, including the linear dimensions and weight indicators of wheat near air shafts, as well as an analysis of the biological characteristics of sprouted wheat grains [20].

Upon scrutinizing the research findings, it was discerned that the discharge of mine air into the atmosphere through air shafts has detrimental effects on the growth of both higher plants and grain crops. Interestingly, as the distance from the emission source increases, the impact of mine air on flora diminishes. The research work in 2016, incorporating physical and chemical analyses along with

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biological assessments of atmospheric air conditions, unearthed a decline in concentration of harmful substances emitted into the air during drilling and blasting operations using emulsion explosives [21]. Subsequently, employing the proposed methodology, calculations were conducted between 2017 and 2018 [22, 23], culminating in an environmental evaluation of the atmospheric air condition surrounding mine air shafts [24]. This evaluation facilitated the establishment of a correlation between the reduction in technogenic impact on atmospheric air and a decrease in the environmental hazard index to 35%.

Therefore, a growing scientific and practical interest has emerged in comprehensively assessing the technogenic impact and environmental hazard index on atmospheric air. This interest is particularly heightened as the volume of annual consumption of environmentally friendly explosives (EE) and TNT-free explosives rises to 78% of the total annual costs. To undertake a thorough environmental evaluation of EE utilization within the mines of PJSC "ZIOP" for iron ore extraction, we will delve into the comparison of variations in harmful gas concentrations. Specifically, we will contrast the usage of 100% TNT-containing explosives in 2008 with the implementation of a blend comprising 22% TNT-containing explosives and 78% EE of the "Ukrainit" type during the same year. Following this comparative analysis, we will proceed to compute the change in the environmental hazard index. This endeavor aims to provide valuable insights into the environmental implications associated with using the "Ukrainit" type EE in the operations of PJSC "ZIOP" mines.

To obtain a qualitative and quantitative assessment of the distribution of the total impact of environmentally hazardous substances on the atmospheric air around the air shafts of PJSC "ZIOP", calculations were made of the ground concentration of environmentally hazardous substances in the "OND-86 Calculator" program. The program is designed to calculate fields of concentrations of harmful substances in the atmosphere, without taking into account the impact of buildings. The software is based on the standards established by the current methodology in Ukraine for calculating concentrations in the atmospheric air of harmful substances contained in emissions from enterprises [25]. These standards are observed when designing the enterprises, as well as when regulating emissions into the atmosphere of existing and reconstructed enterprises. The standards are intended to calculate surface concentrations in a two-meter layer above the earth's surface, as well as the vertical distribution of concentrations. Degree of danger of atmospheric air pollution is characterized by the highest calculated concentration corresponding to unfavorable meteorological conditions, including dangerous wind speed. They do not apply to the calculation of concentrations at long distances (more than 100 km) from the emission source [26].

As an example, let us consider the formation of surface concentration fields of the total impact of environmentally hazardous substances in fractions of units of the maximum permissible concentration (MPC) from the emission source. When calculating, the following initial data were taken into account: atmospheric stratification coefficient A=200, terrain coefficient η = 1.03, average maximum air temperature of the hottest month of the year equal to 33.8°C, average maximum air temperature of the coldest month of the year equal to –4,3°C, average wind speed is 9 m/s. Environmentally hazardous substances: carbon monoxide – maximum momentary permissible concentration ($MPC_{m.r.}$) 5 mg/m^3, hazard class 4, sedimentation coefficient 1, potentiation coefficient – 0.9; nitrogen oxide and dioxide – MPCm.r. 0.085 mg/m^3, hazard class 2, sedimentation coefficient 1, potentiation coefficient 1.3. Emission sources: 3 air shafts – northern air shaft (NAS), drainage air shaft (DAS) and south air shaft (SAS). According to the environmental protection service of PJSC "ZIOP", the intensity of emissions of environmentally hazardous substances from ventilation shafts is presented in table. 1.

Table 1. Intensity of emissions of environmentally hazardous substances from air shafts

Year	Fan performance, m^3/s	Emission intensity	
		CO	$NO+NO_2$
		g/s	g/s
Northern air shaft (NAS)			
2008	217	6.944	0.456
2020	250	1.551	0.429

Drainage air shaft (DAS)			
2008	232	8.120	0.255
2020	180	1.116	0.309
South air shaft (SAS)			
2008	257	7.967	0.514
2020	230	1.427	0.394

Let's delve into propagation of surface concentration fields of environmentally hazardous substances, including carbon monoxide, nitrogen oxides, surrounding the Surface Air Shaft (SAS), for the years 2008 and 2020. This analysed conducted in the context of unfavorable meteorological conditions, while also taking into account the average annual wind speed as illustrated in Fig. 2.

a)

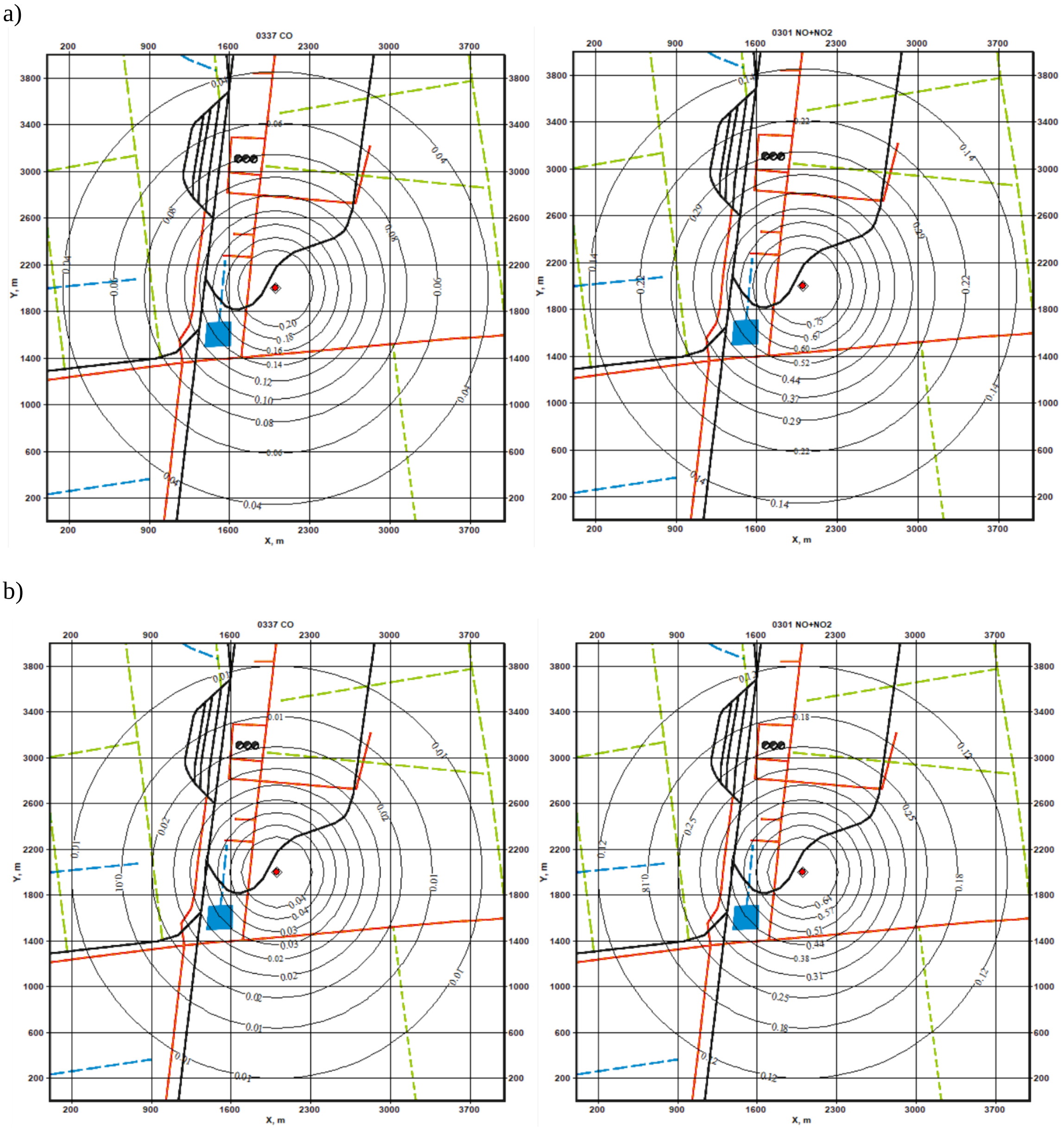

Fig. 2. Fields of ground-level concentrations of hazardous substances around the SAS in 2008 (a) and 2020 (b)

A comprehensive understanding of changes in ground-level concentrations of environmentally hazardous substances like carbon monoxide, nitrogen oxides can be gained by examining their levels relative to the Maximum Permissible Concentration (MPC), depicted in Fig. 3. Upon scrutinizing these concentrations, it becomes apparent that the highest levels of these substances were recorded in 2008, coinciding with the period when 100% TNT-containing E were extensively used in underground mining activities throughout the year. However, a notable shift occurred in 2020, where a combination of 78% "Ukrainit" type EE and 22% TNT-containing E from the overall expenditure on explosives led to a decrease in maximum concentrations compared to 2008. Specifically, carbon monoxide levels witnessed a reduction of 5.0–5.5 times, while nitrogen oxides levels decreased by 1.2–1.3 times. This emphasizes the effectiveness of incorporating "Ukrainit" type EE in underground mining operations, resulting in reduced concentrations of environmentally hazardous substances and contributing to the mitigation of the technogenic burden on atmospheric air. The comprehensive environmental assessment of underground ore mining will culminate with the computation of the environmental hazard index, providing further insights into the environmental impact of such operations.

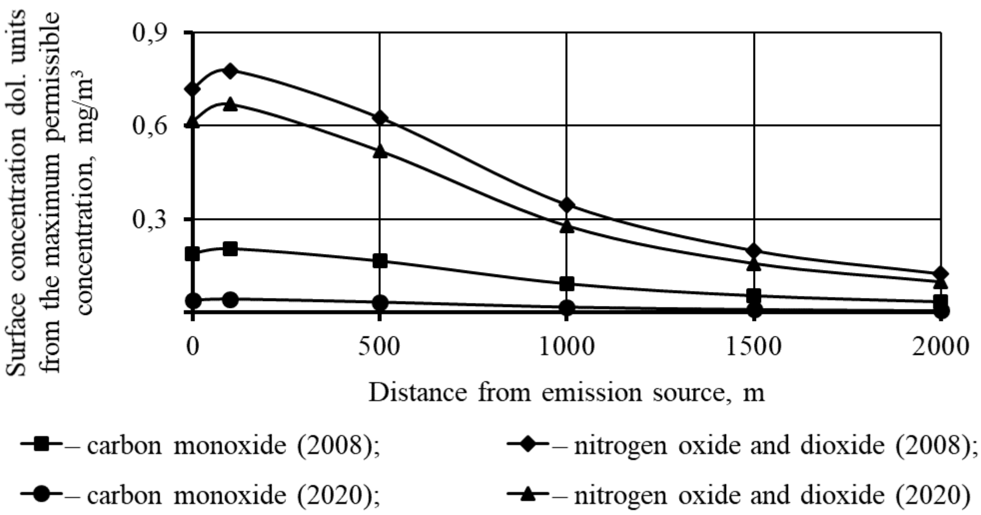

Fig. 3. Dependences of ground-level concentrations of hazardous substances with increasing distance from *SAS*

The ecological impact was determined using the principles in work [27]. It considers the risk to the the population experiencing the negative impact of pollutants released when using E.

Ecological hazard coefficient for the possible occurrence of non-carcinogenic effects in living organisms from exposure to the pollutants in question:

$$HQ_i = \frac{C_i}{RfC} \tag{1}$$

where:

C_i – level of exposure to the i-th substance, mg/m^3;
RfC – safe exposure level, mg/m^3.

Hazard index from combined exposure to environmentally hazardous substances

$$HI = \Sigma HQ_i \tag{2}$$

The results of calculating coefficients and hazard indices for environmental objects when using 100% of TNT-containing E and 78% of EE and 22% of TNT-containing E are presented in Table 2.

Based on the results of calculating the coefficients and hazard indices, a histogram of changes in the hazard index from the distance to the emission source (SAS), using 100% of TNT-containing E (2008) and 78% of EE of the "Ukrainit" type and 22% of TNT-containing explosives was constructed (2020) and is shown in Fig. 4.

Table 2. Intensity of emission of environmentally hazardous substances from air shafts

Index	Distance from emission source (SAS), m				
	100	**500**	**1000**	**1500**	**2000**
100% of TNT-containing E (2008)					
HQ(CO)	0.21	0.17	0.09	0.05	0.03
HQ($NO + NO_2$)	0.78	0.63	0.35	0.20	0.13
HI	0.99	0.80	0.44	0.25	0.16
78% of EE and 22% of TNT-containing E (2020)					
HQ(CO)	0.04	0.03	0.017	0.01	0.006
HQ($NO + NO_2$)	0.67	0.52	0.28	0.157	0.097
HI	0.71	0.55	0.297	0.167	0.103

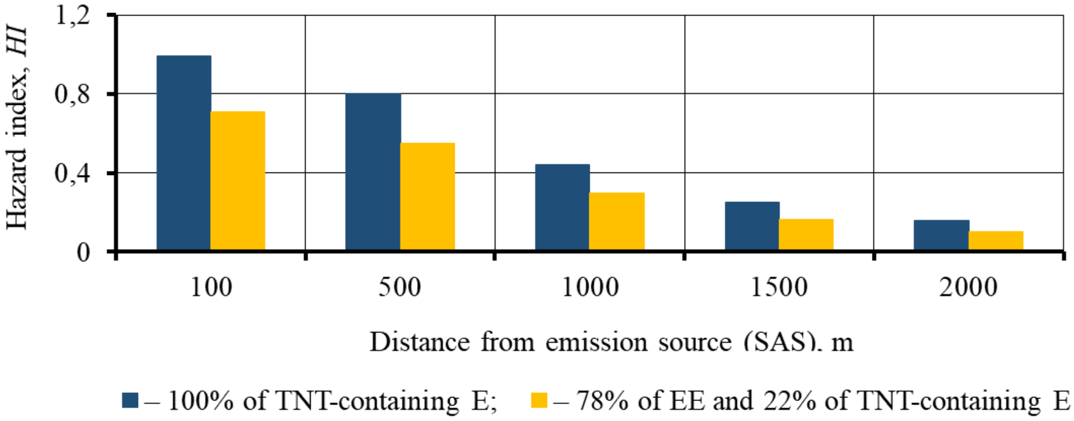

Fig. 4. The nature of the change in the hazard index depending on the distance to the release source

Upon analyzing the results presented in Table 2 and the histogram depicting changes in the hazard index relative to the distance from the emission source (Fig. 4), it becomes evident that the utilization of TNT-containing E in 2008 resulted in the highest values of coefficients and hazard indices for all environmentally hazardous substances. However, a significant transformation in environmental impact dynamics was observed in 2020 under the operational framework of PJSC "ZIOP". Here, a composition comprising 78% "Ukrainit" type EE and 22% TNT-containing E, representing the total annual expenditure on explosives, led to a noteworthy reduction in environmental hazard coefficients. Specifically, carbon monoxide levels decreased by an average of 5.3 times, and nitrogen oxide and dioxide decreased by 1.25 times compared to the usage of TNT-containing E in 2008. Moreover, there was a reduction in the hazard index by an average of 1.5 times when employing EE of the "Ukrainit" type compared to TNT-containing E, resulting in a decrease in the environmental hazard index to 36%. This signifies that the adoption of EE of the "Ukrainit" type in underground ore mining operations contributes to a decrease in the concentrations of environmentally hazardous substances, particularly carbon monoxide and nitrogen oxide and dioxide, generated following blasting operations, thereby facilitating a reduction in the technogenic burden on atmospheric air quality.

5. Conclusions

1. Combination of 78% "Ukrainit" type EE and 22% TNT-containing E resulted in a noticeable decrease in the maximum concentrations of these harmful substances comparing 2008 to 2020. Especially, carbon monoxide levels decreased by 5.0–5.5 times, while nitrogen oxides levels decreased by 1.2-1.3 times. These findings underscore the significant reduction in environmentally hazardous

substance concentrations associated with the use of "Ukrainit" type EE in underground mining operations.

2. The examination of variations in the hazard index concerning the distance from the release source, particularly the mine air shaft, provided valuable insights. In 2008, with the predominant use of TNT-containing E, hazard indices for all environmentally hazardous substances peaked. Subsequent analysis revealed a significant shift in environmental impact dynamics by 2020, especially within the operational scope of PJSC "ZIOP". In this scenario, a blend comprising 78% "Ukrainit" type EE and 22% TNT-containing E, reflecting the total annual expenditure on explosives, led to a considerable reduction in environmental hazard coefficients. Specifically, carbon monoxide levels decreased by an average of 5.3 times, and nitrogen oxides decreased by 1.25 times compared to TNT-based usage in 2008. Furthermore, it was noted that the hazard index decreased by an average of 1.5 times when utilizing "Ukrainit" type EE compared to TNT-containing E. These findings clearly illustrate that the integration of "Ukrainit" type EE in underground ore mining operations results in reduced concentrations of environmentally hazardous substances, such as carbon monoxide, nitrogen oxides, produced during post-blasting activities. Consequently, this reduction plays a crucial role in alleviating the anthropogenic burden on atmospheric air quality.

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