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Event Tree Analysis as a Method of Assessing Occupational Risks in the Production of Titanium Ingots

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ABSTRACT

In the article, with the aim of assessing professional risks associated with X-ray radiation during the production of titanium ingots, the logical-graphical risk analysis method known as "Event Tree Analysis" was used. “Event Tree” is modeled on the basis of inductive procedure of evaluation of possible causes of X-rays having harmful effects on the body of workers during production of titanium ingots in electron beam furnace, as well as causes of harmful effects on the body of workers in this production. The mathematical dependence of X-ray radiation on electric and magnetic fields has been established. The analysis of data and graphical representation of the dependency demonstrates a clear connection between X-ray radiation and the levels of electric and magnetic fields. The results obtained confirm that an increase in the intensity of these fields leads to an increase in X-ray radiation. In this regard, the upper level of the “Event Tree” as a factor of increased levels of electric and magnetic field intensity confirms the importance of taking these factors into account in risk assessment and forecasting of working conditions. To verify the accuracy of the model, validation was performed using statistical data. Graphical analysis showed a correlation between the intensity of electric and magnetic fields and the level of X-ray radiation, which was confirmed by the obtained dependence. A brief description of the named production is presented. Information is provided on the effect of X-ray radiation on the employee's body. The main conclusions highlight the need to use modern personal protective equipment to minimize professional risks. A comparative analysis of the choice of personal protective equipment (PPE) was carried out using the current approach according to intersectoral standards and a new risk-based approach. To improve working conditions in the workplace, it is recommended to use the following PPE as relevant protection against X-ray exposure: helmet, safety glasses, filter masks, insulating protective suit.

1. INTRODUCTION

In the context of modern technological, material, and equipment development, special attention is given to ensuring professional activities comply with occupational health and industrial safety requirements. An inevitable result of technological progress is the increasing risk of exposure to harmful industrial factors affecting human health and life. One of these factors is X-ray radiation. The modern approach to radiation safety control is evolving. If earlier the problem of protection from radiation hazards was reduced to ensuring control over individual potentially dangerous objects, now it is gaining a wider scale. The public's interest in the radiation safety of the population and personnel working with X-ray sources is constantly increasing and remains constantly relevant.

The production of titanium alloy ingots is recognized as dangerous, since electron beam melting technologies are used at the final stages of the production of these ingots of refractory and highly reactive metals. Electron beam melting is provided by using an electron beam as a heating source. Next, the metal solidifies in a flow-through mold with gradual elongation of the ingot.

The 4800 EBCH electron beam furnace is a large-scale titanium smelting equipment that uses high-voltage alternating current electron beam guns to heat and melt the input raw materials in order to form an ingot of the desired size and shape in two stationary melting chambers [1]. Electron beam guns generate potentially dangerous X-ray radiation.

The observation window of the smelting chamber and the lids of the electron-beam furnace are equipped with:

- Protective glass against titanium condensate;
- Heat-resistant glass;
- Leaded glass to protect against X-rays;
- Light filtering glass for brightness adjustment;
- An insulating valve that allows cleaning and replacement

of glasses without disturbing the vacuum environment of the melting chamber. The gate of the insulating valve is made of stainless steel to protect against X-rays.

Electronic guns operate under a fixed accelerating voltage. The power and specific power are regulated within wide limits. The accelerating voltage is selected in such a way as to ensure an optimal ratio between the focusing and penetrating power of the electron beam at the work site and sufficient safety from X-rays at no additional cost.

When electrons are removed from the material, X-rays are formed. The intensity of radiation is determined by the atomic number of the material, high voltage, and the power of the emitted substance. The correctly selected wall thickness of the furnace body and all connected components, special design principles in detail with the use of leaded glass for viewing windows, ensure safety during operation of the furnace.

With the increasing use of X-ray technology in various fields, the potential adverse effects of radiation exposure on worker health must be considered [2, 3]. High-dose radioactive radiation can be fatal, or leads to radiation sickness. Chronic low-dose radiation can lead to the development of tumors (bones and mammary glands), impaired reproductive function [4], and the development of cataracts [5].

For more information about harm to the health of an employee [6]. X-ray radiation can lead to serious health problems, including cardiovascular diseases, cataracts, central nervous system damage, cancer, and other acute radiation syndromes. Passing through a certain area of the body, X-rays produce corresponding changes in tissues and cells depending on the type of tissue and the number of rays absorbed by them, that is, the dose [7].

It has been established that exposure to X-ray radiation can have an adverse effect on human reproductive function, which depends on the dose, duration, intensity and frequency of radiation exposure [8].

Thus, exposure to X-ray radiation and its consequences can significantly deteriorate workers' health, negatively affecting working conditions [9].

In modern conditions, workers at titanium ingot production enterprises often face exposure to dangerous and harmful production factors. The production process includes a set of prerequisites for the occurrence of emergencies related to both technological aspects and violations of labor discipline, labor protection and industrial safety rules.

Any industrial activity creates certain hazards and risks for workers. To identify all potential dangers arising during the work process, it is necessary to assess professional risks, which determine the severity and likelihood of potential consequences.

There are several dozen methods for calculating and assessing risks-ranging from the simplest to mathematically complex ones developed by various organizations. Choosing appropriate methods for calculating and assessing risks that are suitable for an organization's industrial activities is one of the most challenging issues in implementing risk management mechanisms.

In international practice, a common approach to assessing occupational risks [10, 11] consists of the following steps:

1. Identification of hazards leading to risk. At this stage, it is necessary to review everything at the workplace that could potentially cause harm and identify workers who may be exposed to hazards.
2. Evaluation and ranking of risks (their severity, likelihood, etc.), prioritizing them by importance.
3. Determination of preventive measures. At this stage, appropriate measures to eliminate risks and manage them should be identified.
4. Implementation of measures. This step involves creating an action plan for implementing protective and preventive measures (as not all problems may be solved immediately), determining who, what, and when specific tasks will be carried out, and ensuring the resources needed for the implementation of planned measures.
5. Monitoring and review.

The assessment of occupational risks can serve as a scientific basis and guide for employers in risk management, as well as help develop specific preventive and emergency measures based on the assessment results. This contributes to achieving goals in preventing and controlling occupational hazards. In recent years, many foreign researchers have been applying various models for occupational risk assessment [12-14].

The management of occupational risks includes the following modern methods:

1. Fault Tree Analysis (FTA). FTA focuses on specific events and is presented in the form of a logical diagram, which is built top-down, displaying the relationships and dependencies between hazardous events and their root causes. The lowest-level causes may include human errors and component failures [15].

Other researchers note that FTA transforms a physical system into a logical diagram to identify the primary event, making it an effective tool for assessing reliability and risks. FTA can serve as a valuable method for identifying potential hazards. The steps of performing FTA include identifying the primary event and system structure, conducting qualitative analysis, and using the results for decision-making [16].

An event tree is a deductive logical construction that uses the concept of a single final event (typically a failure, accident, or disaster) to find all possible pathways that could lead to its occurrence [17].

Today, technological processes in production are quite complex, making it virtually impossible to cover all causes leading to accidents. It is advisable to use the "event tree" method to analyze the damaging factors that affect the industrial safety of enterprises.

2. Analysis of personnel errors and their consequences (Failure Mode and Effect Analysis (FMEA) [10];

3. Process analysis based on fuzzy approaches [10, 18];

4. Event forecasting using Bayesian networks [19, 20];

5. Event and process analysis using Graphical Evaluation and Review Technique (GERT) networks [10, 21];

6. Event forecasting using neural network technologies [10]. Its use allows for multifactorial analysis of occupational injuries and professional risk factors, as well as identifying groups and categories of workers whose level of professional risk exceeds acceptable limits. The results of the multifactorial analysis of professional risk are used by an automated system for forecasting and managing professional risks, which helps to optimize the occupational safety management system within the enterprise. Forecasting and managing professional risks will positively impact the overall safety of the enterprise and the level of workplace injuries, enabling employers to significantly improve the efficiency of risk assessment, forecasting, and management processes at enterprises or specific workstations [10].

Currently, in Kazakhstan, the transition to a professional risk management system is advisory [22].

Despite active research in radiation safety, gaps remain in the risk assessment for workers engaged in high-energy processes, such as electron beam melting of titanium. At the same time, the need for comprehensive risk assessment using methods like "Event Tree Analysis" remains relevant.

Thus, the primary goal of the study is to model the "Event Tree" to assess the professional risks of X-ray exposure in the production of titanium ingots.

2. METHODS AND MATERIALS OF RESEARCH

The authors studied the working conditions at one of the enterprises in Ust-Kamenogorsk, East Kazakhstan region of the Republic of Kazakhstan. The company is engaged in the production of titanium ingots.

When processing the data obtained on the effects of X-ray radiation, the authors used the reliability analysis method "Event Tree analysis" [23] to analyze hazards and working conditions in the workplace. The evaluation of the "event tree" is a sequence of constructing successive events that originate from the underlying event [24]. This method was used to determine the sequence of development and occurrence of the cause of hazards. The method of "Event tree analysis" allows us to take into account the functional interrelationships of system elements in the form of logical circuits, and is also of considerable interest to specialists involved in the operation, maintenance and supervision of technical facilities. Having such a scheme, a specialist, even without having thorough knowledge of probability theory, can not only find the most critical scenario, but also assess the expected risk if the corresponding event tree is supplemented by the results of measurements of harmful production factors in the workplace [25].

The "Event Tree Analysis" was chosen due to its ability to represent the interrelationships between system elements and assess the likelihood of emergency situations developing.

An event tree is a formalized sequence of potentially possible events that could lead to an emergency situation, originating from a primary event, which is considered the top undesired event and the main event in the fault tree. In event tree analysis [26], chains of subsequent events are examined, leading to the impact of various hazardous factors on workers [27].

The "Event Tree Analysis" method is based on inductive logic, which allows for identifying causal relationships between hazards and their consequences. The choice of this method is justified by its capability to model complex production processes with a high degree of uncertainty. This approach considers the influence of factors such as electrical and magnetic fields on the occurrence of X-ray radiation [28].

A statistical analysis method in the Statistica program was used to evaluate the relationships between variables such as X-rays, electric and magnetic fields.

The intensity of the electric and magnetic fields was determined using a device for measuring the parameters of the electric and magnetic fields of the AT-004 model VE-METER.

3. RESULTS AND DISCUSSION

Figure 1 shows an "Event Tree analysis" including the causes of X-ray radiation, as well as the causes of harmful effects on the body of workers. The decoding of the "Event Tree" designations from Figure 1 is shown in Table 1.

This paper applies the logical-graphic method of "Event Tree Analysis" to assess the occurrence of initiating and subsequent events, graphically displaying the cause-and-effect relationships of the situation in individual scenarios. As can be seen from Figure 1, X-ray radiation (P1) occurs during electron-arc melting. The upper level of the "Event Tree" scheme consists of four factors, such as the flight of electrons from the electron beam cannons of the electron beam furnace 4800 EBCHF (P11), the impact of electrons on the material (P12), the release of thermal energy at the site of the collision of electrons in the workspace and inside the cannon of the electron beam furnace (P13), increased levels of intensity of electric and magnetic fields (P14), which accompany the output of X-ray radiation.

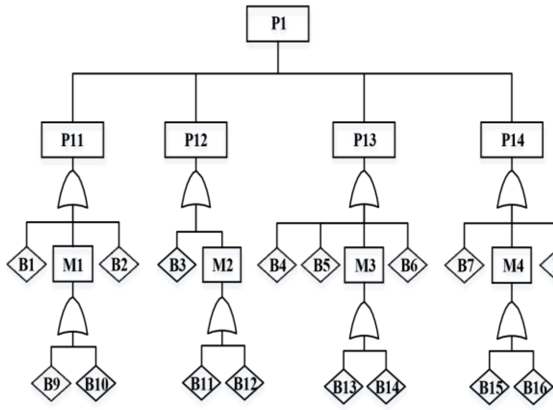


Figure 1. The "Event Tree analysis", including the causes of X-ray radiation, as well as the causes of harmful effects on the body of workers

Table 1. Decoding of the designations of the "Event Tree analysis", including the causes of X-ray radiation, as well as the causes of harmful effects on the body of workers

Designation	Decoding
P1	X-ray radiation
P11	The flight of electrons from the electron beam guns of the electron beam furnace 4800 EBCHF
P12	The stress of electrons on the material
P13	The release of thermal energy at the site of the collision of electrons in the workspace and inside the cannon of the electron beam furnace
P14	Increased levels of electric and magnetic field strength
B1	Careless actions of an employee
M1, M2, M3, M4	Non-use of PPE
B2, B3, B6, B8	Malfunction of the PPE
B4	Lack of protective devices
B5	Damage to protective devices
B7	Malfunction of the mechanisms
B9, B11, B13, B15	Absence of PPE
B10, B12, B14, B16	Deliberate non-use of PPE

As a result of these factors, the causes are identified at the following levels, which show the causes of hazards in the workplace: careless actions of an employee, non-use of PPE, malfunction of PPE, lack of PPE, deliberate non-use of PPE, lack of protective devices, damage to protective devices.

The diagram shows that one of the important reasons is the non-use of PPE (M1, M2, M3, M4), on the basis of which the third level of causes is identified in the form of B9, B10, B11, B12, B13, B14, B15, B16.

Based on the constructed event tree diagram (Figure 1), it can be concluded that several worker errors (careless actions of an employee, non-use of PPE, deliberate non-use of PPE) are sufficient to lead to the undesired event.

Conducting a qualitative analysis of the "Event Tree," which contributes to an in-depth analysis of the production process, focusing on potential hazards, can prevent subsequent accidents and improve working conditions.

The results of the analysis of the "Event Tree" show that most often employees may intentionally not use personal protective equipment during work, as set out in Table 2.

Table 2 presents a comparative analysis of the choice of personal protective equipment (PPE) using the example of the profession of an electron beam smelter.

Table 2 shows the standard normative list of a set of PPE for this profession according to intersectoral standard norms [29], as well as according to a new approach [30] in accordance with the nomenclature of PPE developed by the RSE at the National Research Institute for Occupational Safety and Health of the Ministry of Labor and Social Protection of the Republic of Kazakhstan [31].

As can be seen from Table 2, it is recommended to use a helmet, safety glasses, filter masks and an insulating protective suit as relevant protection against X-ray radiation [31, 32].

In order to improve working conditions and reduce the risk of health disorders when exposed to X-rays, employees of the enterprise must be provided with properly selected PPE.

Table 2. Comparative analysis of the provision of PPE

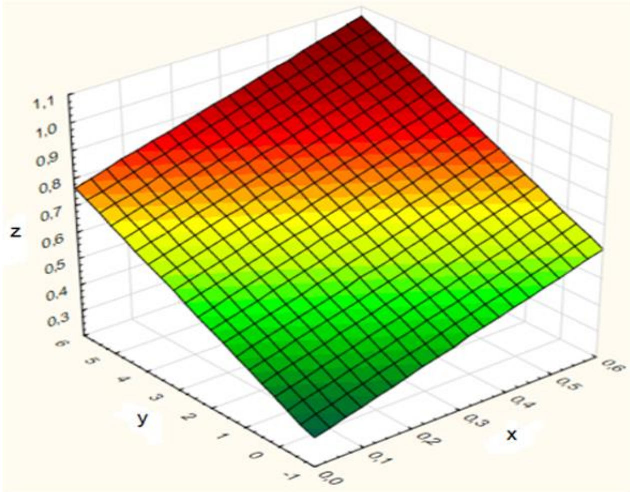
Name of the Profession	PPE According to Standard Standards	PPE According to the Nomenclature
Electron Beam Melting Smelter	Suit made of cotton fabric Underwear Gloves made of cotton fabric Cloth mittens Combined mittens Technical rubber gloves Leather boots Casque Safety glasses NBT shield Earplugs are anti-noise "Earplugs" Petal 200 respirator Filter respirator RU-60M Insulated jacket made of cotton fabric Rubberized boots	1. Protective helmet [22] 2. Insulating half masks with filter and filter-absorbing cartridges [21] 3. Insulating protective suit [21]

To predict working conditions under the influence of X-ray radiation, the following dependence of X-ray radiation on electric and magnetic fields was established:

$$z = 0.3745+0.5\cdot x+0.0651\cdot y \quad (1)$$

From Eq. (1), it can be seen that X-ray radiation (z) increases with the rise in the values of the electric field (x) and the magnetic field (y). The coefficients in the equation indicate the degree of influence each field has on the level of radiation.

A graph of the dependence of X-ray radiation on electric and magnetic fields is shown in Figure 2.



Variable 1 (x) – electric field, V/m
Variable 2 (y) – magnetic field, NT
Variable 3 (z) – X-ray radiation, mSv/hour

Figure 2. Graph of the dependence of X-ray radiation on electric and magnetic fields

An analysis of the data presented in the graph shows that there is a clear connection between X-ray radiation and electric and magnetic fields. This is confirmed by the upper level of the "event tree" as a factor of increased levels of intensity of electric and magnetic fields (P14) (Figure 1).

This fact indicates the need for strict control and monitoring of electric and magnetic field levels in the workplace to ensure safe working conditions. Applying this relationship can help in developing effective measures to reduce X-ray radiation exposure and ensure safe working conditions in enterprises.

The "Event Tree" model allows for the systematic identification and analysis of potential causes of X-ray radiation. This methodology can be adapted for various types of enterprises where X-ray equipment or similar radiation sources are used, to accurately assess the risks associated with their operation.

4. CONCLUSIONS

This study demonstrates the importance of using the "Event Tree Analysis" method to assess occupational risks associated with X-ray radiation exposure in the production of titanium ingots. Modeling the "Event Tree" has helped identify key factors affecting the level of X-ray radiation, such as electric and magnetic fields, and establish their mathematical relationship. The hazard analysis using the "Event Tree" showed that the causes could also include careless actions by the worker, non-use of PPE, malfunction of PPE, lack of PPE, deliberate non-use of PPE, lack of protective devices, damage to protective devices. Based on the analysis of risk-oriented approaches to selecting personal protective equipment (PPE), effective measures have been proposed to improve working conditions. These measures include the use of helmets, protective glasses, masks, and insulating suits to protect against radiation. Therefore, adequate protection from X-rays is crucial to ensure the safety and reduce the occupational risk of employees.

The use of the developed "Event Tree" model in assessing occupational risks at other enterprises represents an effective tool for comprehensive risk assessment and management related to X-ray radiation, contributing to overall improvement in industrial safety.

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