REVIEW ARTICLE

CONTENTS

Pulmonotoxic xenobiotics and methods of their determination in ambient air of nuclear power plant equipment

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ABSTRACT

Aim: To identify appropriate methods for determining the content of radioactive and non-radioactive pulmotoxic xenobiotics in the ambient air of NPP equipment to ensure its reliability, radiation and environmental safety, as well as to reduce the risks of occupational pathologies for workers and protect people's health.

Materials and Methods: Analytical methods of analysis of modern methods of determining the content of radioactive and non-radioactive pulmonary toxic xenobiotics in the ambient air of NPP equipment.

Conclusions: a) during operation of NPP equipment, pulmotoxic xenobiotics enter the surrounding air, which can then enter the human respiratory system in the form of radioactive or non-radioactive substances; b) significant methods of determining the content of pulmotoxic xenobiotics in the air are: gas chromatography; gas chromatography-mass spectrometry; liquid scintillation; photometric, ionometric, polarographic, titrometric, turbidimetric, atomic absorption, radiometric and γ-spectrometric measurements; c) radioactive pulmonotoxic xenobiotics cause radiation pathologies in the respiratory organs as a result of internal radioactive irradiation of the body; d) the effects of non-radioactive pulmotoxic xenobiotics are accompanied by irritation and inflammatory processes in the respiratory organs, as well as toxic swelling of the lungs; e) there is a connection between the presence of pulmotoxic xenobiotics in the air and the course of human respiratory diseases as a result of breathing such air.

KEY WORDS: pulmotoxic xenobiotics, pulmonology, occupational pathology, ambient air, environmental monitoring, nuclear energy, measurement methods

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INTRODUCTION

The main nuclear power facilities are nuclear power plants (NPP) using controlled nuclear reactions in nuclear reactors. Emissions from NPP equipment into the atmosphere have a negative impact on the environment and human health. Ukraine has a developed nuclear power industry, which is based on NPP – Khmelnytskyi, Rivne, Zaporizhzhia and South-Ukrainian NPP. These NPP are high-risk facilities, and therefore the prospects for their development are related to their safe operation and protection of territories, civilians and the environment in the area where the plant is located; under various negative factors (violation of technological processes, limits and conditions of safe operation, man-made accidents and incidents, natural phenomena, sabotage for terrorist purposes, hostilities, etc.), emergencies may occur at NPP that pose a significant risk to the natural environment, the health of personnel and the population of the surrounding areas [1].

NPP due to the accumulation of significant amounts of radioactive products during operation and the possibility of their release beyond the prescribed limits in case of accidents represent a source of potential hazard or a source of risk of radiation exposure to personnel, the public and the environment [2].

It is known that: a) to ensure continuous operation of NPP, various auxiliary man-made facilities are located and operate on their territory, which emit and discharge non-radiation pollutants into the environment; b) during the entire period of NPP operation, under various negative technical and natural circumstances (disruption of the technological process, explosion of equipment due to lightning, adverse meteorological conditions, unauthorized emissions, etc. c) The most chemically hazardous man-made facilities on the territory of the NPP are the start-up and backup boiler house, diesel generator stations, oil and fuel facilities, welding sites, metalworking sites, chemical reagent

tanks, a gas station, as well as equipment containing ozone-depleting refrigerants (freons), and others [3]. As a result of their operation, various pollutants are generated and released into the atmosphere through chimneys. The main pollutants are: nitrogen oxides, sulfur compounds, carbon oxides, suspended particulate matter, chlorine compounds, fluorine compounds, soot, non-methane volatile organic compounds, CH_4, NH_3, metals and their compounds, freons, etc. [3].

Thus, during normal operation or accidents of Rivne NPP equipment, the sources of pulmonotoxic xenobiotics (PTXs) emissions into the atmosphere are: reactor compartment with nuclear power units; systems of the installation for holding gas blowdowns during nuclear fuel overload; special ventilation systems; unit for thermo-catalytic combustion of hydrogen gas flows; technical systems for ensuring water-chemical regimes of circulating cooling of equipment of the first and second circuits of nuclear power units; special sewage system; reactor circuit water treatment system; reactor circuit purge water treatment system and organized leaks; ladder water treatment system; water treatment system for pools and emergency boric acid storage tanks; steam generator purge water treatment system; a boric acid regeneration system; a wastewater treatment system for special laundries; an atmospheric air liquefaction unit for producing oxygen and nitrogen with the use of CFCs for cooling; a hydrogen cooling unit in a hydrogen-cooled turbine generator with the use of CFCs; a maintenance and repair unit with sections for machining, gas and electric cutting or welding of metal and plastic structures (welding, cutting, surfacing, spraying); equipment for ventilation units; a road transport support unit; a power plant for NPP's own needs using liquid fuel oil; diesel power plants for emergency power supply to NPP; technical systems for drinking water supply; technical systems for wastewater treatment for discharge into water bodies; chemical laboratories; dosimetric control laboratories; warehouses with solid and liquid radioactive waste of decommissioned NPPs with ventilation systems; installation for production of gaseous H_2 and O_2 by electrolysis of aqueous solutions; facilities for solid and liquid radioactive waste management with ventilation systems; chemical warehouse with ventilation systems; warehouse with mineral energy oils; warehouse with synthetic fire-resistant energy oils; warehouse with diesel fuel [4-6].

One of the priority areas of national security in Ukraine is to ensure radiation-safe living conditions for citizens and society, environmental protection and rational use of natural resources, and this goal can be achieved, among other things, by monitoring the content of radioactive and non-radioactive harmful substances, such as PTXs, in the air surrounding NPP equipment [7]. Pulmonotoxicity is the ability of chemicals, including xenobiotics, to cause structural and functional disorders of the respiratory system, and selective effects on different parts of the respiratory system can occur both through local and resorptive action of toxicants [8]. In this case, acute lesions of PTXs are accompanied by the formation of a number of pathological processes: irritation and inflammation in the respiratory tract (acute laryngitis and tracheobronchitis), lung parenchyma (acute pneumonia), and toxic pulmonary edema [8].

PTXs are often in the air in the form of aerosols, including radioactive ones, and have a fibrogenic effect, which increases the risk of developing occupational respiratory diseases. It is known that there is a connection between the presence of PTXs in the ambient air of NPP equipment in concentrations exceeding the established standards and the course of human respiratory diseases due to breathing such air [8]. Thus, there is a need for continuous research of the sources of PTXs and methods for their determination in the ambient air of NPP equipment.

AIM

The aim of the present work was the identification of appropriate methods for determining the content of radioactive and non-radioactive pulmonotoxic xenobiotics in the ambient air of nuclear power plant equipment to ensure its reliability, radiation and environmental safety, as well as to reduce the risks of occupational pathologies for workers and protect human health.

MATERIALS AND METHODS

Analytical methods for analyzing modern methods for determining the content of radioactive and non-radioactive PTXs in the ambient air of NPP equipment.

REVIEW AND DISCUSSION

Even with absolute reliability and trouble-free operation, any NPP significantly affects the environment through gas and aerosol (including radioactive) emissions into the atmosphere [9]. Most of the radionuclides contained in gas and aerosol emissions are retained by purification filters or rapidly decay, losing radioactivity, but there is still a significant amount that enters the environment and contaminates it, for example, with tritium (T (or ^3H) compounds: T compounds include T_2, NT, NTO, T_2O, DTO, DT, CH_3T.

In addition to the usual gas and aerosol emissions, any NPP periodically releases aerosols into the atmosphere, which are formed as a result of corrosion of the nuclear

reactor and its first circuit. These aerosols contain radionuclides that are the product of uranium nuclear fission. The most significant radionuclides are: ^{51}Cr; ^{54}Mg; ^{60}Co; ^{95}Nb; ^{106}Ru; ^{144}Ce, etc. Once in the biosphere, radioactive isotopes or their decay products are eventually involved in biochemical and biophysical processes that occur inside every living organism.

Some of these isotopes or their decay products are dangerous for all living things, as they can disrupt metabolic processes. In [9]: the necessity of creating new technologies and technical means for detecting aerosol radioactive emissions from NPPs and establishing radioecological monitoring and control over them in real time is substantiated; the main technical characteristics of the created complex for monitoring α- and β-radiation of radioactive aerosols are presented. References [10, 11] note the use of such xenobiotics as NH_3, H_3BO_3, KOH, C_2H_7NO (monoethanolamine), C_4H_9NO (morpholine), N_2H_4 (hydrazine) to ensure water-chemical conditions of equipment, including Zaporizhzhya NPP. During the operation of NPP equipment, these substances can be released into the surrounding air in the form of vapor, gas or aerosol, and then can enter the human respiratory system. Accidents involving spills of liquid radioactive media, such as the coolant of the first circuit of a WWER reactor, lead to increased concentrations of radionuclides such as ^{51}Cr; ^{54}Mg; ^{60}Co; ^{95}Nb; ^{106}Ru; ^{144}Ce in the air of the process room and in ventilation emissions [12, 13]. It is shown in [14] that xenobiotics such as $C_2H_8O_7P_2$ (oxyethylidene diphosphonic acid) and NaOCl were used to ensure the water-chemical regime of the technical water supply system for responsible consumers of the reactor department and backup diesel power plants of the Rivne NPP. Reference [15] proposes a technology for the treatment of industrial water waste from NPPs based on the use of a natural mineral sorbent, bentonite. The paper shows the possibility of liquid radioactive waste (LRAW) treatment on the example of gangway water with a significant salt content, as well as energy oils and surfactants. To implement such a technology, ozone (O_3) and ultrasonic irradiation are required.

In [16] discusses the processes of industrial wastewater treatment by treating it with ozone. Reference [17] proposes a technology for the treatment of industrial water radioactive waste NPP using O_3 and ultrasonic cavitation or electric discharge at high pH values of liquid waste. Paper [18]: provides a critical analysis of existing experimental and practically implemented oxidative methods for the destruction of LRAW metal-organic complexes; highlights the results of combined oxidation (ultraviolet and O_3), supercritical oxidation in the presence of hydrogen peroxide (H_2O_2), cavitation discharge using ozone). It is shown that today the main source of radioactive waste (RAW) in Ukraine is NPP. The largest and most hazardous part of the total amount of RAW is LRAW, which is characterized by significant volumes, activity and the potential for uncontrolled release into the environment [18]. In the process of NPP operation, radioactively contaminated waste water is generated and accumulated from various sources.

The main sources of gangway water formation include: leakage of the water coolant of the first NPP circuit and nuclear fuel pools; decontamination water solutions; drainage of special laundries and showers. It has been shown that the most effective way to destroy highly stable LRAW complexes today is their oxidative decomposition or removal of organic compounds using physicochemical processes, such as ozonation, cavitation (electro-hydro-discharge method), supercritical water oxidation (hydrothermal treatment), addition of H_2O_2 to aqueous solutions, or the use of reagents capable of forming oxidants in the course of chemical reactions, such as $KMnO_4$ or Fenton's reagent [18].

It is known that radioactive iodine is one of the dose-forming radionuclides in public exposure from nuclear reactor releases [19]. Work [20] shows the possibility of controlling the individual effective dose of internal radioactive exposure when PTXs in the form of radioactive compounds NTO, DTO, T_20, NT, DT, T_2, CH_3T enter the human body by measuring the volumetric activity in body secretions: in the condensate of water vapour from exhaled air and in urine. Iodine isotope ^{131}I is considered as an important factor of radiation exposure from nuclear reactor releases, and a feature of controlling emissions of radioactive iodine isotope ^{131}I is to take into account the variety of physical forms and chemical compounds of radioactive iodine, since 150 to 246 products of radioactive iodine interaction can be formed when ^{131}I interacts with water coolant and structural materials [21]. It is noted in [5, 6] that gaseous radioactive waste is gaseous or aerosolized radioactive products in the air.

The gas-air mixture removed directly from the NPP process equipment contains a significant amount of caustic, toxic and radioactive substances. The impurities include: a) inert radioactive gases – ^{41}Ar, ^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{133}Xe, ^{133m}Xe, ^{135}Xe, ^{135m}Xe; b) iodine nuclides ^{131}I, ^{133}I, ^{135}I c) radioactive aerosols as a mixture of nuclear fuel fission products – ^{131}I, ^{89}Sr, ^{90}Sr, ^{91}Sr, ^{103}Ru, ^{137}Cs, ^{141}Ce, ^{144}Ce, ^{51}Cr, ^{54}Mn, ^{55}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{95}Zr, ^{110m}Ag, ^{22}Na, ^{24}Na, ^{88}Rb, ^{99}Mo, ^{140}Ba, ^{140}La, etc. d) corrosion products of structural materials activated in the neutron flux – ^{58}Co, ^{60}Co, ^{54}Mn, ^{110}Ag, ^{59}Fe, ^{51}Cr, ^{95}Zr, ^{95}Nb, etc. e) activation products of corrective impurities in nuclear reactor water coolant – ^{13}N, ^{16}N, ^{17}N, ^{18}F, ^{7}Li,

^{24}Na, ^{1}H, ^{2}H, ^{3}H, ^{14}C, etc. e) ^{14}C compounds in gaseous emissions – CO, CO_2, CH_4, C_2H_6, C_4H_{10}, etc. It is proposed to determine the content of gaseous and vaporous radioactive and non-radioactive substances in the air – H_2O, H_2, N_2, O_2, Ar, CO, CH_4, CO_2, C_2H_4, C_2H_6, C_2H_2, C_3H_6, C_3H_8, C_4H_8, C_4H_{10}, CH_3I, Kr, Xe, H_2O_2 (some of which are PTXs), using gas chromatography (GCh) methods [21, 22]. In [23] considers the results of research in the field of radiation physicochemical processes occurring in the air under the influence of various types of radioactive radiation, including in NPP air.

Thus, during radioactive irradiation of air, O_3 (ozone) is formed in it, which is chemically aggressive, easily enters into chemical reactions, including with organic compounds, and, if inhaled into the human body, can lead to respiratory diseases [24]. Thus, it has been shown in [24] that, depending on the concentration of O_3 in the air, the direct effect of O_3 on the human body causes fatigue, headache, irritation of the respiratory tract and related respiratory disorders, cough, vomiting, exacerbation of chronic bronchitis, asthma, pulmonary emphysema, pulmonary edema, i.e., O_3 is a pulmonotoxic xenobiotic. Indirectly, O_3 acts on the blood similarly to ionizing radiation: at an O_3 concentration of 0.8 g/m^3, half-hour inhalation of O_3 is equivalent to radioactive exposure of 100 R. In addition to its general toxic effects, O_3 has carcinogenic, mutational, genotoxic effects on humans and significantly reduces immunity to infections, and it is toxic by inhalation and irritates the mucous membranes of the eyes and respiratory tract, damaging lung surfactant [25].

The sequence of painful manifestations when O_3 is inhaled: first, drowsiness occurs, then breathing changes – it becomes deep, irregular; at the end, there are breaks in breathing; death occurs, apparently, as a result of respiratory paralysis. Pathological and anatomical studies show a characteristic picture of poisoning: the blood does not clot, the lungs are permeated with many hemorrhages. In the presence of nitrogen oxides in the air, the toxicity of O_3 increases 20 times [26].

Thus, the concentration of O_3 in the air of 2 mg/dm^3 causes coughing, burning of the larynx, weakness if a person inhales such air for several seconds, inhalation for 5 minutes develops pulmonary edema, and inhalation for 10 mins can be fatal [26].

Paper [27] presents the results of a study of the sources of harmful radioactive and nonradioactive substances and methods for determining their content in the air during the operation of double-circuit NPP equipment in Ukraine; proves that during the operation of NPP equipment, harmful substances enter the ambient air, which can then enter the human respiratory system in the form of radioactive or nonradioactive substances; proposes an improved structural diagram of a 7-channel gas chromatograph for determining the content of radioactive and nonradioactive substances in the ambient air of NPP equipment.

Paper [28] describes the complex for solid radioactive waste treatment at the Rivne NPP using plasma processing: this produces pyrolysis gases containing a toxic component in the form of CO, NO, NO_2, SO_2, SO_3, HCN, which can enter the ambient air and further into the human respiratory system. Work [29] show that during the operation of NPP electrical gas equipment, gas (SF_6) and toxic products of its degradation can enter the surrounding air: gaseous – SOF_2, F_2, SOF_4, SO_2F_2, SO_2, HF, CF_4, SF_4, WF_6; solid – S_2, CuF_2, AlF_3, FeF_3.

Work [30] show that when performing electric welding using metal structures, welding aerosols accumulate in the atmospheric air, including the following individual substances or their compounds with other individual substances, such as solids – Al, Si, B, V, W, Fe, Cd, Ca, Co, Mn, Cu, Ni, Mo, Sn, Pb, Ti, Cr, Zn, Zr, fluorine salts; gaseous – CO, CO_2, O_3, NO; NO_2, HF. Work [31] show that during welding operations in the repair of equipment, phosphine (PH_3) is released into the ambient air, which is a toxic substance with a general toxic effect, and during inhalation, it disrupts metabolism and affects the central nervous system and skeletal system, corrodes/irritates the skin, damages/irritates the eyes, liver, kidneys, spleen, ureters, bladder.

During welding operations with the use of plastic structures, the following substances accumulate in the air: CO; HCl; HCN; $COCl_2$; CH_2O (formaldehyde); C_4H_6 (1,3-butadiene); C_2H_6O (ethanol); C_3H_6O (acetone); white spirit; $C_2H_4O_2$ (acetic acid); $C_2H_2O_4$ (oxalic acid); C_6H_6 (benzene); C_7H_8 (toluene); C_8H_{10} (xylenes); C_6H_6O (phenol); carboxylic acid chlorohydrides; unsaturated hydrocarbons; C_2H_4O (acetaldehyde); $C_{16}H_{22}O_4$ (dibutyl phthalate); $C_{10}H_{10}O_4$ (dimethyl phthalate); $C_{24}H_{38}O$ (di-(2-ethylhexyl)-phthalate); C_2H_3Cl (vinyl chloride); $CHCl_3$ (chloroform); CH_2Cl_2 (dichloromethane); $C_4H_8O_2$ (dichloroethane); $C_4H_8O_2$ (dioxane); C_4F_8 (perfluoroisobutylene); CS_2 [32]. In [33] show that fluoroplastics are widely used in NPP equipment. When such fluoroplastics are heated, they are destroyed with the release of such toxic components as HF, C_4F_8 (perfluoroisobutylene); COF_2 (carbonyl fluoride); C_2F_4 (tetrafluoroethylene) into the surrounding air.

Paper [34] describes the main mechanisms and syndromes of PTXs exposure to the respiratory system. At the same time, PTXs can be transformed in the human body. It is noted that the syndromes of respiratory damage under the influence of PTXs can be: asphyxiation; bronchospasm; hypoxia; acute pul-

monary edema; myasthenic syndrome. When PTXs are exposed to the respiratory system, the following consequences are possible: irritation of the upper respiratory tract; burns; tissue decomposition under the influence of ionizing α-, β-, and γ-radiation from radioactive substances that have entered the respiratory system. Thus, the asphyxiating effect of PTXs is based on their ability to penetrate the lungs and cause damage to alveolar endothelial cells, resulting in filling the alveolar space with transudate coming from the capillary pulmonary network. When cauterizing PTXs affect the respiratory system, the pathogenesis of shock is dominated by severe pain, as well as extensive hemolysis of erythrocytes (hemolytic shock) or an allergic reaction (anaphylactic shock) [34].

The adult lung is a stable organ with low proliferative activity, so the effects of radioactive lung exposure do not appear immediately [35, 36]. At the same time, localized exposure may result in radiation pneumonia, which is accompanied by the death of epithelial cells, inflammation of the airways, pulmonary alveoli, and blood vessels. These effects can cause pulmonary insufficiency and even death within a few months after chest irradiation. The respiratory organs contain cellular structures that differ significantly in their resistance to radiation. Thus, the cartilaginous tissue of the airways and pleura are radioresistant, lymphatic tissue and the vascular system of the lungs, as well as bronchiolar epithelium and cells lining the alveoli, are radiosensitive. As a result of radiation exposure, changes occur in the respiratory system that are in full compliance with the development of clinical and anatomical signs of radiation pathology.

For example, in the first 3–4 days of acute radiation sickness, swelling and partial disintegration of argyrophilic fibers are observed; hyperemia, red blood cell diapedema and edema in the alveoli, subpleural emphysema. After the latent period, a new phase begins, characterized by increased vascular permeability, perivascular blood loss, hemorrhage, necrosis, which are often observed, bacterial infection, neutropenic bronchopneumonia. Survivors undergo resorption and regeneration with proliferation of connective tissue and sclerotic phenomena. Respiratory changes develop against a background of sharply suppressed cellular reactions, so in the midst of the disease there is no phagocytosis of bacteria and tissue decay products. Doses that do not have a significant effect on the epithelium cause only mild fibrosis.

Pneumonias, which are secondary infectious complications, can be a decisive link in the fatal outcome of radiation damage to the body. Although the lungs are classified as radioresistant organs, information on radiosensitivity is very controversial. At sublethal doses, no special effects are observed. But after exposure to relatively higher doses, there is a change in the frequency and depth of respiratory movements. Congestion and emphysema occur in the lungs. It is assumed that the main factor in this process is the destruction of capillaries, followed by erythropedesis and collagenosis, and then sclerotization of lung tissue. Various forms of pneumonia occur: from local, mild, serous to severe hemorrhagic. Recovery processes are slow. In the mechanism of pulmonary pathology development, the occurrence of increased vascular permeability and hemicirculatory disorders in the lung tissue is important.

The pathology develops along the following chain: bronchial lesions lead to impaired air permeability → decreased gas exchange, development of atelectasis → pneumonia → pleurisy → in the long term - radiation fibrosis [35, 36].

Paper [37] shows that in NPP technological processes, when using fire-resistant synthetic turbine oils (based on trixenyl phosphates) in hydrogen-cooled turbine generators [38], these oils can produce the toxic substance P_2O_5, which, when interacting with water, can in turn produce the toxic acid H_3PO_4. These substances are released from these oils into the surrounding air. It can be assumed that in the event of thermal defects in the bearings of a hydrogen-cooled turbine generator, the toxic substance PH_3 [39] can be formed in the fire-resistant synthetic turbine oil and released into the surrounding air.

The process of PH_3 formation can take place along the following chain: 1) $P_2O_5+H_2O=2HPO_3$; 2) $P_2O_5+3H_2O=2H_3PO_4$; 3) $2P_2O_5 \rightarrow P_4O_6+2O_2$; 4) $P_4O_6+6H_2O=4H_3PO_3$; 5) $4H_3PO_3 \rightarrow 2H_3PO_4+PH_3$ [39]. In the presence of dissolved hydrogen gas in fire-resistant synthetic turbine oil, a chemical reaction is possible with the formation of PH_3 according to the scheme $P_2O_5+8H_2=2PH_3+5H_2O$.

Table 1 provides information on the most significant radioactive and non-radioactive PTXs and methods for their determination in NPP air.

Thus, the results of the study show that during the operation of NPP equipment, radioactive and non-radioactive PTXs can enter the ambient air in the form of steam, gas or aerosol, which can then enter the human respiratory system and cause damage to them; allow to improve methods and technical means of environmental monitoring of the ambient air of NPP equipment to ensure radiation and environmental safety, reduce the risks of occupational pathologies for workers, protection of human health during accidents or normal operation of NPP equipment.

Table 1. Radioactive and non-radioactive PTXs and methods for their determination in the air NPP

PTXs in the air; (methods for determining PTXs)
Radioactive pulmonary toxic xenobiotics
^{41}Ar, ^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{133}Xe, ^{133m}Xe, ^{135}Xe, ^{135m}Xe, ^{131}I, ^{133}I, ^{135}I, HTO, DTO, T_2O, HT, DT, T_2, CH_3T; (RGSM); (LSM) [IEC 60761-3. Equipment for continuous monitoring of radioactivity in gaseous effluents, Part 3, Specific requirements for radiactive noble gas monitors; IEC 60761-4, Equipment for continuous monitoring of radioactivity in gaseous effluents, Part 4, Specific requirements for radiactive iodine monitors]; [20]
Elements, organic and inorganic compounds of elements: ^{137}Cs, ^{134}Cs, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{90}Sr, ^{89}Sr, ^{90}Sr, ^{91}Sr, ^{51}Cr, ^{54}Mn, ^{55}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{110m}Ag, ^{95}Nb; (RGSM; RCR for ^{90}Sr); [IEC 60761-2. Equipment for continuous monitoring of radioactivity in gaseous effluents, Part 2, Specific requirements for radiactive aerosol monitors including transuranic aerosols]
Non-radioactive pulmonary toxic xenobiotics
HCN; (GCh); [MU 4775-88. Guidelines for gas chromatographic measurement of the concentrations of hydrogen cyanide and acrylic acid nitrile in the air of the working area]
N_2H_4 (hydrazine); (PhMM); [MU 1657-77. Guidelines for the photometric determination of hydrazine in air]
NO, NO_2; (PhMM); [MU 4187-86. Methodological guidelines for the photometric measurement of nitrogen oxide and dioxide concentrations in workplace air]
HNO_3; (ICh); [ISO 21438-2:2009. Workplace atmospheres – Determination of inorganic acids by ion chromatography – Part 2: Volatile acids, except hydrofluoric acid (hydrochloric acid, hydrobromic acid and nitric acid) (IDT)]; PND F 13.1:2:3.19-98. Quantitative chemical analysis of atmospheric air and air emissions. Methods for measuring the mass concentrations of nitrogen dioxide and nitric acid (total), nitrogen oxide, sulfur trioxide and sulfuric acid (total), sulfur dioxide, hydrogen chloride, hydrogen fluoride, phosphoric acid and ammonia in industrial emissions samples, ambient air and working area air by ion chromatography]
$C_2H_2O_4$ (oxalic acid); (PhMM); [MUK 4.1.1732-03. Spectrophotometric measurement of mass concentrations of ethanedonic acid dihydrate (oxalic acid dihydrate) in working area air. Methodical instructions]
$C_2H_4O_2$ (acetic acid); (GCh); [MU 5904-91. Methodological guidelines for gas chromatographic measurement of monochloroacetic and acetic acid concentrations in workplace air]
C_2H_7NO (monoethanolamine); (PhMM); [MU 2568-82. Methodological guidelines for the photometric measurement of concentrations of primary aliphatic amines (methylamine, ethylamine, propylamine, butylamine, hexylamine, monoethanolamine) in working area air]
Freons; (PhMM); [MU 1699-77. Methodological guidelines for the photometric determination of organofluorine compounds (diethyl ester of perfluorodipic acid, diethyl ester of perfluoroglutaric acid, perfluorodibutyl ester, freons, benzotrifluoride, hexafluoropropylene, perfluoroacetone dihydrate, trifluoroethyl alcohol, trifluorobutyl alcohol, tetrafluoropropyl alcohol, octafluoromethyl alcohol, trifluorochloropropane) in air]
H_2O_2; (PhMM); [MU 4586-88. Methodological guidelines for the photometric measurement of hydrogen peroxide and organic peroxides concentrations in workplace air]
H_2, CO, CH_4, CO_2, C_2H_4, C_2H_6, C_2H_2, C_3H_6, C_3H_8, C_4H_8, C_4H_{10}; (GCh); [ASTM D 3612-012. Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography. ASTM International]
$COCl_2$; (PhMM); [MU 4768-88. Methodological guidelines for the photometric measurement of phosgene concentrations in workplace air]
CS_2; (GCh); [MU 3973-85. Methodological guidelines for gas chromatographic measurement of concentrations of carbon disulfide in working area air]
CH_2O (formaldehyde); (PhMM); [MU 4595-85. Methodological instructions for gas chromatographic measurement of formaldehyde concentrations in working area air]
$C_{16}H_{22}O_4$ (dibutyl phthalate); (GCh); [MU 2222-80. Methodological guidelines for gas chromatographic determination of dibutyl phthalate and dioctyl phthalate in air]
SF_6; (GCh); [MU 2697-83. Methodological guidelines for gas chromatographic determination of sulfur hexafluoride in air]
CCl_4; (GCh); [MU 1577-77. Methodological guidelines for gas chromatographic determination of allyl chloride, carbon tetrachloride and 1,2-dichloropropane in air]
NaOH, KOH; (PhMM); [MU 5937-91. Methodical instructions for photometric measurement of caustic alkali aerosol concentrations in workplace air]
Cl_2; (PhMM); [MU 1644a-77. Methodological guidelines for the photometric determination of chlorine in air]
H_2S; (GCh); [MU 5304-90. Methodological guidelines for gas chromatographic measurement of hydrogen sulfide concentrations in working area air]
HCl; (IMM); [MU 5932-91. Methodological guidelines for the ionometric measurement of hydrogen chloride concentrations in workplace air]
NH_3; (PhMM); [MU 4785-88. Methodological guidelines for the photometric measurement of concentrations of MU and formaldehyde in the combined presence in workplace air]
I_2; (PhMM); [MU 16446-77. Methodological guidelines for the photometric determination of iodine in air]
CH_3I; (GCh); [22]

PH_3; (LC); [A guide to Dräger indicator tubes and CMS chips. Analysis of soil, water and air as well as technical gases. 17th edition. Dräger Safety AG & Co. KGaA. Lübeck, 2015, 458 p.]
C_4F_8 (perfluorooctylene); (GCh); [40]
SO_2, SO_3; (PhMM); [MU 4588-88. Methodological guidelines for the photometric measurement of sulfuric acid and sulfur dioxide concentrations in the presence of sulfates in workplace air]
H_2SO_4; (TDA); [MU 08-47/355-2014. Working area air. Turbidimetric method for measuring the mass concentration of sulfuric acid]
P_2O_5+H_3PO_4; (ICh); [ISO 21438-1:2022. Workplace atmospheres – Determination of inorganic acids by ion chromatography – Part 1: Non-volatile acids (sulfuric acid and phosphoric acid, ISO/TC 146/SC 2, ICS Classification: 13.040.30 Workplace atmospheres, Edition 2022, 22 p.]
CH_2Cl_2 (dichloromethane); $C_2H_4Cl_2$ (dichlorethane), C_6H_6 (benzene); C_7H_8 (toluene), C_6H_6O (phenol); (GCh-MS); [GOST R ISO 16017-1-2007. Atmospheric air, working area and confined spaces. sampling of volatile organic compounds using a sorption tube followed by thermal desorption and gas chromatographic analysis on capillary columns. Part 1. Sampling by pumping; ISO 16017-1:2000. Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography — Part 1: Pumped sampling (IDT)]
Elements, organic and inorganic compounds of elements: Al, Si, B, V, W, Fe, Cd, Ca, Co, Mn, Cu, Ni, Mo, Sn, Pb, Ti, Cr, Zn, Zr, fluoride salts, HF, O_3; (PhMM, IMM, PGA, AAA, GCh, TMA, AES); [ISO 15202-3:2004. Workplace air – Determination of metals and metalloids in airborne particulate matter by inductively coupled plasm a atom icemission spectrom etry – Part 3: Analysis (IDT); MU 4945-88. Methodological guidelines for the determination of harmful substances in welding aerosol (solid phase and gases)]
Notes: LSM – liquid scintillation method; RGSM – radiometric and gamma spectrometric measurements; RCR – radiation and chemical removal; GCh – gas chromatography; GCh-MS – gas chromatography-mass spectrometry; PhMM – photometric measurements; IMM – ionometric measurements; TDA – turbidimetric analysis; TMA – titrometric analysis; PGA – polarographic analysis; AAA – atomic absorption analysis; ICh – ion chromatography; AES – atomic emission spectrometry; LC – linear and colourful.

CONCLUSIONS

1. It is shown that: a) during the operation of NPP equipment, PTXs can be released into the surrounding air in the form of vapor, gas or aerosol, which can then enter the human respiratory system in the form of radioactive or non-radioactive substances – ^{41}Ar, ^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{133}Xe, ^{133m}Xe, ^{135}Xe, ^{135m}Xe, ^{131}I, ^{133}I, ^{135}I, HTO, DTO, T_2O, HT, DT, T_2, CH_3T, ^{137}Cs, ^{134}Cs, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{89}Sr, ^{90}Sr, ^{91}Sr, ^{51}Cr, ^{54}Mn, ^{55}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{110m}Ag, ^{95}Nb, NO, NO_2, HNO_3, SO_2, SO_3, H_2SO_4, SF_6, N_2H_4, H_2O_2, Cl_2, HCl, H_2S, CS_2, CCl_4, NH_3, NaOH, KOH, HCN, $COCl_2$, acetic acid, formaldehyde, perfluoroisobutylene, freons; elements, organic and inorganic compounds of elements – Al, Si, B, V, W, Fe, Cd, Ca, Co, Mn, Cu, Ni, Mo, Sn, Pb, Ti, Cr, Zn, Zr, fluoride salts, HF, O_3; b) Significant methods for determining the content of PTXs in NPP air include: gas chromatography; gas chromatography-mass spectrometry; liquid scintillation; photometric, ionometric, polarographic, titrometric, turbidimetric, atomic absorption, radiometric, and γ-spectrometric measurements; c) exposure to radioactive PTXs due to radioactive irradiation of the body in the respiratory system leads to the development of clinical and anatomical signs of radiation pathology; d) exposure to non-radioactive PCBs leads to pathological processes: irritation and inflammation in the respiratory system, as well as toxic pulmonary edema; e) there is a link between the presence of PTXs in the ambient air of NPP equipment in concentrations exceeding the established standards and the course of human respiratory diseases caused by breathing such air.
2. The prospects of the obtained research results lie in the possibility of using them to improve the systems of ensuring: reliability, radiation and environmental safety of NPP equipment; health protection and reduction of risks of occupational pathologies in case of respiratory diseases of people under the influence of PTXs during the operation of NPP equipment.

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CONFLICT OF INTEREST

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