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ENSURING THE SAFETY OF NUCLEAR POWER PLANTS WITH SCWR (VVER-SKD)

On the basis of analysis of the published data on the safety of NPPs with Generation IV SCWR reactors it was shown that SCWR (VVER-SKD) has advantages over VVER-1000 by its main engineering, economical and thermal characteristics. While considering the concept of Generation IV reactors, it was shown that NPPs with SCWR would be equipped with the enhanced safety systems. Some ways of optimization of these systems were considered as well.

Keywords: SCWR reactor, safety, optimization of safety systems.

It is assumed that one of the promising designs of the future reactors (Generation IV) may be the Super Critical Water-cooled Reactor or SCWR [1-9], which has the improved technical and economic characteristics [2-9] as compared to previous generations of reactors. Among them are:

- the use of simplified schemes and processes, resulting in reduction of the flow cross sections of pipelines (2.5-3 times), and the size of control and safety valves, and the decision to use no secondary circuit equipment (steam generators, pumps, separators, etc.);
- high efficiency (45%);
- low consumption of natural uranium (~130 t / GWh el.);
- the possibility of closing the fuel cycle;
- reduction of specific investment in the installation: SCWR differs from other nuclear power plants (NPP) by its 1.5 - 2 times lower capital costs, and its projected cost will be 20-30% lower than the cost of the VVER;
- lower metal content: SCWR specific quantity of metal is about 1.4-1.6 t / MWe (the similar index for VVER-1000 is 3.25 t / MW el.).

However, despite these features, it is possible to make a definitive conclusion about the suitability of reactor units with SCWR (VVER-SKD) for large-scale use only provided that the requirements to ensure their safety meet the INPRO requirements for innovative nuclear reactors [10].

In many ways, the safety of nuclear power plants (NPP) is determined by characteristics of their safety systems (SS), which may affect the design of the reactor core and the NPP in general.

Thorough designing the systems of normal operation (SNO) at the early stages of design will make it possible to combine functions of some of these systems and safety systems, to define the starting and stopping algorithm of the reactor facility operation. In addition, information about the SS and SNO is required for designing of the containment and configuration of the equipment outside the containment.

In open publications there is very little information from which one could make a conclusion in what extent the SCWR (VVER-SKD) complies the regulatory and operational documents on safety. The purpose of this work is to analyze some of the available publications, which describe how it is expected to provide a high level of safety at SCWR NPPs, what kinds of safety systems are going to be used there, and how they differ from the safety systems of Generation-III VVERs.

Analysis of the development of technology and operating experience of thermal and nuclear power has led to understanding that energy, both thermal and nuclear, will be developed by increasing the pressure and temperature of steam at the turbine inlet. This in accordance with thermal dynamics will increase the coefficient of performance (COP) of the steam cycle and reduce the specific steam consumption per unit of the energy produced [2, 11].

Going this way, the reactor designers offered a number of the concepts of direct-flow thermal neutron reactors with water coolant at supercritical pressure (SCLWR) and of fast neutrons reactors (SCFR) with almost the same thermal diagram [2, 4, 8, 9].

Great advantage of these reactors is the ability to use standard equipment, which has been already developed and implemented at thermal power plants (TPP). It is assumed that the identity of thermal circuits of NPP with thermal and fast reactors (nearly the same temperature conditions in them) will lead to a uniform structure of nuclear energy in the future.

It should be noted availability of the foreign (BWR - pressurized Boiling Water Reactor) and Russian (pressurized boiling water reactors VK-50, VK-300) experience of successful and safe operation of the single-circuit units with a vessel-type reactor and boiling coolant [1], which can be used in the development of single-circuit NPP with VVER-SKD.

Of particular interest are the solutions for VK-50 reactor sustainability, for start-up mode of BWR and VK-50, for changing the spectrum of the neutrons in the BWR to increase reproduction rate or burnout. [2].

Single-circuit scheme of VVER-SKD differs from the above-mentioned schemes because a coolant in the reactor water is used with supercritical parameters (SCP). It should be noted that the critical parameters are water pressure of 22.1 MPa and temperature of 374°C. At supercritical pressure there is no liquid-steam phase transition. Water under SCP could be considered as single-phase medium which properties depend strongly on the temperature. Heat is removed mainly to pseudo-critical temperature range that corresponds to the maximum heat. For the pressure of 25 MPa, the temperature is ~385°C.

Fig. 1 shows a typical single-circuit SCWR installation with feeding of steam from the reactor to the turbine [4]. On the outlet of a heat-insulated pipe the steam comes out of the reactor and hits the turbine.

Here a single-pass scheme is used, with coolant flow in the reactor core, in accordance to which the entire heating of coolant occurs during its motion in the core upwards (Fig. 2) [7, 9, 12]

Design solution provides cooling of the reactor vessel with water at a temperature of 290°C, which enables to use the construction materials specially developed for VVER and apply the technology of production of vessels with increased wall thickness.

A significant change in enthalpy makes it possible to achieve 10 times reduction of the coolant flow through the reactor compared to the VVER-1000. These features are taken into account in the design of the core, where the information about the formation of the neutron spectrum, the level of nuclear safety and the stability of the reactor is necessary.

The VVER-1000 fuel assembly design is taken as the basis for VVER-SKD FA [12, 13]. The cluster system of absorbing elements is used. For this purpose, there are 18 guiding channels inside the FAs. The center channel is designed for installation of measuring devices.

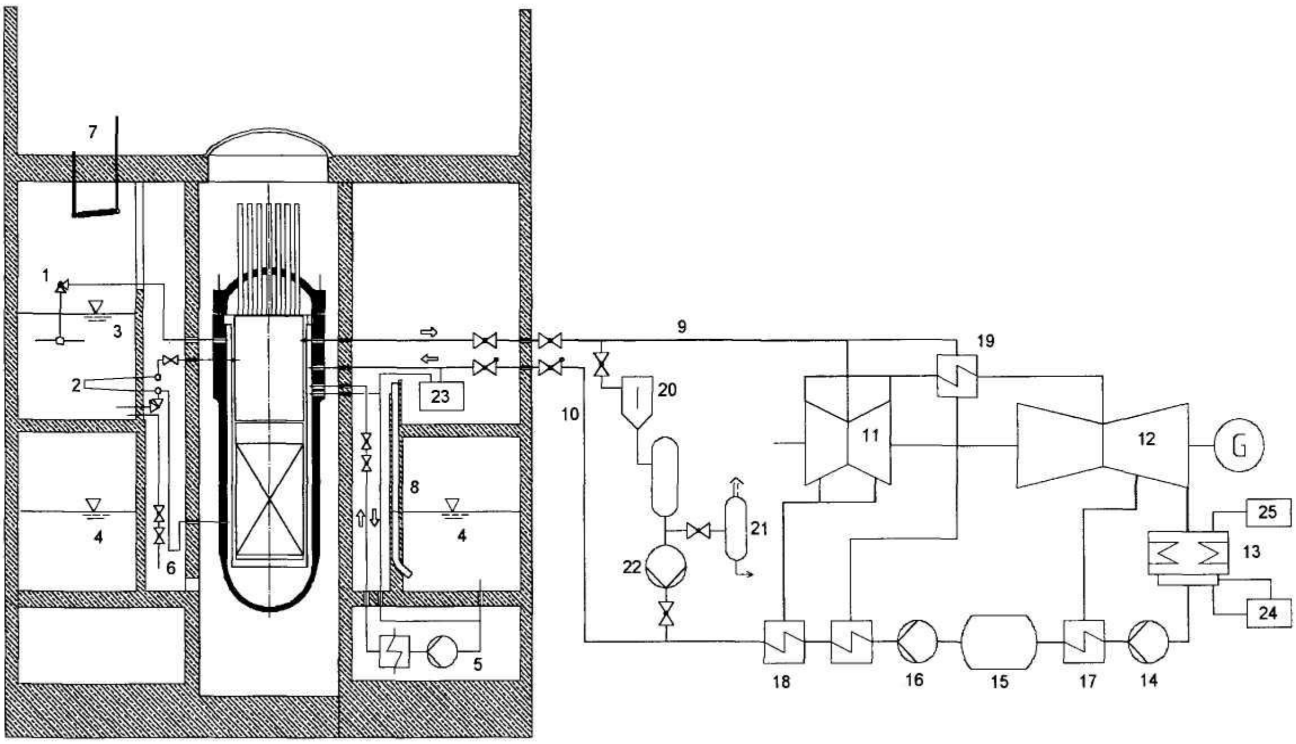

Fig. 1. SCWR Circuit diagram, schematic:
1 — safety relief valves; *2* — Emergency condenser; *3* — core flooding pool; *4* — pressure suppression pool; *5* — Low pressure injection, decay heat removal; *6* — Drywell flooding line; *7* — Containment cooling condenser; *8* — vent pipes; *9* — Main steam line ; *10* — Feedwater line; *11* — HP turbine; *12* — LP turbine; *13* — Condenser; *14* — Condensate water pump; *15* — Feedwater tank; *16* — Main feedwater pump; *17—19* — Reheaters; *20* — water-steam separator; *21* — flush tank; *22* — Start-up recirculation pump; *23* — Reactor water demin. system; *24* — Condensate demin. system; *25* — Degassing System

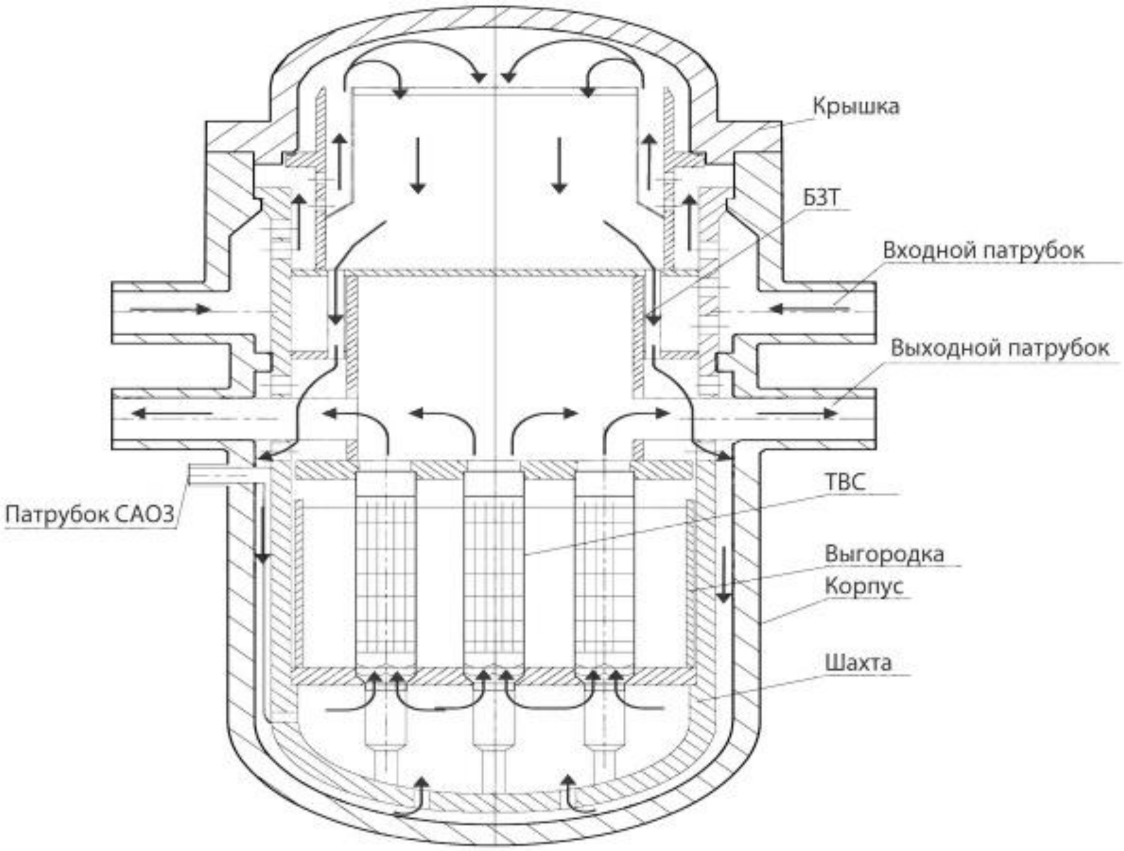

Fig. 2. VVER-SKD: main constructive components and single-circuit circulation scheme (БЗТ - BZT — protective tubes unit, ТВС – TVS - fuel assembly)

Table 1. Main characteristics of the VVER-SKD and VVER-1000

Parameter	Single-circuit installation with VVER-SKD	VVER-1000 (B-392 design)
Neutron spectrum	Heat and fast-resonance	Heat
Electric capacity, MW	1700	1000
Coefficient of performance, %	45	33—34
Heat capacity, MW	3863	3000
Coolant parameters: Pressure, Mpa/ outlet temperature °C	24,5 / 290	15,7 / 289
Inlet temperature, °C	540	320
Vessel	VVER-1000	VVER - 1000
Energy intensity (volume energy release), kW / l	80	111
Fuel	UO_2	UO_2
enrichment on U-235, %	16,3	4,4—3,3
FA diameter, mm	9,1	9,1

VVER-SKD has a number of advantages in its basic technical and economical parameters and thermal characteristics compared with G-III design of VVER-1000 (Table 1):

- rather high efficiency that can reach 45%. This not only results in fuel savings, but also improves the environment around the NPP;
- large temperature difference between the coolant at the inlet and outlet of the reactor (250—270°C) makes it possible to reduce the flow of coolant through the reactor core;

Hard (fast resonance) neutron spectrum makes it possible to achieve a high reproduction rate of fuel (~1), reduce the consumption of uranium, ^{238}U, and to ensure the use of the transmutation of long-lived fission products in the neutron field.

In order to determine which SS and how many of them should be installed on VVER-SKD for ensuring its reliable safety level, we will first consider the concept of safety of the supercritical pressurized water reactor [14].

Safety of nuclear power plants is ensured by limitation of doses to workers and the public, and by restriction of release of radioactive substances into the environment at normal operation, design-basis and beyond design basis accidents. This can be achieved through the development of technical and organizational safety measures to prevent accidents, limitation of their radiological consequences, providing a low probability of an accident with a large radiological consequences.

Radiation safety can be achieved through consistent implementation of the well-known defense-in-depth principle, which includes a strategy to prevent accidents and limitation of their consequences; it also provides for the application of sequential physical barriers to the potentially possible spread into the environment of ionizing radiation and radioactive substances; the use of systems of technical and organizational measures to protect the barriers and maintain their effectiveness, and direct measures to protect the population (Fig. 3) [14-17].

In accordance with the defense-in-depth concept the VVER-SKD design provides safety systems intended to perform the following critical safety functions (CSF) [14]:

CSF -1 "Subcriticality" - shutdown of the reactor and maintaining it in a subcritical state;

CSF -2 "Core Cooling" - supplying of cooling water into the core;

CSF -3 "Heat removal to ultimate absorber" - providing of heat transfer to the ultimate absorber;

CSF -4 "Integrity of circuit boundaries" - retention of radioactive substances within the established boundaries;

CSF -5 "Integrity of pressure boundaries" – prevention of release of radioactive substances into the environment.

To provide the safety systems with the possibility to perform their functions, an additional critical safety function CSF-0 "Operability of the equipment" is added.

At development of safety systems the problem of reliable operation should be solved with taking into consideration the following types of potential failures:

- single failure or a human error;
- long undetected failure;
- common cause failure.

Basic principles of ensuring reliability of safety systems that should be implemented in the design of a power unit are as follows:

- redundancy;
- application of the principle of diversity for basic safety features (passive and active systems);
- design of components and systems in accordance with the principle of single failure;
- physical separation of channels and systems;
- resistance of equipment to emergency external conditions and impacts, including seismic resistance, waterproofing, fire- and thermal resistance, etc;
- direct and shadowed protection of safety systems and their structural channels against external impacts;
- automation of control, including direct action devices;
- continuous or periodic monitoring of systems operability and their automatic internal diagnosis;
- well-grounded conservative approach at designing, including the use of protective barriers and safety systems; determination of the list of initiating events and accident scenarios; determination of the range of emergency parameters and characteristics, and the design margins.

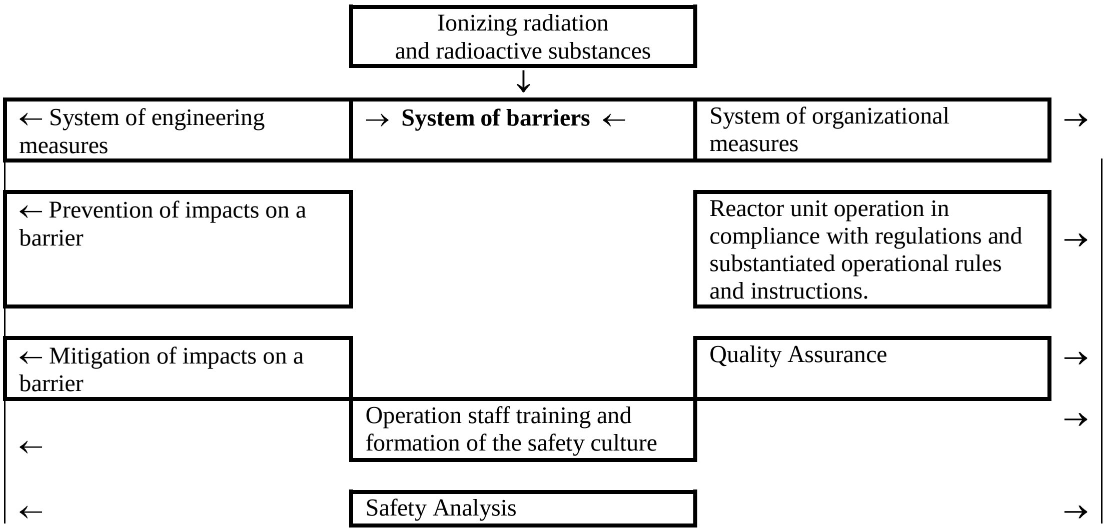

Fig. 3. The radiation safety concept

Developing of safety systems for nuclear power plants with VVER-SKD is based on many years of operational experience and the latest developments in the use of safety systems at nuclear power plants with VVER-1000 reactors. Therefore, these reactors have similarities in their safety equipment components and structural design. But since the installation is developed as the Generation IV reactor, the safety systems of VVER-SKD must comply with the principles and criteria of safety, set by INPRO for these types of reactors.

In the modern nuclear industry the safety systems, in general, are active, that is, their effect depends on the operation of electrical and mechanical drives of various equipment, such as sensors, valves, pumps, accumulators, heat exchangers and systems of internal power consumption. Reactors of III and IV generations are equipped with more effective safety systems, some of which are passive, that is, much more efficient, safer and more economical.

The tables lists the most important VVER-SKD safety systems and the critical safety functions (CSF) they should provide [14] (Table 2). For comparison there is a list of safety systems, and the safety functions (SF) they provide for VVER-1000 (V-320 design) [15-17] (Table 3).

Comparing the data presented in Tables 2 and 3 for two reactors, one can come to conclusion that passive safety systems are actively applied in VVER-SKD. In particular, it is worth noting a separate system of passive protection (flooding) of the reactor core (in transliteration - SPZAZ), which, in addition to accumulators has a water tank. Triggering of SPZAZ accumulators occurs automatically when the pressure in the reactor is lower than the pressure in them. Water supply from the SPZAZ tank into the reactor is performed by opening the check valve under the action of the hydrostatic pressure of the liquid column in the tank at low pressure in the reactor.

The complex of VVER-SKD safety systems also includes a passive heat removal system, which is based on passive elements.

Table 2. Summary of the proposed safety systems of VVER-SKD

Safety System	Critical safety function					
	CSF-0	CSF-1	CSF-2	CSF-3	CSF-4	CSF-5
Emergency protection	+	+				
The system of the core passive flooding	+		+			
Emergency core cooling system	+	+	+			
Emergency feedwater system	+		+			
Reactor overpressure protection system:	+		+	+	+	
Fast-acting steam dump valve (SDV) (transliteration -BRU)	+		+	+	+	
pulse safety valves (transliteration IPU)	+				+	
Passive heat removal system	+			+		
Localization of the containment system (Fast-acting steam isolation valves on the steam line and feedwater piping) (transliteration – BZOK)	+					+
Emergency gas removal system	+		+			
Emergency power supply system	+					

NOTE: BZOK - main steam isolation valve

Table 3. List of VVER-1000 safety systems (B-320 design)

Safety system	Safety function				
	FB -1	FB -2	FB -3	FB -4	FB -5
Boron control	+	+			
High pressure emergency core cooling system	+	+			
System of hydro-accumulators (passive part of ECCS)		+			
Low pressure emergency and planned core cooldown system		+		+	
Primary circuit pressure compensation system					+
Steam dump system			+		
Primary circuit emergency gas removal system					+
Emergency feedwater system			+		

NOTES:
1. FB-1 – providing the reactor subcriticality.
2. FB -2 —maintain reserve of coolant in the primary circuit.
3. FB -3 — removal of heat from the primary circuit to the second circuit (pressure maintenance of the 2nd circuit).
4. FB -4 — removal of heat from the reactor core.
5. FB -5 — pressure control in the primary circuit.
6. ECCS —emergency core cooling system.

In accordance with the structure of the protective safety systems construction, all SS of VVER-SKD have three independent, physically separated channels. The output of each channel is 50%. The use of passive safety systems eliminates some elements of the internal redundancy of active SS channels.

In particular, we consider it possible to eliminate one of the three channels of the following SS:

1) the active part of the emergency core cooling system;
2) reactor overpressure protection system;
3) spray system;
4) emergency power supply system;
5) emergency feedwater system;
6) emergency gas removal system.

This makes it possible to achieve reduction of the number of equipment, piping, cables, the installation and operation costs without significant reduction in the level of the reactor safety.

In addition, it is proposed to extend the functional requirements and design basis of the passive safety systems in the direction of enabling them to overcome the design basis accidents. Thus, due to the additional reserve of coolant one can increase the time of operation of passive safety systems and accident control without operator's intervention and the need for power supply for 72 hours.

Conclusions

1. Generation-IV VVER-SKD has a number of advantages in the feasibility and thermal performance compared with the VVER-1000 reactor, which is expressed through the following characteristics:

- high efficiency, which can reach 45%;
- much smaller flow of coolant through the core;
- fuel reproduction rate is close to 1.

2. Passive elements prevail in the reactor safety systems of VVER-SKD. The use of passive safety systems makes it possible to optimize the number of SS in NPPs VVER-SKD by eliminating some of the elements of the internal redundancy of active SS channels. Instead, it is proposed to extend the function of the passive safety systems in the direction of enabling them to overcome the design basis accidents.

3. The number of safety systems in VVER-SKD design corresponds to the basic principles of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) [10], the IAEA fundamental safety principles [18], and complies with the requirements of national safety regulations. [19]

In addition to the previous suggestions about the use of innovative nuclear energy generating plants in the national nuclear power industry [20, 21], the information presented above gives the ground to consider the reactor unit VVER-SKD as a promising option of development of nuclear energy technologies in Ukraine.

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ARMS NPP AND EARLY WARNING SYSTEM FOR RADIATION ACCIDENTS ñGAMMAò ð THE BASIS OF THE STATE AUTOMATED SYSTEM OF RADIATION MONITORING OF THE ENVIRONMENT

The description and analysis was made of automated systems of radiation monitoring of the environment (ARMSE), which are in operation in Ukraine and can become the basis for the design and installation of the united national ARMS system (the EGASKRO). It is shown that the radiation accidents early warning system ñGammaò can be the basis of the EGASKRO. The local-level EGASKRO network can be formed on the basis of ARMS around the NPP sites.

Keywords: automated system of radiation monitoring, the environment, nuclear power plant, NPP, system of early warning, radiation accidents, united national automated system of radiation monitoring

Despite the decades of attempts to create all-Ukrainian, or, as it is called in official documents, the United State Automated Radiation Monitoring System (in transliteration ï the EGASKRO), this has not happened yet. Implementation of these efforts was not enforced even by the decision of the National Security and Defense of Ukraine from 08.04.2011 and the Order of the Cabinet of Ministers of Ukraine ¯ 44-r of 25.01.2012, [1, 2].

However, the components of this system exist and function. They should serve as a basis for building a full-scale national Automated Radiation Monitoring System (ARMS). Its enlarged organizational and functional structure is shown in Fig. 1. It should be noted that each of the structural components has its own organizational and functional structure, which is not shown here, but which will be discussed in more details below.

Currently available components of the national ARMS (EGASKRO) - are, first, the industry-wide systems consisting of on-site ARMS for monitoring of the environment. They are successfully and reliably operated at Ukrainian NPPs. Secondly, it is an early warning system for radiation accidents "Gamma", covering municipal and territorial levels of monitoring. The concept and the scheme of such a system was proposed in the late 1990s, by Kharkiv and Kiev scientists and experts [3, 4]

This article provides description and analysis of the existing and functioning in Ukraine automated radiation monitoring systems, which could serve as the basis for designing and creating the EGASKRO based on organizational, engineering and informational compatibility.

ARMS for monitoring of the environment at Ukrainian NPPs. As the low hierarchical level of ARMS in Ukraine one can consider ARMS operating at Ukrainian nuclear power plants ï they are the object-level systems owned by the nuclear power industry of the country.

ARMS operated at NPP are designed for implementing continuous automatic monitoring of the radiation situation on the industrial site in the sanitary protection zone (SPZ), the surveillance zone (ZN) of NPP in all modes of a plant operation, including the design and beyond design basis accidents, as well as during the NPP decommissioning.

Letôs consider organizational and functional structures of ARMS for monitoring of the environment that are available at Ukrainian NPPs:

ARMS at ***Rivne NPP***, put into commercial operation in 2007, is an automated complex of the posts of radiation monitoring, of which 16 are located on the territory of industrial NPP site, and 13 - in the sanitary protection zone (SPZ) and the surveillance area (SA) of the plant [5 6]. The system provides control of the radiation situation on the territory of a 3 000 sq.km, with a population of about 130 000 people in 90 towns.

Monitoring of the radiation situation around NPP is carried out continuously in automatic mode, which allows one to receive information from the monitoring posts, to carry out systematic analysis of data, forecast the radiation environment for all towns of the 30-kilometer surveillance area.

Studies have shown that, in general, the system of ARMS monitoring posts at Rivne NPP in terms of their number and location is sufficient to carry out its functions and is able in its present configuration to register the level of releases that lead to the necessity of declaring emergency preparedness, the introduction of counter-measures to protect the population in the emergencies, and to respond to the exceed of the allowable releases.

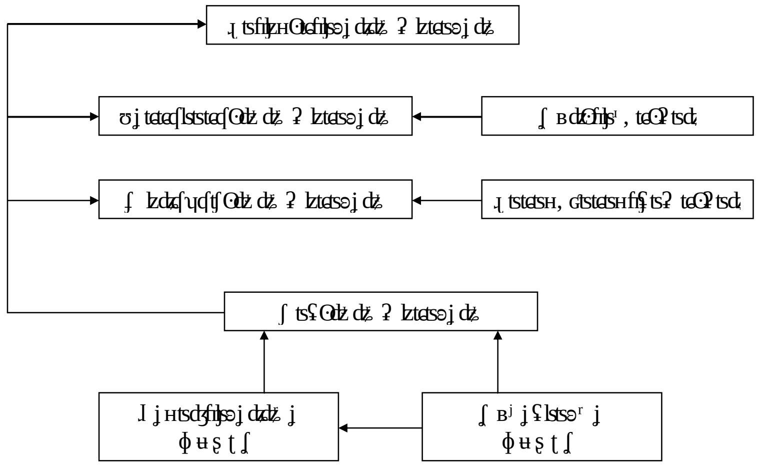


Fig. 1. Organizational and functional structure of national-wide ARMS (ñEGASKROò)

Nevertheless, it was recommended to consider the possibility of increasing the number of remote monitoring posts in accordance with the map of the distribution of the mathematical expectation of the exposure dose rate (EDR) of gamma radiation on the local territory.

In 2012, in order to improve efficiency and information content on the existing RNPP ARMS, the plant initiated works on its reconstruction. Some of these works include modernization of the monitoring posts network, which should increase the probability of detecting virtually any release, first of all - exceeding the permissible level.

Despite the fact that installing of additional posts of ARMS would increase the efficiency of the system, the plant experts decided that due to the fact that the existing ARMS completely fulfills its function for effective monitoring, it is unreasonable to change the existing network of posts due to high financial costs of this work.

Thus, at present the arrangement of posts of ARMS at RNPP has the same local configuration as before the modernization: there are 16 posts on-site, 2 - in the sanitary protective (buffer) zone and 11 in the surveillance area.

In the monitoring posts they perform measurements of activity of gas-aerosol releases through ventilation stacks of NPP units, liquid effluents, dose rate, and concentration of iodine and aerosols on-site and in settlements in the area of RNPP location.

The ARMS composition provides for two mobile monitoring posts installed on off-road vehicles. Mobile posts are equipped with a set of hardware to monitor radiation, chemical and meteorological parameters of the environment, as well as equipment for sampling, field measurements, and stand-alone operation. In addition, the cars are outfitted to determine the coordinates of objects on the ground and transmit information via satellite channels. Because of this they can work anywhere in the 30-kilometer surveillance area of the plant, as well as to assist in the radiation investigation at other Ukrainian NPPs.

The composition of a central post of monitoring (CPM) of ARMS includes two meteorological complexes, which are able to determine more than 30 meteorological parameters, including intensity of solar radiation, the balance of incoming and outgoing radiation from the earth's surface, visibility and weather conditions on the codes of the World Meteorological Organization.

In addition, these meteorological complexes perform remote scanning of the atmosphere up to an altitude of 3000 m with determination of the horizontal wind speed and direction, speed of vertical air movements, air temperature by layers, categories of atmospheric stability.

The information on the meteorological conditions and radiation parameters is used in the software package for operational forecasting of radiation situation in the RNPP surveillance area, developed at the Institute for Radiation Protection of the Academy of Technological Sciences of Ukraine.

By this software complex the analysis is performed of radioecological consequences of possible accidents. Results of the analysis are used to support decision-making on protective measures for the NPP staff and residents of all settlements of the 30-kilometer surveillance area at an emergency or radiation accident at Rivne NPP.

To ensure the functioning of the software package at the RNPP site the fiber-optic communications were laid to ensure the transfer of technological and radiation parameters from all units. Data transfer is performed on-line. Total of about 85,000 technological parameters is transmitted from all NPP units.

The structure of ARMS includes automatic telephone exchange connected with fiber-optic lines with Rivne NPP and with communication hub of the city of Kuznetsovsk. As a back-up, the satellite communication channels are provided for transmitting information.

Information obtained by means of ARMS is submitted to the NPP management, to NAEC "Energoatom" and the State Nuclear Regulatory Inspectorate of Ukraine, to Rivne regional state administration, the regional department of the State Service for Emergency Situations and Ecology.

In 2002, at ***Zaporozhye NPP*** (ZNPP) it was commissioned the information-measuring system (IMS), called the "Ring", which is an integral part of the general automated system of radiation monitoring at the facilities of the plant [7]. At its core, the IMS "Ring" is an on-site ARMS at ZNPP.

The purpose of the IMS "Ring" functioning is to provide prompt and reliable information necessary for analysis of radiation impact of the nuclear power plant facilities on the environment and the population in order to eliminate or minimize these impacts, as well as for detection and identification of sources of releases and effluents of radioactive substances, including uncontrolled leaks.

The functions and tasks of IMS "Ring" is to support crisis response actions in case of accidents at nuclear power plants with release of radioactive substances outside the NPP industrial site borders.

It is designed to:

- registration of releases of radionuclides into the environment with alarming of deviation from normal values;
- registration of uncontrolled accidental effluents of contaminated water in the cooling pond with alarming of deviations from normal values;
- assessment and prediction of the radiation situation on the industrial site, in the SPZ and surveillance area during all modes of NPP operation, including the design and beyond design accidents;
- registration of levels of radioactive contaminants in the region from sources not related to NPP operation.

Automatic measurement of the dose rate of gamma radiation, volume activity and meteorological parameters is carried out with a periodicity of survey detectors query - 2 minutes.

In 2010 it was prepared the Terms of Reference "The automated system of radiation monitoring of Zaporizhzhya NPP", which contained the requirements for the upgraded ARMS system, and in 2012 a conceptual decision was made on modification of ZNPP ARMS.

Unfortunately, for various reasons, the modernization of ARMS at Zaporizhzhya NPP was not completed. Only the number of control posts was increased.

On the basis of the calculations it was proposed to upgrade the network of ARMS posts (location and number) in such way that, on the basis of data on the parameters of a particular NPP release and meteorological features of the area that determine its spread in the atmosphere, it would be possible to ensure the completeness of monitoring and promptly receive objective results of measurement of the parameters of radiation situation in the environment, for all modes of Zaporizhzhya NPP operation.

Compared to the old scheme of ARMS (before modernization) a new post was added in the area of Marganets town.

Thus, the currently installed ZNPP ARMS accounts 31 post: 13 ï on-site and 18 - in the SPZ and surveillance area of the plant.

In addition, the ARMS includes three local control centers (LCC) [8].

At ZNPP it is planned to install software complex of computational methods and tools (based on software and hardware complex "Prosa") for prompt assessment and prediction of the effects of radiation accidents and development of recommendations to reduce them [7].

It is expected that adaptation of computational methods will be carried out on the modern powerful personal computer with a multi-user interface, which will be placed in the LCC-3 premises in the laboratory for external radiation monitoring (LERM). Therefore, LCC-3 during normal ZNPP operation will solve the problems of radiation monitoring both for radiation hazardous facilities of NPP and the area of its location. In case of emergency a headquarters is arranged on the basis of LCC-3 for organization of radiation protection of personnel involved in the accident, and the region's population.

Radiation monitoring in the SPZ and SA by means of ARMS is held also at ***Khmelnitsky NPP*** (KNPP) [9]. The purpose of ARMS creation there was to improve radiation monitoring by automating the processes of measurement, collection, processing, visualization, archiving and storage of information about the parameters of the radiation situation at the NPP site and in the area surrounding the nuclear power plant.

ARMS collects information on-line once in 2 minutes, saves it for a long time, and provides current and historical information on meteorological parameters and the radiation environment monitoring at designated locations. It is considered that this scope of information is sufficient to make a conclusion about exceeding or not exceeding the permissible levels of exposure of plant personnel at the site, and the population living in the vicinity of its location.

There were no special studies to substantiate the number and location of ARMS posts at Khmelnitsky NPP. They were determined empirically by siting to the standard points of the radiation monitoring network (RM) that best met the requirements of industry standard of Ukraine on creation of ARMS. [10]

At present, the ARMS has 15 posts-containers for radiation monitoring, four of which are located at the site, and the rest ones - in the 30-kilometer zone. At the site there are also 14 posts to monitor the dose of gamma radiation. The information from them is transmitted to the data collection station of the central control post located in the LERM building of radiation safety shop, and to two data collection stations located at the NPP site. Information is supplied by the cable lines and radio channels (for inspection stations in the SPZ and SA). The system provides automatic measurement of the following radiation and meteorological parameters: gamma radiation EDR; volume activity of aerosol and volume activity of iodine radioisotopes in the air; volume activity of radionuclides in water; wind speed and direction; atmospheric pressure; relative humidity; amount of rainfall; radiation balance of the earth's surface, and total solar radiation; atmospheric stability category.

Stationary posts-containers are equipped with security and fire alarm systems and climate control systems. ARMS may operate in one of the three modes: basic mode, full-scale monitoring, and technological mode. Basic mode corresponds to normal operation of KhNPP. Switching of ARMS into mode of full-scale monitoring is carried out automatically or on a command of duty engineer at exceeding of the level of gamma radiation, or in the cases stipulated by the Rules of Radiation Monitoring of the NPP. The staff provides around the clock monitoring of all hardware and software of ARMS.

On the ***South-Ukrainian NPP*** (SU NPP) in February 2014 four upgraded aspiration post of the automated system of radiation monitoring in the NPP environment were put into pilot operation.

The ARMS put into operation at this NPP performs the tasks of collecting, processing, storing and providing on-line information on the state of the environment. The software of the new automated system makes it possible not only to analyze the current radiation situation, but also to predict it, based on meteorological parameters. The modern complex of technical means on the basis of which the ARMS was created, provides high reliability, efficiency, quality control and information support.

The basis of ARMS is composed of three central posts similar by their functions, located directly on the control panel of radiation monitoring in the crisis center and the external dosimetry laboratory of the NPP. Their indications via special duplicated channels are received from peripheral monitoring posts, 12 of which are installed in the sanitary protection zone (radius of 2.5 km), and 13 - in the surveillance area (radius of 30 km) of the plant. Automatic querying of the posts is carried out at least once in 3 minutes.

As is the case of KhNPP, there were no research on justification of the number and location of ARMS posts for SU NPP. Network of posts was formed by siting to the standard points of the radiation monitoring network, which best met the requirements of industry standard of Ukraine on creation of ARMS. [10].

Duplication of the central control points and communication channels provides reliable operation of the system under the most unfavorable external and internal impacts. So, the ARMS may function uninterruptedly in conditions of normal operation of NPP, and in emergency. Switching to the measurement mode is carried out automatically when the established level of gamma-radiation is exceeded.

Upgraded aspiration posts entered into pilot operation at the third stage of implementation of the ARMS project, are in standby mode in conditions of normal NPP operation. Turning to the measurement mode is performed automatically or manually in case of emergency.

Thus, the central control points in addition to the values of exposure dose of gamma radiation, meteorological parameters and activity of radionuclides in water of industrial and stormwater drain and discharge channel will receive on-line the information about the volumetric activity of radioactive aerosols and iodine-131 in air.

In addition to fixed monitoring posts the ARMS includes two mobile laboratories. They are placed on off-road vehicles in which laboratory personnel can perform sampling and carry out the necessary measurements anywhere in the SPZ and SA. Special equipment provides reliable direct connection with the central points of observation.

Pilot operation of the third stage of ARMS lasted until the end of 2014. And today its three monitoring posts (in the cities of Voznesensk and Yuzhnoukrainsk, as well as in the village Alexandrovka) passed the procedure of the state metrological verification, and their data are displayed on the website of South-Ukrainian NPP in the on-line mode.

Ways and means of improving the ARMS at NPPs. The above description of ARMS that are currently in operation at NPPs in Ukraine, shows that these systems are formed, basically, subject to the industry standard of Ukraine [10], and perform their functions. However, it should be noted that the requirements of [10] to form a network of control posts has not been implemented in full scope. So, the used at Ukrainian NPPs ARMS do not provide representative information about the radiation situation in the area of nuclear power plants, because in accordance with [10] ARMS posts are located mainly in the settlements. During normal operation of nuclear power plants, these posts are not able to "detect" deviations from normal plant operation at current levels of releases.

Daily monitoring of releases at NPPs in Ukraine is carried out on three groups of radionuclides: long-lived aerosols (LLA), inert radioactive gases (IRG) and the radioisotopes of iodine (^{131}I, etc.). The average daily value of RNPP releases are at the level of 10^{11} Bq/day for the IRG, 10^{5} Bq/day for LLN, $10^{5}…10^{6}$ Bq/day for ^{131}I; for ZNPP they are 10^{11} Bq/day, $10^{5}…10^{6}$ Bq/day, and $10^{4}…10^{5}$ Bq/day, respectively. As one can see, the IRG releases significantly, on 5 to 7 orders of magnitude, exceed the emissions of LLA and ^{131}I.

Radiation gamma background from NPP releases is caused mainly by IRG (contribution of LLA and iodine radioisotopes is four to six orders of magnitude lower). It is hardly more than 0.2% of the natural background, so it is not possible to observe the fluctuations of background radiation from the plant. Correlation analysis that took into account the wind direction, atmospheric stability category, distance to the plant and other factors did not reveal the influence of NPP [11, 12].

Table 1 shows the calculated dependence of the maximum contribution of techogenic radiation background on the amount of releases of various groups of radionuclides at a distance of 1 km from the nuclear power plant [11, 13]. Estimated value of the background (gamma radiation EDR) corresponds to the releases of each of the separate groups of radionuclides present in the appropriate columns. According to the long-term observations in the area of Rivne and Zaporizhzhya NPPs the background radiation varies in the range ± 3 mR/h (± 30% of the natural background). The contribution to the background radiation at 3 mR/h is possible with a minimum amount of releases of ZNPP: IRG ï $1.7·10^{14}$ Bq/day, LLA ð $3.7·10^{13}$ Bq/day, iodine radioisotopes ï $3.7·10^{13}$ Bq/day; RNPP: IRG ð $3.4·10^{14}$ Bq/day, LLA ð $5.6·10^{13}$ Bq/day, ^{131}I ð $5.5·10^{13}$ Bq/day. Currently, nuclear power plants account for releases of IRG at 10^{11} Bq/day, i.e. by 3-4 orders of magnitude lower than the releases for which the contribution of IRG in the background radiation can be compared with the magnitude of the fluctuations of the natural background radiation, which indicates the inefficiency of the application of ARMS for monitoring of radiation conditions in the area of NPP in normal operation.

Table 1 also shows the values of techogenic background, corresponding to the control levels and the permissible releases of three groups of radionuclides. As it can be seen, the releases of LLA and ^{131}I, comparable in magnitude to the control levels will not be detected, as well as the releases at the level of permissible releases. IRG releases at the permissible level can increase the level of background radiation several times and, therefore, they will be clearly visible in the analysis of the dynamics of the ARMS detectors.

The above analysis of NPP releases indicates that ARMS at NPP will promptly and fairly reflect the radiation situation at the condition that it will be formed by releases with the activity of 10^{13} Bq/day or more. It means that ARMS is an accident alarming system, which should form a constituent part of a full-time system of radiation monitoring of the environment, to be created at the plant in accordance with the design, and operated in accordance with the regulations of the Rules of radiation monitoring of the environment.

For normal radiation conditions the appropriate mode of ARMS operation can only provide monitoring over compliance with sanitary standards for NPP releases.

It should be also noted that network of ARMS posts created at NPP under the requirements of [10] and [14] are "transparent" for radionuclides emitted from NPPs and distributed in the atmosphere. Fig. 2 shows the location of 13 posts of ARMS in the SPZ and SA of Rivne NPP and 14 posts in the SA of Zaporizhzhya NPP. This figure also indicates the probable ground traces of the plume of NPP release under adverse weather conditions, in which the width of the plume is 10°…15°. We can see that in many areas the plum does not cover any post of ARMS. This is a consequence of the fact that at creation of a network of ARMS posts it was ignored the requirement of [10] on taking into consideration the natural features of the environment in the vicinity of NPP location, and in particular, the land topography. This fact does not allow to representatively evaluate the radiation situation in the environment at different operating modes of the NPP, to determine objectively the radiation doses of the population, to reliably predict (based on computer simulations) formation of a possible radiation situation, and to be proactively prepared to make optimal decisions in the event of an accident.

Calculations have shown [15, 16], that the smallest number of detectors (monitoring posts), located in the SPZ and able to record the plume of a release at any wind direction and at worst weather conditions, should be about 22 - 25, and in the SA (taking into consideration the environmental characteristics of the territory) about 100 monitoring posts [17].

None of the Ukrainian nuclear power plants, and eight out of ten Russian NPP do not satisfy this condition, although the results of studies to substantiate their location and number of points (posts) of ARMS, that were carried out in Ukraine and Russia [13, 15, 16, 19-21], indicated the need to consider the above factors.

It will be possible to receive representative and accurate data of measurements and forecasting only on the condition that, along with the demographic characteristics of the monitoring area there will be considered the major environmental and meteorological factors shaping the radiation situation in the vicinity of nuclear power plants [22].

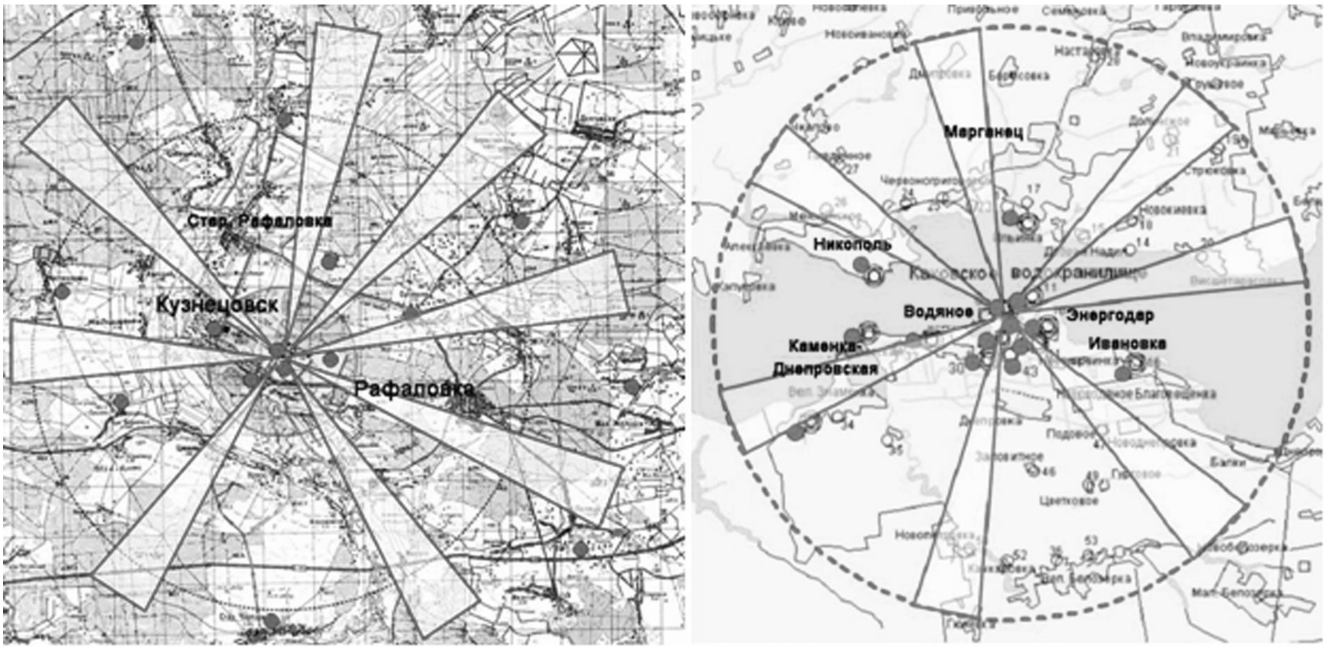
To do this, the network of ARMS posts must be formed on the basis of ecological and hygienic principle, and taking into consideration both the hygienic and ecological approaches to radiation monitoring. This means that for the automated radiation monitoring it should be created a network of monitoring points, which would take into account not only the most adverse weather conditions, and topography, types of landscapes, the contamination density, population size, and other quantifiable characteristics of the land and the source of emission, but also the economic, physical and technical criteria determining the location of detectors and their operating parameters [16, 22].

Table 1. Technogenic radiation background of radionuclide releases from NPP (the data of 2006-2011 years)

EDR (calculated), mR/hr	Strength of release, Bq/day		
	LLN	IRG	^{131}I
RNPP (actual releases)*			
$\approx 10^{-8}$	$2{,}6\cdot10^{5}\ldots4{,}1\cdot10^{5}$		
$10^{-4}\ldots10^{-3}$		$1{,}0\cdot10^{11}\ldots2{,}0\cdot10^{11}$	
$\approx 10^{-8}$			$2{,}4\cdot10^{5}\ldots1{,}2\cdot10^{6}$
RNPP (Control level)			
$\approx 10^{-6}$	$1{,}7\cdot10^{7}$		
$\approx 10^{-2}$		$3{,}1\cdot10^{12}$	
$\approx 10^{-6}$			$1{,}3\cdot10^{8}$
RNPP (permissible releases)			
$\approx 10^{-4}$	$2{,}9\cdot10^{8}$		
≈ 2		$8{,}3\cdot10^{13}$	
$\approx 10^{-4}$			$4{,}2\cdot10^{9}$
ZNPP (actual releases)**			
$10^{-8}\ldots10^{-7}$	$5{,}8\cdot10^{5}\ldots8{,}2\cdot10^{5}$		
$10^{-3}\ldots10^{-2}$		$9{,}0\cdot10^{10}\ldots1{,}5\cdot10^{11}$	
$10^{-8}\ldots10^{-7}$			$2{,}4\cdot10^{5}\ldots8{,}4\cdot10^{5}$
ZNPP (Control level)			
$\approx 10^{-6}$	$2{,}0\cdot10^{7}$		
$\approx 10^{-2}$		$3{,}0\cdot10^{12}$	
$\approx 10^{-5}$			$3{,}0\cdot10^{8}$
ZNPP (permissible releases)			
$\approx 10^{-3}$	$2{,}2\cdot10^{9}$		
≈ 10		$7{,}0\cdot10^{14}$	
$\approx 10^{-3}$			$6{,}0\cdot10^{9}$
EDR and corresponding NPP releases (calculated)			
0,5	$6{,}0\cdot10^{12}$	$3{,}0\cdot10^{13}$	$6{,}0\cdot10^{12}$
1	$1{,}2\cdot10^{13}$	$6{,}0\cdot10^{13}$	$1{,}2\cdot10^{13}$
5	$6{,}0\cdot10^{13}$	$3{,}0\cdot10^{14}$	$6{,}0\cdot10^{13}$
10	$1{,}2\cdot10^{14}$	$6{,}0\cdot10^{14}$	$1{,}2\cdot10^{14}$
15	$1{,}8\cdot10^{14}$	$9{,}0\cdot10^{14}$	$1{,}8\cdot10^{14}$

* ð The average background radiation in the SA of RNPP is 7-15 mR/hr

** ð The average background radiation in the SA of ZNPP is 6-10 mR/hr



a в

Fig. 2. Location of ARMS posts in the surveillance zone of Rivne NPP(a) and Zaporizhzhya NPP (b) and probable ground traces of the plume of NPP releases

Such network should be formed on the basis of monitoring of meteorological data, landscape-geochemical and demographic zoning of the studying territory [18].

For practical implementation at nuclear power plants of the proposed approach it should be developed and implemented a new methodological guide for environmental monitoring around NPPs, which should contain typical methodology of forming a monitoring network, including the network of ARMS posts, and than appropriate changes should be made in the standard regulations of radiation monitoring at NPP [22].

Thus, on the basis of the above, it can be stated that the local level of EGASKRO system in Ukraine has already been formed based on the ARMS around NPPs. Improvement of NPP ARMS in the direction of improving the representativeness and accuracy of measurements of the radiation monitoring can be achieved by integrating environmental principles through the use of radio-ecological monitoring. Such a move would require the revision and development of a new system of methodical support of radiation monitoring of environment around NPP, including the automated one, which will eliminate the existing shortcomings and make it adequate to modern scientific views and trends.

The early warning system for radiation accidents "Gamma". In 1992-1994 as technical assistance to Ukraine from the Commission of the European Communities within the framework of the TACIS program the English firm PA Consulting Group developed a design of the early warning system for radiation accidents "Gamma-1", which was to become a part of the European early warning system. Implementation of the project "Gamma-1" on a competitive basis was contracted to the German company Hormann. The first phase of the project included creation of a network of detectors around the Rivne and Zaporizhzhya NPPs, the regional centers in Rovno (now the city of Rivne) and in Zaporozhye, as well as the national crisis center in Kiev.

In 1997, the system was installed and put into operation (Fig. 3). The center for collecting and processing the information was located in Kyiv on the territory of the Ministry of Environmental Protection and Nuclear Safety of Ukraine [23]. At the end of 1999, the Training Centre (the project "Gamma-2") was opened in Ukrainian Scientific Research Institute for Ecological Problems (UkrSRIEP, Kharkov) for training of operators and managers of "Gamma-1".

After the systems "Gamma-1" and "Gamma-2" were put into operation, the firm Hormann for two years provided support of their operation. In 2000, the Environmental Fund of the Kharkiv region UkrSRIEP allocated funding for the establishment of the Kharkiv regional center of radiation monitoring. In March 2001, this center was established on the basis of the Training Center. There were two gamma-ray detectors and the weather station, with one of these detectors placed in the National Scientific Center "Kharkiv Institute of Physics and Technology" of the National Academy of Sciences of Ukraine.

In 2003, it was decided to send the measurement data that were received by the National Monitoring Centre, located in Kiev, to the Kharkiv UkrSRIEP. In this regard, in the period of 2003-2004 software and computer equipment of systems "Gamma-1" and "Gamma-2" in the regional and national centers was restored and upgraded, and the work of 14 gamma-ray detectors located in regions of Rivne and Zaporozhye NPP was restored as well.

However, there were no financial support for the period from 2005 and up to the end of 2008 funding for carrying out maintenance works on "Gamma-1" and "Gamma-2" systems. In December 2008, only scarce funding was received to perform research work in the framework of which in 2008-2009 the functioning of the monitoring center of Zaporizhzhya, 9 monitoring stations in the Zaporozhye region and 10 stations in the Rivne region was resumed. After this, the funding was terminated.

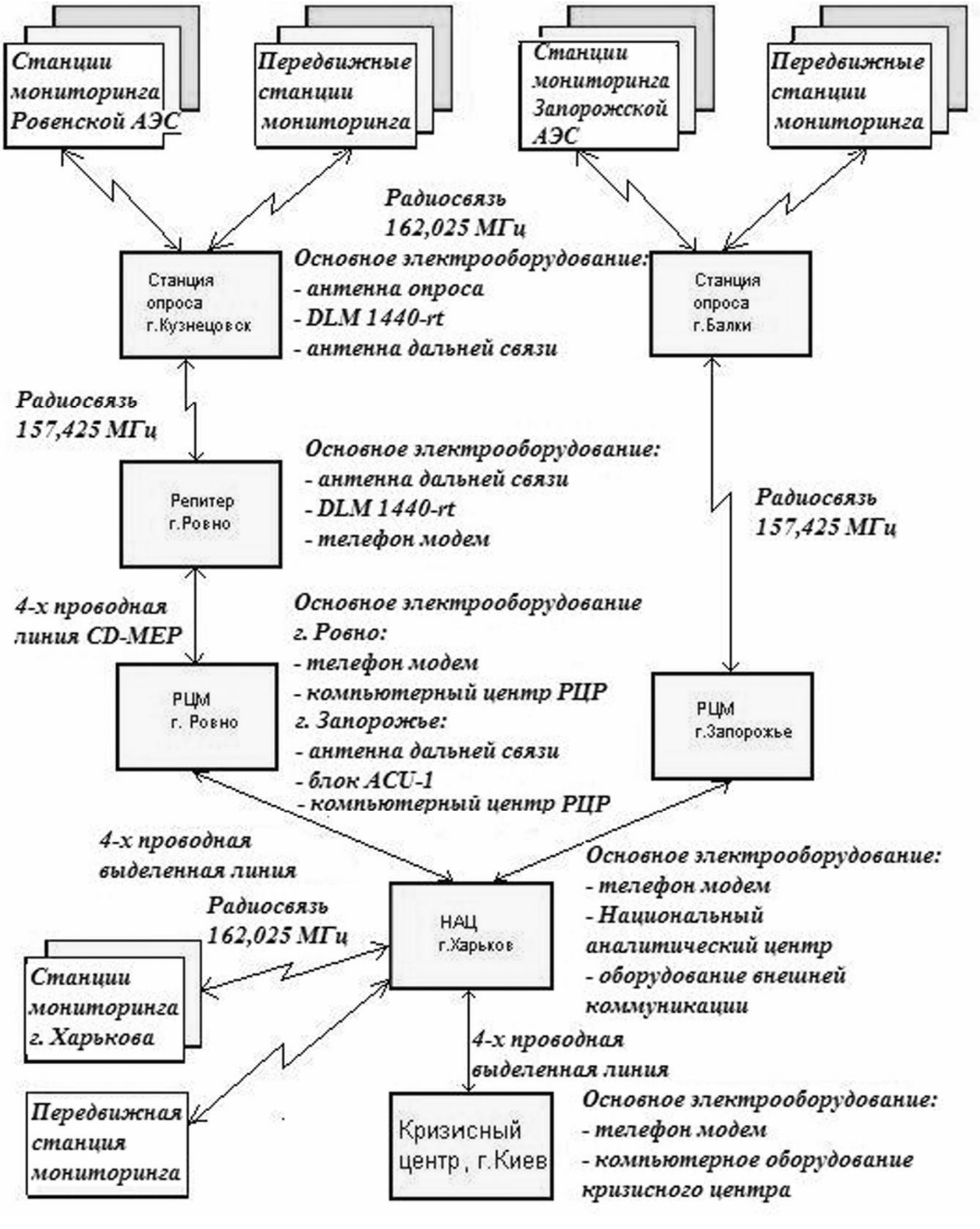


Fig. 3. Scheme of the first stage of the "Gamma-1"

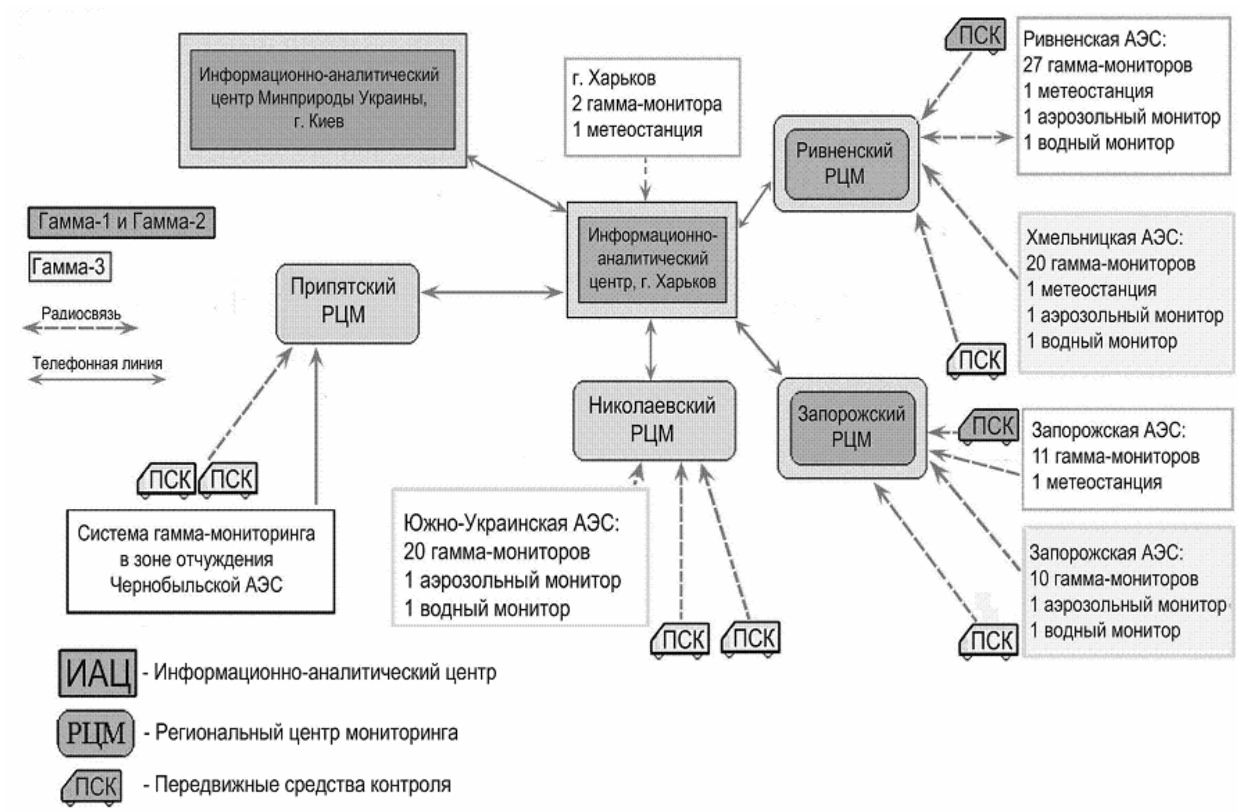


Fig. 4. Scheme of the "Gamma" system after its extension

Unfortunately, since 2009, due to lack of funding the system "Gamma-1" has ceased to exist. Currently the only system in operation is the "Gamma-2" system in Kharkov region.

After the proposed extension (Fig. 4), the "Gamma" system should have covered additionally the Khmelnytsky and South-Ukrainian nuclear power plants, and should have included the system of radiation monitoring of the exclusion zone. But currently, no work is carried out on development of the "Gamma" system in Ukraine.

It should be noted that the established in Ukraine automated system of radiation monitoring and early warning of radiation accidents "Gamma-1" is the unique one because for the first time developers managed to put into practice a number of original ideas, such as the use of instrumentation to measure on-line beta- and alpha-active aerosols in air, and gamma activity of water (the Styr river, RNPP). It was demonstrated that monitoring of the content of beta - and alpha-active aerosols is the most sensitive method of registering changes of background radiation, which allows the operator to notice an emergency at the very initial stage of its development [12]. This is caused by low activity of beta- and alpha-active natural radionuclides in air in aerosol form. Therefore, even a small additional release of these aerosols is registered by the systemôs detectors.

Sensitivity of the system is increased also due to the fact that the contribution of beta - and alpha- active of natural aerosols caused by radon decay products, is subtracted from the measured values of total activity.

The ñGammaò system (ñGamma-1ò + ñGamma-2ò) is designed to cover all hierarchical levels of the EGASKRO and is in fact the first and yet the only step toward establishing a unified Ukrainian country-wide radiation monitoring system. However, despite the fact that the existing basis - methodological (determination of the location and the number of detectors), electronic components (detectors), soft-and hardware, and mathematical one (for data processing, forecasting and modeling of radiation situation) - is obsolete and require revision and updating, taking into consideration current scientific and technical approaches to the creation of systems of radiation monitoring, including the automated ones, the actual experience of its creation and operation deserves careful study and further development.

Formation of the EGASKRO network. The basis for the EGASKRO network is the existing network of ARMS posts related to various organizational and functional levels of the system structure. Such a network should consist of: posts for on-site (local) monitoring the dose of gamma radiation; combined detectors that measure meteorological parameters and determine the state of the atmosphere; process detectors of NPP or other nuclear and radiation hazardous objects for determining the parameters of the release of radionuclides into the atmosphere. Furthermore, the system should contain software of upper and lower levels, the first of which provides processing of the data from detectors for converting them into a specific format (for the use as input data during predictive calculations), and the second, which is based on the computation models of radionuclides transfer in the atmosphere and the aquatic media, as well as mathematical methods for estimating radiation doses to personnel and the public, and providing forecast of radioactive contamination of the environment.

In forming the network of EGASKRO as well as in the case of nuclear power plants ARMS, it is necessary to put into its basis the ecological and hygienic principle, taking into consideration the hygienic and ecological approaches to radiation monitoring.

Conclusions and Proposals

Thus, given that Ukraine has a large number of radiation-hazardous facilities, in order to ensure the radiation safety of the public and the environment, it is extremely necessary to create a united automated system of radiation monitoring that will effectively and reliably evaluate radiological situation at the territory of Ukraine. When designing the radiation monitoring system it is necessary to use in maximal extent the experience of foreign countries, the recommendations of Euratom, domestic experience in creation and operation of the "Gamma" system, ARMS systems operating at nuclear power plants, as well as the results of research carried out in accordance with modern approaches to the methodology of development of radiation monitoring systems.

The above review and analysis of the experience of the organization and operation of the existing in Ukraine automated radiation monitoring systems, allows us to offer, as an option, the following scheme of formation of the automated radiation monitoring stations in the country:

- integration of the monitoring posts into "rings" of different diameters around the radiation-hazardous objects, placing that posts taking into consideration environmental, meteorological and demographic characteristics of the monitored territory;
- the use simultaneously with the stationary automated radiation monitoring of the mobile measuring stations and meteorological stations;
- placement of automated hydrological monitoring posts on the most important water bodies;
- organization of communication of the data acquisition system with a system of notification on the radiation hazards;
- location of the posts on the borders of the state.

In addition, based on the Ukrainian experience in formation and functioning of ARMS at nuclear power plants and the "Gamma" system, we offer the following program of work to create a united automated system of radiation monitoring at the territory of Ukraine.

At the first stage of the program it is suggested:

- to create a Control center for the systemôs operation;
- to clearly separate the functions of scientific and methodological support of the system and technical support and operation;
- to create an Information center (and a web-portal) for collection, storage, and processing of the data, as well as for provision them to the interested organizations and individuals;
- because Ukraine is an observer state of the Council of the Baltic Sea, it is necessary to provide the opportunity to exchange information about the radiation conditions of the environment with other states;
- to convert radiation monitoring posts of Ukrgidrometcentre into automated stations operating on-line;
- to establish an independent network (from the industrial network) of monitoring posts around the radiation-hazardous objects, as well as on the parts of the rivers, where the radiation-hazardous objects are located, and on cross-border areas;
- supplement the system with mobile measuring stations, detectors for different types of ionizing radiation, automated hydrological posts, weather stations, as well as with modern software for forecasting, simulation of emergency situations and taking appropriate countermeasures.

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ESTIMATION OF EQUIVALENT DOSE CAPACITY OF THE COSMIC RAY MESONS AND ELECTRONS IN A MULTI-STOREY BUILDING IN KYIV

This article provides the results of measurements of the directly ionizing component of cosmic rays (mesons and electrons) at the ground level in Kyiv (Ukraine) by NaI(Tl)-detector (20 cm diameter and 12 cm height). To separate the pulse-height spectra of the cosmic charged particles the existing concrete floor slabs of a multi-storey building with a total thickness of 0.4 m and 6.5 m were used. The estimated annual equivalent dose capacity in the air are (197±17) μSv/y and (103±7) μSv/y, respectively.

Key words: cosmic rays, equivalent dose capacity

Nowadays the radiation doses associated with the secondary components of cosmic radiation near the Earth's surface are being reassessed [1, 2]. These experimental studies include determination of flows and energy spectra of directly ionizing particles (electrons and mesons), and particles with indirect ionization (neutrons, and gamma rays). Particular attention is paid to detection and determination of energy of $\pi^{\pm}$- and $\mu^{\pm}$-mesons, which while penetrating the detector through, lose only part of their kinetic energy. Due to this we can record energy response on passage of a fast charged particle, leaving out of detection the kinetic energy of the particle. Such knowledge can give more reliable assessment of the absorbed / equivalent dose capacity in air.

The main objectives of this work are:

- to determine the content of flow of penetrating cosmic particles and energy spectra of its individual components in a multi-storage building depending on the total thickness of floors;
- to assess the absorbed dose capacity in the air for different floors.

When working with NaI (Tl) detectors of (∅ 20 × 12) cm size the authors faced the need to find such a place for the detector, where the natural gamma background radiation would be minimal. It was found that when placing the detector in the basement, the gamma background radiation with energies up to 3 MeV from K-40 and radionuclides of the decay chain of natural uranium and thorium is about twice as much as obtained in open air. In this case, we were questioned by the presence of high-energy background radiation. To determine its energy spectrum, it was necessary to calibrate the spectrometer for the energies higher than 3 MeV. It was decided to use the amplifier with attenuator. That is, by having the spectrometer calibrated at the greatest amplification by two lines ε_1=1,462 MeV(K-40) and ε_2=2,615 MeV (Th-232) and then reducing by the attenuator the amplification in *n* times, we have got the calibration of a new energy scale of energies $n\varepsilon_1$ and $n\varepsilon_2$ in the same channels as the ε_1 and ε_2 lines with the previous larger amplification. Perhaps this way was used for calibration of high-energy cosmic background radiation, for example, in [1]. Such energy calibration helped us define the behavior of high-energy background radiation (Fig. 1), which is a part of the cosmic radiation in Kyiv at altitude of 100-120 meters above the sea level. At the recorded spectra there is a peak in the range of 80-90 MeV, which slopes down to 250 MeV. The position of this peak depends on geometrical dimensions of the detector, which is consistent with data of [1], where in the response spectrum of the NaI(Tl) detector with dimensions (∅ 12,7 × 12,7) cm had a peak in the area of ~ 72 MeV.

Searches were conducted to find such a place for the detector, in which the high-energy background would have the lowest level. It was found that the background was two times lower in the basement of a multi-storey building with the reinforced concrete ceiling of 6.5 m thickness (Fig. 1, 2), than in the one with ceiling of 0.4 m thickness (Fig. 1, 1). The spectra were similar to each other with a difference of energy dependence in the area of 10-40 MeV and slight shift of the peak from 85 MeV (for the thick ceiling) to 90 MeV (for the thinner one). The equipment that was used for determination of the response spectra allowed to record amplitudes greater than 255 MeV. Such events were recorded in a single channel that corresponded to the energy of 256 MeV. A separate study of these responses indicates that the range gradually vanishes almost at 360 MeV.

By observing the passage of lead screens in places of measurement it can be determined which charged particles are recorded. On Fig. 2, *1*, it is shown the passage of 12 mm lead screen with the iron padding of 4 mm thickness, which is placed above the detector in a room with a thin reinforced concrete ceiling. In the basement we used lead screen of 25 mm thickness (Fig. 2, *2*) which fully absorbs electrons with energies <500 MeV. The passage of this screen by ɔ-quanta was calculated for energies of 10, 20, 60 and 100 MeV (Fig. 2, *3*). To reduce statistical error of experimental results the averaging was conducted for each 20 MeV except the first (3 MeV) and the last two (60 MeV and 45 MeV, respectively) points in the spectrum. The behavior of experimental path in two dimensions is the same: in the region of 10-40 MeV the energy dependence of path indicates that secondary electrons, and possibly gamma quanta are present in the flow of cosmic radiation, with greater flow of these particles corresponding the thinner reinforced concrete floor.

The electrons of such energies are mentioned in the book of Heitler [3]. In [2] in this energy region it b was studied electronic flows of cosmic background that are associated with the collapse of ε-mesons. Neutral π^0-mesons have half-lives of $0{,}84 \cdot 10^{-16}$ sec. and are disintegrated mainly in two gamma quanta with energy ~ 65 MeV. The smaller value of passage of lead screens in case of thin reinforced concrete ceiling corresponds to larger flux of gamma rays with such energy. And considering the about twice larger total flux cosmic particles in measurement *1* relatively to measurement *2*, we can expect significant flux of ɔ-quanta with energy of 65 MeV in open air. In the area of responses 100-200 MeV and existing errors penetration of screens is >1, i.e. high-energy particles generate a in a lead screen many new particles (cascade particles) ï this is the commonly known Rossi effect for the lead thickness ~ 10 mm [4].

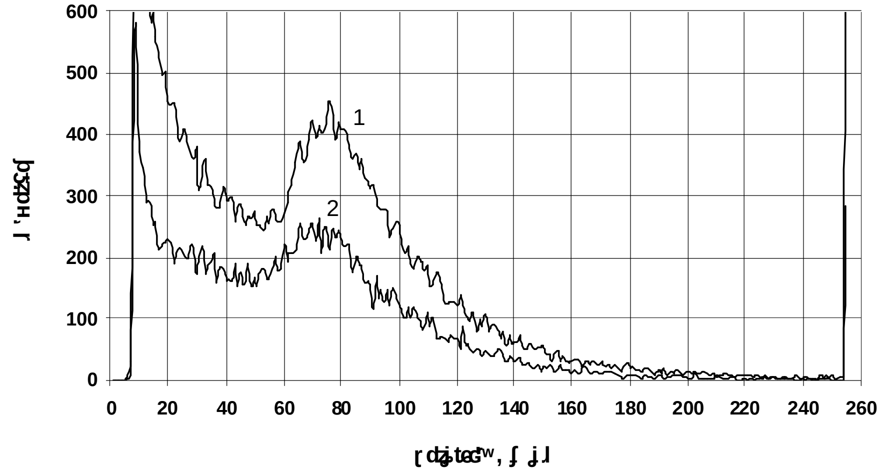

Fig. 1. Response spectra of NaI (Tl) detectors for cosmic radiation in rooms with reinforced concrete ceilings of 0.4 m (1) and 6.5 m (2) thickness. Exposure - 2:00 hours

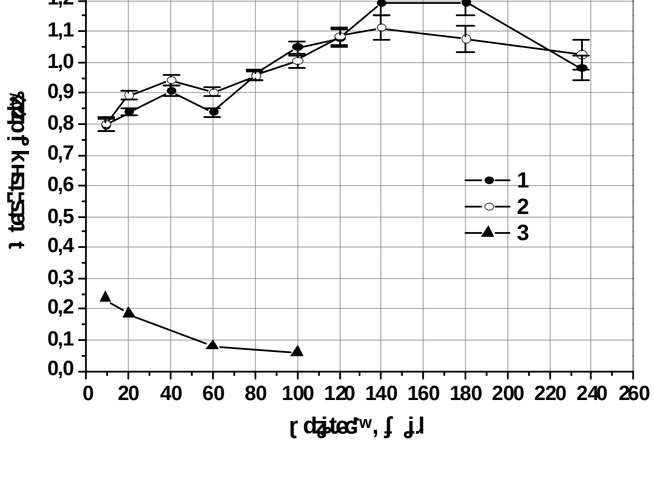

Fig. 2. Experimental curves for cosmic radiation passing through lead screens in the following conditions of measurements:
1 - 12 mm screen Pb + Fe 4 mm in a room with the reinforced concrete ceiling of 0.4 m;
2 - 25 mm Pb screen in a room with the reinforced concrete ceiling of 6.5 m;
3 - Calculation of gamma rays passing through the screen of 25 mm Pb

Table 1. Path and energy for mesons in some substances

ɼ, MeV		5	10	50	100	500	1 000	3 500	35 000	350 000
ε - mesons										
β		0,297	0,407	0,734	0,858	0,984	0,995	1,000	1,000	1,000
βγ		0,311	0,445	1,082	1,670	5,644	10,42	34,11	332,2	3 314
Cu	*dE*/*d*(ρ*x*), MeV·cm^2·g^{-1}	0,0435	0,136	1,896	5,252	36,70	72,82	229,2	1 755	13 090
	R, cm	0,0435	0,136	1,896	5,252	36,70	72,82	229,2	1 755	13 090
NaI(Tl)	*dE*/*d*(ρ*x*), MeV·cm^2·g^{-1}	7,366	4,452	1,715	1,379	1,351	1,484	1,785	2,410	3,807
	R, cm	0,124	0,384	5,209	14,32	98,54	194,3	605,1	4 535	31 740
Air	*dE*/*d*(ρ*x*), MeV·cm^2·g^{-1}	11,47	6,694	2,437	1,921	1,790	1,928	2,249	2,850	3,533
	R, cm	218,6	702,6	1,02·10^4	2,85·10^4	2,05·10^5	4,12·10^5	1,32·10^6	1,05·10^7	8,45·10^7
$K_{ʧtsɘ/NaI}$		1,557	1,504	1,421	1,393	1,325	1,299	1,260	1,183	0,928
$K^*_{ʧtsɘ/NaI}$		1,604	1,547	1,450	1,419	1,359	1,334	1,293	1,228	1,067
´ - mesons										
β		0,261	0,360	0,677	0,813	0,976	0,992	0,999	1,000	1,000
βγ		0,270	0,385	0,919	1,395	4,472	8,103	26,06	251,8	2 509
NaI(Tl)	*dE*/*d*(ρ*x*), MeV·cm^2·g^{-1}	9,053	5,437	1,949	1,479	1,313	1,427	1,717	2,318	3,335
	R, cm	0,101	0,313	4,440	12,73	97,06	196,3	624,0	4 699	34 350
Air	*dE*/*d*(ρ*x*), MeV·cm^2·g^{-1}	14,33	8,281	2,792	2,076	1,755	1,868	2,178	2,790	3,416
	R, cm	174,7	564,4	8,59·10^3	2,52·10^4	2,01·10^5	4,13·10^5	1,36·10^6	1,08·10^7	8,67·10^7
$K_{ʧtsɘ/NaI}$		1,583	1,523	1,433	1,404	1,337	1,309	1,269	1,204	1,024

The decay of $\pi^{\pm}$-mesons generates $\mu^{\pm}$-mesons. If this process occurs near the Earth's surface, the question arises: is it possible to use the response spectra for detecting the presence of flow of $\pi^{\pm}$-mesons that permeate the detector. For this we need to learn how to count the path of $\pi^{\pm}$- and $\mu^{\pm}$-mesons in the detector depending on their energy.

The path of a charged particle (Δ*R*, cm) can be determined by the energy inputs per unit of thickness for each energy *E* in the range of energy input and output [ɼ ɘ꞊, ɼ ɘq꞊] with step Δ*E* :

$$\Delta R = \sum_{E_{\text{âèõ}}}^{E_{\text{âõ}}} \frac{\Delta E}{\rho \left(\frac{dE}{\rho dx} \right)_{\text{NaI}}}, \qquad (1)$$

where Δ*E* - energy interval in which energy inputs are constant, MeV; ρ ð density of detector material, g/cm^3; $\left(\frac{dE}{\rho dx} \right)_{\text{NaI}}$ ð energy inputs of heavy charged particles with kinetic energy ɼ per unit of the material thickness, MeV·cm^2·g^{-1}. If ɼ ɘq꞊=0, than Δ*R*=*R*, where *R* ð full path of a particle with kinetic energy ɼ ɘ꞊.

Assigning different initial values to ɼ ɘ꞊, we will have a set of possible amplitudes of the detector responses for the different charged particles with different input energies.

Energy inputs of charged particles consist of ionization inputs when atoms of a material are ionized, and of radiation inputs associated with radiation of particles. Radiation inputs of heavy charged particles with *E* = 3500 MeV are up to 0.4%, so they can be ignored at lower energies. They become significant and should be taken into account at energies of ~300 000 MeV.

The ionization inputs of heavy particles $\pi^{\pm}$ and $\mu^{\pm}$ can be described by Bethe-Bloch formulae in its contemporary version [5]:

$$\frac{dE}{\rho dx} = 0{,}307 \frac{Z}{A\beta^2} \left(\frac{1}{2} \ln \frac{2 m_e c^2 (\beta\gamma)^2 T_{\max}}{I^2} - \beta^2 - \eta \right), \qquad (2)$$

$$E = m_{\rm m}c^2(\gamma - 1);\ \beta = \frac{v}{c};\ \gamma = \frac{1}{\sqrt{1-\beta^2}};$$

$$T_{\max} = \frac{2m_{\rm e}c^2(\beta\gamma)^2}{1 + 2\gamma\dfrac{m_{\rm e}}{m_{\rm m}} + \left(\dfrac{m_{\rm e}}{m_{\rm m}}\right)^2},$$

where Z, ϕ ð the serial number of the element absorbing material and its atomic number, respectively; $m_{\rm j}$, $m_{\rm m}$ ð mass of the electron and meson, respectively, g; v ð speed of heavy particles cm/s; $\sigma_{\max}$ ð maximum energy that the electron can get in ionization of material MeV; ш≠13.5 Z ð average ionization energy of material-absorbent eV; η ð corrective amendment, which takes into account the process of passage of fast particles through the absorbent material.

By (2) the energy costs were calculated for ´- and ε-seasons in the material of scintillation NaI (Tl) detector and in air (Table. 1). Calculations for copper are given for an attentive reader that can compare our results with at η=0 with the recent estimates presented in [5].

With the ability to calculate the ionization energy costs of the meson with the energy E in the NaI(Tl) detector one can determine the amplitude of responses $E_{\text{ә‘нс}}$ for a certain path $\Delta R_{\rm NaI}$

$$E_{\hat{a}^3\ddot{a}\tilde{a}} = \Delta R_{\rm NaI}\cdot\rho_{\rm NaI}\cdot\left(\frac{dE}{d(\rho x)}\right)_{\rm NaI}. \qquad (3)$$

To calculate responses of the detector we introduced the following restrictions: maximum kinetic energy of mesons $E_{\text{ә}}$ = 3500 MeV; values of paths in the detector $\Delta R_{\rm NaI}$ - 12 cm, 15 cm and 18 cm. At the maximum input energy of the ε-mesons the responses for the specified paths are 60, 80 and 100 MeV, respectively, and further, while reducing the energy input to 500 MeV with the step of 5 MeV the amplitudes of responses decline, reaching 50, 65 and 80 MeV, respectively. For ´-mesons responses are about 5 MeV smaller than for ε-mesons; such a small difference in the responses makes identification impossible.

In the region of responses 50-100 MeV the contributors are $\varepsilon^{\pm}$- and ´$^{\pm}$, which are completely slowed down in the detector or permeate through the detector. The process of slowing ´$^{\pm}$-mesons mostly ends in decay to $\varepsilon^{\pm}$ -mesons with release of energy <30 MeV. And at decay of slowed down $\varepsilon^{\pm}$-mesons to ȷ$^{\pm}$ the energy <100 is released. In the detector response to these threshold values of energy the kinetic energy of mesons that decay is added, and the energy of one (´-meson decay) or two (ε-meson decay) neutrinos is subtracted. That is, we may expect that the energy response of ε-mesons will be close to 100 MeV or even greater.

According to calculations of responses of mesons, penetrating through the detector it is impossible to determine their input kinetic energy. Existence of responses with energies 100-250 MeV is likely related to the registration of high-energy particles ($E_{\text{ә}}$>3 500 MeV) when their radiation losses become noticeable, and nuclear disintegration products ("Stars") at interaction with these particles.

Preliminary data concerning the processes of registration of fast charged particles in NaI (Tl) detectors and calculations of energy inputs for mesons are given for evaluation of the dose rate of cosmic radiation in air. Energy of mesons that were absorbed by the NaI (Tl) detector, causes the equivalent dose rate of the detector (Ì ÅÄ$_{\rm NaI}$, Sv/h), and is calculated as simple sum of products $E_{\text{ә‘нс}}\cdot N(E_{\text{ә‘нс}})$ across the whole response spectrum.

$$\grave{I}\,\text{ÅÄ}_{\rm NaI} = \frac{k}{Mt}\cdot\sum_{\hat{A}_{\rm ç}}^{\hat{A}_{\rm \hat{e}}} E_{\hat{a}^3\ddot{a}\tilde{a}}\cdot N(E_{\hat{a}^3\ddot{a}\tilde{a}}), \qquad (4)$$

where k=1,6·10^{-13} J/MeV; M ð mass of the detector, kg; t ð the exposure time, hours; $N(E_{\text{ә‘нс}})$ ð he number of responses in the channel with the energy E; $E_{\text{ç}}$, $E_{\text{ê}}$ ð initial and final energy of the response spectra, respectively, MeV.

Difficulties arise when converting Ì ÅÄ$_{\rm NaI}$ into equivalent dose rate, for example, in air (Ì ÅÄ$_{\text{ïîâ}}$, Sv). The authors [1] use such converting, which in our notation has the form:

$$\text{ɿ ʅ ʃ}_{\text{ïîâ}} = \frac{k}{Mt} \cdot \sum_{\text{Å}_{\text{ʧ}}}^{\text{Å}_{\text{ç}}} K_{\text{ïîâ/NaI}} \cdot E_{\text{â³äã}} \cdot N(E_{\text{â³äã}})\,; \tag{5}$$

$$K_{\text{ʧʦʚ/NaI}} = \frac{\left(\dfrac{dE}{d(\rho x)}\right)_{\text{ʧʦʚ}}}{\left(\dfrac{dE}{d(\rho x)}\right)_{\text{NaI}}}, \tag{6}$$

where $(dE/d(\rho x))_{\text{ʧʦʚ}}$ and $(dE/d(\rho x))_{\text{NaI}}$ ð the mass stopping power for the response ʅ ɘ'ʜɢ in air and NaI, respectively MeV·cm^2·g^{-1}.

where $(dE/d(\rho x))_{\text{ʧʦʚ}}$ and $(dE/d(\rho x))_{\text{Na}}$ - stopping forces (the mass stopping power) for the response ʅ ɘ'ʜɢ in the air and NaI, respectively MeV·cm^2·g^{-1}.

We calculated $K_{\text{ʧʦʚ/NaI}}$ by (6) for a wide range of energy of mesons (Table 1) and compared the obtained values with the $K^{*}_{\text{ʧʦʚ/NaI}}$ value for the full power inputs, which was calculated using (3):

$$K^{*}_{\text{ʧʦʚ/NaI}} = \frac{R_{\text{NaI}} \cdot \rho_{\text{NaI}}}{R_{\text{ïîâ}} \cdot \rho_{\text{ïîâ}}}, \tag{7}$$

where R_{NaI} and $R_{\text{ʧʦʚ}}$ ð full path of the meson with energy E in NaI and in air, respectively, cm. In the range of kinetic energies of 5ð 35 000 MeV the values $K_{\text{ʧʦʚ/NaI}}$ and $K^{*}_{\text{ʧʦʚ/NaI}}$ differ by not more than 4%.

Since ε- and ´-mesons vary within 2-3%, ɿ ʅ ʃ ʧʦʚ was calculated only for ε-mesons. Additionally we should emphasize that (4) is used in [1] for mesons with energies <120 MeV which are completely absorbed by the detector with maximum diagonal of 18 cm. The above consideration of the processes in the detector indicates that it register the mesons, which lose only part of their kinetic energy. Since the energy of mesons is known, we should take into account in $K_{\text{ʧʦʚ/NaI}}$ the energy inputs of mesons in the detector with responses greater than 150 MeV.

To calculate the contribution to EDR of the detector responses with energies >255 MeV the average value ʅ ɘ'ʜɢ=300 MeV was used. The used NaI (Tl) detector has a maximum diagonal of 23 cm, so the observed maximum response gives by (3) an evaluation of $(dE/d(\rho x))_{\text{NaI}}$=3,55 MeV·cm^2·g^{-1}, which in terms of (2) corresponds to registration of mesons with energies 270 000ð 280 000 MeV.

Thus, evaluation of the equivalent dose rate in air is associated with determination of the type of charged particles and with energy spectrum of registration of responses in the range 8 ï 360 MeV, considering peculiarities of $K_{\text{ʧʦʚ/NaI}}$ behavior due to the registration of electrons and/or ɔ-quanta. Registration of ɔ-quanta indicates the emerging in the detector of electrons or electron-positron pairs. In this regard, the relationships (6) or (7) took into account the contribution of energy inputs of electrons. By the share of cosmic rays that penetrate a lead screen (Fig. 2) we can estimate the relative contribution of gamma quanta, electrons and mesons. But this approach is not entirely justified, because we donôt count cross section of ɔ-quanta interaction with the material.

The absolute error of calculation by ɿ ʅ ʃ ʧʦʚ (5) was determined as:

$$\Delta \text{ÏÅÄ}_{\text{ʧʦʚ}} = \frac{k}{Mt} \cdot \sqrt{\sum_{\text{Å}_{\text{ʧ}}}^{\text{Å}_{\text{ç}}} \left(K_{\text{ʧʦʚ/NaI}} \cdot E_{\text{â³äã}} \cdot N(E_{\text{â³äã}})\right)^2 \cdot \left(\delta E_{\text{â³äã}}{}^2 + \delta K^2_{\text{ʧʦʚ/NaI}} + \left(\frac{1}{\sqrt{N(E_{\text{â³äã}})}}\right)^2\right)}, \tag{8}$$

where $\delta E_{\text{ɘ'ʜɢ}}$, $\delta K_{\text{ʧʦʚ/NaI}}$ ð relative error of determination and energy response $K_{\text{ʧʦʚ/N}}$, respectively.

Calculations of ɿ ʅ ʃ ʧʦʚ were carried out for thin and thick reinforced concrete ceilings in the following ranges of the energy spectrum:

1) 8-50 MeV ï presence of electrons and ɔ-quanta is possible (contribution for measuring 1 is 16%, and for measuring 2 - 10%), consideration of which leads to a reduction of $K_{\text{ʧʦʚ/NaI}}$ on 7% (measurement

1) and 6% (measurement 2); $\delta K_{\text{ʧʦɚ/NaI}}$=0.1, $\delta E_{\text{ɘʻʜɢ}}$=0.03;

2) 51-70 MeV ïɔ-quanta from the decay of ´^{0}-mesons are present (measurement 1 - 16%, measurement 2 - 10%), $K_{\text{ʧʦɚ/NaI}}$ is reduced by 9% and 7%, respectively; $\delta K_{\text{ʧʦɚ/NaI}}$=0.1, $\delta E_{\text{ɘʻʜɢ}}$=0.03;

3) 71-150 MeV - presence of electrons from the decay of ε-mesons is possible, $K_{\text{ʧʦɚ/NaI}}$ is reduced by 10%; $\delta K_{\text{ʧʦɚ/NaI}}$=0.1, $\delta E_{\text{ɘʻʜɢ}}$=0.03;

4) 151-255 MeV - contribution of mesons with energies of >3 500 MeV which are absorbed partially in the detector; $\delta K_{\text{ʧʦɚ/NaI}}$=0.15, $\delta E_{\text{ɘʻʜɢ}}$=0.03;

5) 255 MeV - contribution mesons with energies >200 000 MeV; $\delta K_{\text{ʧʦɚ/NaI}}$=0.15, $\delta E_{\text{ɘʻʜɢ}}$=0.1.

For the response spectrum of mesons with taking into account 6.5-meter reinforced concrete ceiling ɟ ʈ ʈ $_{\text{ʧʦɚ}}$=(103±7) mSv/year, and for the 0.4-meter one - ɟ ʈ ʈ $_{\text{ʧʦɚ}}$=(197±17) mSv/year. The latter value is smaller than the value stated in [1] ɟ ʈ ʈ $_{\text{ʧʦɚ}}$=(274±5) mSv/year, as different energy ranges were used and conditions of the measurements were different as well.

This work provides further study of cosmic background in the city of Kiev.

Conclusions

1. Concrete ceiling of a multistory building reduce the flow of mesons and almost completely absorbed photon and electron components of cosmic rays.

2. We detected γ-quanta with energies of ~65 MeV from decay of π^0-mesons, and electrons with energies <40 MeV from the decay of $\varepsilon^{\pm}$ mesons. Availability of π^0-mesons in the places of the experiments indirectly points to the possibility of formation of $\pi^{\pm}$-mesons

3. Responses of the detector with energies >255 MeV can be explained by the presence of mesons with energies >200 000 MeV.

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PRINCIPLES OF CHOICE OF COUNTER-MEASURES FOR DIFFERENT TYPES OF ECOSYSTEMS

This article reviews the authorsô and the published data on the problem of ecosystems decontamination. It is shown that countermeasures are effective in places with the greatest radiological capacity of ecosystems, especially those measures, which can increase the values of radiological capacity factors of ecosystems or their components. The number of possible effects of contaminants on the biosphere and the effects of protective measures was analyzed and a system was proposed of rehabilitation of contaminated territories and mainly the soil.

Keywords: ecosystem, the radiological capacity, contamination, decontamination, protective measures (countermeasures)

The history of accidents at nuclear plants counts a lot planned and implemented protective measures (PM) that can be used with at different effectiveness to eliminate the accidents consequences [1]. Various PM were implemented in the run of the Chernobyl accident and during elimination of its consequences. The main objectives that underlie the PM selection are: decontamination of ecosystems; reduction of individual doses for workers and the public; reduction of collective doses to the population, defined by a special reduction factor [2, 3]. However there are almost no assessments of the impact of PM on the ecosystems. A number of implemented protective measures (counter-measures), such as the burial of so called "Rust-colored Forest[1]", mechanical removal of the upper layer of radionuclide contaminated soil (by bulldozers, scrapers, graders), led to the complete destruction of soil and forest ecosystems, which are then required to be fixed and recreated.

It seems important and necessary to carry out the analysis and classification of the main PM-based theories and models of radiological capacity to assess how protective measures affect the parameters of radiological capacity of ecosystems and determine the optimum scheme of their application.

Protective measures in different ecosystems. We begin our consideration with a broad range of protective measures applied in ***agro-ecosystems***. Table 1 shows the list of the main PM in agricultural production and assess their impact on: decontamination coefficient $K_{н}$ (defined as the ratio of the level of contamination prior to application of PM to its value after the application); dose reduction coefficient $K_{fђ}$ (defined as the ratio of the radiation dose before the application of PM to its value after such application); the value of ecosystem radiological capacity factor F (which determines the amount of radionuclides accumulated in the ecosystem [1])

Assessing the PM by the example of their implementation in the Milyachi village of Dubrovytsky district, Rivne region, one can see (Table 1) that their effectiveness varies. Some of them (for example, fixing the soil surface, removal of top soil layer) only affect on the individual dose reduction. The collective dose is reduced by the radioactive decay only. Other PM can also significantly reduce the collective dose (by decreasing the $K_{fђ}$).

It should be emphasized that as a rule, PM that are widely used in agriculture do not change (at least, do not degrade) the quality of agro-ecosystems, and thus do not affect the value of their radiation capacity factor (Table 1). The exception is the use of the Turf-Cutter, a special machine for turf removing (3-5 cm of the surface layer). In this case a part of the fertile layer is lost, which causes some decrease in radiological capacity factor (F = 0.9) of agro-ecosystems. It is especially dangerous to the ecosystem to mechanically remove fertile layer (10-15 cm) with a bulldozer or other heavy equipment. For the conditions of Polissya it means outcrop of sand and almost total loss of ecosystem biota by soil of fertile layer (F = 0.05). Moreover, after outcrop of sand at the Chernobyl site special countermeasures had been required for consolidation of soil, dust suppression and re-vegetation.

Phytodecontamination (FD) is a method of decontamination of contaminated soils using plants. Application of PD has been discussed in the first studies on radioecology of plants [4]. At the same time, the problem of PD of soil from ^{137}Cs and other radionuclides of the Chernobyl release requires deep research and development. We have been actively engaged in the problems of PD of soils from ^{137}Cs and other radionuclides since the 1986 Chernobyl accident [5]. Now is the time to review these experimental laboratory and field studies conducted by us on the Chernobyl precipitations of radionuclides in soils of Ukrainian Polissya, and in particular, on our

[1] The forest killed by accidental release of radiation from the Chernobyl

radioecological test site "Buryakivka" in the 5-km zone of Chernobyl NPP, on which phyto-decontamination of contaminated soils was implemented.

It is important to emphasize that the basic paradigm of the before-Chernobyl agricultural radiology was to minimize the "removal" of radionuclides by plants with the purpose to reduce the radiation dose to the population. This is the basis of the current agricultural practices in the contaminated areas. On the contrary, we examined all the factors and possibilities of maximizing the "removal" of radionuclides with a specific purpose – phytodecontamination of contaminated soil of Ukraine. Referring to the basic formula, which determines the ratio of "removal" of radionuclides by plants ($K_э$, shares) [3]:

$$K_э = \frac{C_п \cdot K_н \cdot B}{A},$$

where $C_п$ - concentration of radionuclides in the soil, Bq/kg; $K_н$ – the coefficient of radionuclide accumulation by plants, shares; B - crop of plants biomass per unit area in kg/m^2; A – the value of the accumulated radionuclides per unit area, Bq/m^2.

It's obvious, that the ability to control the performance of PD is contained in three parameters – $K_н$, B and A.

Change of the value of accumulated radionuclides A in the soil without the use of plants is only possible by mechanical methods of decontamination: the use of bulldozers, scrapers, graders, etc. Those methods were used during the liquidation of the Chernobyl disaster consequences; however, they also led to the loss of topsoil. Mechanical removal of the top layer of soil contaminated with radionuclides (10-15 cm) in Polesie on sandy podzolic soils has led to almost complete loss of fertility and outcrop of alluvial sands. It is clear that beyond the borders of the NPP site this method is not suitable for agricultural lands of Ukraine. We have shown [3] that for the turf-covered plots the optimal method of decontamination is the removal of turf using the Turf Cutter – a machine for undercutting the most contaminated with radionuclides (90%) upper layer of soil. But this method is highly effective only on the unplowed lands.

Table 1. General characteristics of the implemented PM (Milyachi village, Dubrovitsky district, Rivne region, 1988-1993.)

In the collective farms

Protective measures	Area hectares	Amount of applying, tons	$K_н$	F
Deep plowing	990	–	1,5–2,0	1
Applying high amounts of fertilities	720	360	2,0–2,5	1
Liming the soil	420	1260	1,5–2,5	1
Improving of pastures (replacement of wild grasses by crops of grass stands)	250	75	2,5–3,0	1
Applying manure and sapropel	440	13200	1,7–1,9	1

In the private farms

Protective measures	Area, hectares	Number of cattle	Amount of applying, tons	$K_н$	F
Using bolus	–	80	240 items.	2,2–2,8	1
Adding humolites to feed cattle	–	150	45 kg	1,5–1,9	1
Adding ferrocene to feed cattle	–	50	7 kg	2,0–3,0	1
The use of Turf-Cutter on pastures	0,5	3		18–20	0,9

It is the PD method that can be the most effective one for decontamination of the lands plowed after the ChNPP accident in Ukraine and Belarus. If it is difficult to influence on the amount of accumulation *A*, one can and should affect on the form of radionuclides in the soil. According to our research, the most effective way is to increase the share of bio-available forms of radionuclides in the soil solution. The real methods of influence on increasing the bioavailability of ^{137}Cs according to the results of our research are: irrigation of soils (increasing its humidity); applying necessary microbiota on the soil for transformation of fixed forms of radionuclides into bioavailable forms, for example, applying silicate bacteria [1, 2, 6]; and the use of optimal crop of plants- predecessors.

There was limited use of large-scale protective measures in ***forest ecosystems*** in Ukraine [2]. Among the large-scale PM one can mention the complex procedure of burial of the "Rust-colored Forest". It is obvious that this procedure has led to almost complete destruction of the forest ecosystem, and the factor of its radiological capacity has dropped to almost zero.

Burial of that radioactive forest under the layer of sand has led to reduction in external exposure dose of personnel engaged in emergency response, but it has created a dangerous long-term source of radionuclide contamination of soil and groundwater, and thus only "delayed" in time the solution of hard radioecological problem.

There were discussed also other PM for forest ecosystems, for example, mechanical removal of litter, containing in case of forest ecosystems up to 90% of the radioactivity. It is known that complete removal of litter leads to withering and eventually to death of the forest (*F* = 0). In practice, this PM can only be used for the preparation of the forest to the full cutting down.

PM in ***aquatic ecosystems*** have been implemented only in a very small part [2, 3]. After the accident, the Kiev dam reservoir almost turned into a sedimentation pond of Chernobyl NPP, with *F* = 0,8 and bottom sediments containing up to 10^{-5} Ci/kg of radionuclides. According to our estimates at a given level of radionuclide contamination there exists a real threat to the welfare of the benthic biota of the reservoir, where environmentally acceptable levels of radionuclide release and accumulation are exceeded. Among the implemented PM for this water body we can mark out an attempt to "cut" special "bottom traps" across the reservoir. It was shown that those traps were not effective [2]. This is understandable, because the implementation of these measures cannot increase the radiological capacity factor of bottom sediments, because the active thickness of sludge and the rate of accumulation of radionuclides **ȿ** dz by silts are not changed.

Analysis of the effectiveness of protective measures. Most part of the Chernobyl release precipitated on the terrestrial continental ecosystems. Therefore, the most part of protective measures was implemented on terrestrial ecosystems, particularly in the 30-kilometer zone of the Chernobyl NPP. Low effectiveness of hundreds of filter dams built in the 10-kilometer zone of ChernobylNPP is caused by the fact that the head of water created by the dams, decreases the soil radiological capacity factor (*F* = 0,9), and thus reduces the situation to the case of radiological capacity of sediments (*F* = 0,7) . So, essential part of radionuclides from the soil dissolves and enters the aqueous phase, and the filter capacity of the body of the dam is too low to trap noticeable amount of radionuclides from the surface water flow. It is found that radiological capacity factor of such filter dams does not exceed *F* = 0.1.

We have developed a model for evaluation of radiological capacity of a system containing a cascade of reservoirs [2] that allow us to suggest creating a cascade of ponds as a highly effective PM. It is proposed to block the surface water flow / stream with a cascade of three small retaining dams (the dams are low, overflow-type, and after filling the upper pond water flows into the lower one, and then in the third pond). Upon reaching the slow speed of water flow in the system the radiological capacity factor of each of the ponds does not exceed 0.5-0.6. At the same time, according to the model, radiological capacity of the cascade will be 0.8-0.9. If you apply highly active sludge in these ponds, you can increase radiological capacity of the cascade to 0.99. Such a system can be created in advance at the hazardous areas or quickly constructed in a short time.

Letȏs consider another example of a typical continental ecosystems ï a slope ecosystem. Our research at the test site "Novoselki" on the slope ecosystem on the bank of the river Uzh: "forest- forest edge - terrace - river" clearly showed that ^{137}Cs was concentrated on the edge of the terrace. This phenomenon can be used as the basis for real PM. We mean, creating on the path of the most intense runoff (and concentration) of radionuclides of a special highly productive (by biomass and removal of radionuclides) terraces in the soil of which one can "trap" and then concentrate in abundant biomass (using PD) quite a big amount of "flowing" radionuclides. Calculation of the dynamics of redistribution of radionuclides in a typical slope ecosystem shows the ability to create highly productive terraces concentrating more than 60-70% of the flow of radionuclides, and thereby to protect rivers and ponds against excessive discharge of radionuclides. Model calculations of radiological capacity of such slope ecosystem has enabled us to confirm feasibility and effectiveness of the proposed new PM [3].

It should be emphasized that no PM for effective decontamination of forests has not been developed yet. In fact, high radiological capacity of the forest ecosystems (*F*=0,90…0,97) means that it is difficult to decontaminate the territory without destruction of the forest ecosystem (an example is burial of the ñRust-colored Forestò). Therefore the most environmentally acceptable way of a forest decontamination is a system of ñentrapmentò of radionuclides which are removed from the forest by the surface runoff. A typical situation is when radionuclides from the forest ecosystem are being discharged into a stream or a small river flowing through the forest or out of it. In this case, as it was shown by our calculations on radiological capacity models, the optimal solution would be creation on in the path of maximum surface runoff of radionuclides of small ponds. This allows one to ñconcentrateò the radionuclides in the bottom sediments of these ponds.

Depending on the specific situation one may create a strategy and an optimal algorithm for the use of various methods of decontamination of contaminated areas of lands in the 30-kilometer exclusion zone of Chernobyl NPP. The best way would be to use this system of PM in places of concentration of radionuclides in bio-landscapes of the Chernobyl zone. Our estimates and theoretical calculations of radiological capacity of individual ecosystem elements make it possible to determine zones and areas of concentration of radionuclides, at which can be optimally used the proposed PM on decontamination of soil, and to solve strategic tasks of radiological capacity control at the large ecosystem - the Chernobyl exclusion zone [5].

The strategy for the use of PM at landscapes can include two main ways. The first way is to determine the areas of accumulation of radionuclides in the landscape and to use PM exactly in those areas where high values of radiological capacity factors are detected. The second possible way is to form landscapes using landscape management measures so as to increase radiological capacity in convenient parts of the landscape where it is possible to bury radionuclides for a long time or effectively use PM. Such elements of the landscape can be ravines, swamps, and so on. The results of our comparative analysis of the effectiveness of various PM in agro-ecosystems are shown in Table 3.

Table 3. Effectiveness of various protective measures in agro-ecosystems

PM	ȿ fŋɖʃʤн	ȿ fŋʢʦʣ	Time of implementation. years
Soil solidification (fixing)	1,2	1,2	1
Removing turf with Turf-Cutter	20	20	1
Removal of the surface layer of soil: with plow, bulldozers, scrapers	6ð 8	2	1
Deep plowing	2ð 3	1	1
Changing the type of farming (from dairy husbandry to animal husbandry)	2ð 3	1	1
Applying of increased doses of fertilizers	2ð 3	1	1
Phytodecontamination	3ð 5	3ð 5	4ð 5
Liming of acid soils	1,5 - 2,5	1	1ð 3
Improving of pastures	2,5 - 3,0	1	3ð 5
Applying manure and sapropel	1,7 - 1,9	1	1ð 3
Using bolus	2,2 - 2,8	2	Still applied
Adding humolites to feed cattle	1,5 - 1.9	2	Still applied
Adding ferrocene to feed cattle	2ð 3	2ð 3	Still applied
Use of ferrocene filters for milk decontamination	5ð 10	5ð 10	Still applied
Foliar application of soluble fertilizers for	1,5	1	2ð 3

growing of crops (such as corn)			

From Table 3 one can see that traditional methods for decontamination of contaminated areas are effective in reducing individual doses of irradiation of people using these areas, and do not affect the value of the collective dose. This is because the mixing of radionuclides during plowing and reduction of coming radionuclides into plants have little effect on long-term total removal of radionuclides by the plants, and so as on the value of the collective dose. In fact, we have time-extended consumption by the public of radionuclides contained in the food.

If you focus on reducing the collective dose to the population of certain regions of Ukraine, there is no doubt in the advantage of such methods as PD and mechanical decontamination of soil by removal of a thin layer of turf (using Turf-Cutter). Despite the low-developed technology of these methods, they can be the basis for the formation of an optimal system of methods and means of decontamination of contaminated areas. The method of mechanical decontamination by Turf-Cutter can be especially successful at the lands that have not be plowed after the Chernobyl accident. In this case, according to our estimates, the consistent application of the method of removing a thin layer of turf and phytodecontamination will make it possible in 4-5 years to 60-100 times reduce the value of the collective dose of the population that work on these lands.

Table. 4 shows the generalized data of the Ministry of Emergencies of Ukraine on the scope of the effective use of such PM as improved grassland in Ukraine specified by years.

The PM implemented on aquatic ecosystems during the liquidation of the Chernobyl accident were analyzed by us according to the criteria of their effect on radiological capacity of the ecosystems (Table 5).

The overall decline in the collective dose due to application of these PM for the Ukrainian population we estimated as 11 million man-rem. In this case the better is the use of high radiological capacity aquatic ecosystems, in particular sediment reservoirs, the higher is the effectiveness of PM. The general principle of selecting the best PM for aquatic ecosystems is that the planned PM should increase the factor of radiological capacity of aquatic ecosystems, and thereby retain the proceeds of radionuclides intake by humans.

Typical elements of the ecosystem, forming radionuclides runoff in the in river Dnipro are slope ecosystems of consequent type and landscape ecosystems of parallel type. In the ecosystems of the consequent-type the discharge of radionuclides occurs element-by-element from one into another part of the landscape. An example of the parallel system is a watercourse (a river or stream), in which the radionuclides are dicharged independently. In real landscapes more complex combination options are realized.

Analysis of radiological capacity of a landscape should begin with classification of the territory and the allocation of places (or zones) of concentration of radionuclides, where different PM would be realized in the best way. Evaluation of quantities of radiological capacity for all major components can be made by taking into account the probability of retention of radionuclides in these elements of the landscape.

Application of GIS technology [7] made it possible to determine in the Chernobyl NPP exclusion zone the areas, where the accumulation of radionuclides takes place. This study has allowed to allocate in the exclusion zone the ecosystems and their components, which can be optimally used specific PM for the remediation. It is case it is possible to minimize the amount of PM application (for example, the use of Turf-Cutter technology) and their environmental consequences.

The general conclusion that can be made is that PM are effective in places with the greatest radiological capacity of ecosystems, especially those PM, which may increase the value of the factors of radiological capacity of ecosystems or their elements.

Possible version of the optimal system of PM. On the basis of our assessments a universal algorithm has been developed for the decontamination of soils contaminated with radionuclides. The algorithm is suitable for the use on the territory of Ukraine in the zone of the Chernobyl disaster and other accidents at nuclear facilities

If the land is well turfed, than the optimal way is to use the machine of Turf Cutter type to remove the top layer of contaminated soil (turf) of 2…5 cm thick. It is known that almost 90…97 % of radionuclide contamination even after 20-30 years after the accident is concentrated in the top 5-cm layer of soil. In this case one can achieve high $K_н$ ї up to 20…60 units. If the soil that require decontamination, is sandy and bad-turfed, the pre-turfing may be applied on it. Our experiments on the test site "Buryakivka" have shown that the use of special water-retaining screens and effective herb mixtures allows one to generate in 2-3 years sufficiently thick turf, even on sandy soil. This artificially turf-covered soil can then be successfully decontaminated by a mechanical method using the Turf Cutter technology.

Table 4. Use of PM for the improvement of pastures and meadows in Ukraine (the level of contamination of soil ^{137}Cs ð 5…15 Ci/km^2)

Years	Area, thousands hectares	Reduction of collective dose, thousand man-rem	Cost of work, thousand USD	ñBenefitò, thousand USD	ñCostð Benefitò, thousand USD
1986	0	0	0	0	0
1987	2,0	16	52	640	588
1988	5,5	44	143	1760	1617
1989	11,3	90	294	3600	3306
1990	53,8	430	1399	17200	15800
1991	126,9	1015	3299	40600	37300
1992	177,2	1418	3299	56720	53420
1993	62,3	498	1620	19920	18300
TOTAL	439,0	3511	11414	28096	1273000

Table 5. Protective measures implemented on aquatic ecosystems

Protective measures	Effectiveness[1] (on the value of decrease in the collective dose, thousand man-rem)	The impact on the ecosystemôs radiological capacity factor.
Adjusting the Dnieper cascade of reservoirs in spring and autumn of 1987	effective (32)	It maintains high radiological capacity by slowing the flow of radionuclides (F=0,8…0,9)
Creation of cross-type pit traps along the bed of the Kiev storage reservoir	Not effective	(F=0,7) no effect on the radiological capacity factor (F = 0,7)
Retaining wall in the ground to protect the river Pripyat from the drainage flow of radionuclides from Chernobyl cooling pond	Sufficiently effective	Improves radiological capacity factor (F=0,8)
The construction of a protective dam on the Krasnyanskaya floodplain of the river Pripyat	Highly effective (500)	Improves radiological capacity by establishing a regime of dam
Creation of additional water purification system for drinking water sources for the city of Kiev	Highly effective (for the city of Kiev in 1986 ð 10 300)	Improves radiological capacity by retaining radionuclides in water purification facilities
Rejection of irrigation from the Dnieper cascade	Sufficiently effective (200)	Increasing the time for deposition of radionuclides in bottom sediments of the cascade

[1] Having an expected effect

The second version of the algorithm for effective decontamination of soils was developed by us for soils that were plowed after the accident. In this case, radionuclide contamination after plowing may be uniformly distributed in the soil 20 cm deep or deeper. In this case, the most effective method is to use the PD. This method is described above in details. It is shown that the optimal crop rotation system of plants with high concentration factors of radionuclides ($K_{[illegible]}$ ð 2…10 units) and with significant yields of biomass (4…8 kg/m^2) for 4-5 years allows one to significantly reduce the level of radioactive contamination of soils (up to 5 times on ^{137}Cs) [3].

Thus, on the basis of two main methods of decontamination - mechanical decontamination using the Turf Cutter technology and the Phytodecontamination method one can build an optimal algorithm for decontamination of contaminated soil in Ukraine and in other countries.

Conclusion

The most interesting, on our opinion, regarding the scope of application and the possibilities to reduce not only the individual but also the collective doses are the Turf-Cutter method of mechanical removal of turf (0-5 cm of soil layer) for the soils that have not been plowed after the accident, and the PD method for plowed soils in combination with other techniques and methods described in Table 3.

The principles, methods and approaches suggested above are suitable for a wide variety of ecosystems (inland water) and for different types of contamination (radionuclide, chemical and biological).

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METHODOLOGICAL BASIS FOR QUALIFICATION OF THE MAIN STEAM ISOLATION VALVE IN THE BEYOND DESIGN BASIS ACCIDENT CONDITIONS OF OUTFLOW OF STEAM-WATER MIXTURE

The work presents the computational and empirical methods and performance criteria for qualification of the main steam isolation valve (MSIV) in accident scenarios with outflow of steam-water mixture from the steam generator. Outflow of steam-water mixture through MSIV is possible in the beyond design basis accidents with primary-to-secondary leakages with full failure of functions of pressure control and/or isolation for emergency steam generator feed water. As a result of the preliminary analysis by the proposed method, the qualification criteria were determined for the modes of steam-water mixture outflow through MSIV at stable processes and water hammer mode.

Keywords: main steam isolation valve, beyond design basis accidents, qualifications, steam-water mixture

One of the lessons from the accident at the Fukushima Daiichi nuclear power plant (NPP) is connected with the need to substantiate the technical performance (qualification) of systems important to safety in the design basis accidents and "hard" accident conditions. In particular, in the course of the accident the failures of passive safety and control systems that do not require long-term power supply were revealed [1].

Comprehensive (Consolidated) Program of Safety Enhancement of Ukrainian NPPs identifies activities on qualifying valves and fittings of the secondary circuit in the design basis accidents and "hard" modes of accident scenarios with "over-steaming" of elements of automation systems, as well as "non-design" modes of outflow of two-phase steam-water mixture through the operating bodies of the valves. One of the listed activities is the qualification of the main steam isolation valve (MSIV) in the possible modes of outflow of steam-water medium.

The analysis of the deterministic simulation of emergency processes within the Safety Analysis Reports (SAR) of serial power units with VVER-1000 / V320, conducted in [2] showed that outflow of the steam-water medium in the pipes of the secondary circuit is possible in the conditions of beyond design basis accidents with inter-circuit leakages and complete failure of pressure control functions and / or isolation of emergency steam generator on feedwater.

For these accident conditions, this study suggests computational and empirical methods of MSIV qualification for two approximations:

- steady state of medium-steam filling the emergency steam generator (SG) – a quasi-stable approach;
- water hammer mode in MSIV caused by thermal-hydraulic instability in the SG volume - an unstable approach.

The main provisions and assumptions of the proposed methods are as follows:

1) The SG volume on feed water is considered as a point system with averaged thermal-hydraulics parameters (Fig. 1);

2) Changes to the boundary conditions of computational models of thermal-hydraulic of the flow parameters into the leak ($G_Т$) and the specific enthalpy of the coolant ($i_Т$), flow rate ($G_{ПИ}$) and the specific enthalpy of the feedwater ($i_{ПИ}$) is determined on the basis of deterministic modeling of an accident with an average-size inter-circuit leak;

3) The computational model of MSIV qualification to the conditions of possible outflow of the steam-water medium is shown in Fig. 1.

In view of these assumptions the mathematical model of flooding the steam generator can be written in the following form:

$$\rho \frac{dV}{dt} = G_Т + G_{ПВ} - G_Б - G_{ИП} + G_К , \qquad (1)$$

$$G_Т(\tau) = \mu_Т F_Т \sqrt{\rho (P_Р - P_{ПГ})} \qquad (2)$$

$$G_{Б}(t) = \mu_{ПГ} F_{Б} \sqrt{\rho_{Б} (P_{ПГ} - P_{К})}, \qquad (3)$$

$$G_{Б} i_{Б} = G_{Т} i_{Т} + G_{ПВ} i_{ПВ} + (G_{ИП} - G_{К})(i_{П} - i_{К}), \qquad (4)$$

$$V(t = 0) = V_{0}, \qquad (5)$$

where ρ - density of the coolant; V - volume of boiler water in SG; t - current time; $G_{Т}$ - the water flow into the leak; $G_{ПВ}$ - feedwater consumption; $G_{Б}$ - flow of the medium in MSIV; $G_{ИП}$, $G_{К}$ - the intensity of evaporation and condensation [2], respectively; $\mu_{Т}$, $\mu_{ПГ}$ - coefficients of hydraulic flow into a leak and MSIV, respectively [3]; $F_{Т}$, $F_{Б}$ - the cross section area of a leak and the MSIV pipe, respectively; $P_{Р}$, $P_{ПГ}$, $P_{К}$ - the pressure in the 1st circuit, in the steam generator, and the turbine, respectively; $\rho_{Б}$ - density of the medium in MSIV; $i_{Т}$, $i_{ПИ}$, $i_{Б}$, $i_{П}$, $i_{К}$ - specific enthalpy of the coolant, feed water, MSIV medium, and condensate, respectively; V_{0}- volume of boiler water in SG at the start of an accident.

Conservative condition for entering steam-water mixture on MSIV at the moment of SG flooding $t_{ПГ}$:

$$V(t_{ПГ}) \geq V_{ПГ}, \qquad (6)$$

where $V_{ПГ}$ — the SG volume "free" from metal structures.

Conditions of necessary MSIV qualification on steam-water mixture in quasi-stable approximation:

$$t_{ср} \geq t_{ПГ}, \qquad (7)$$

where $t_{ср}$ — MSIV response time after the start of the accident process.

When a steam-water medium enters the MSIV and until the operation of MSIV the dominant loads on the working body (valve stem) are the overcome of the dynamic pressure difference between the inlet and outlet chambers of the valve channel and hydraulic resistance caused by the movement of the stem relatively to the medium flow (dissipative losses on the hydraulic resistance). For these mechanisms the conservative semi-empirical criterion of MSIV qualification on water-steam medium at quasi-stable conditions [2]:

$$K_{КС} = \frac{\rho_{П} G_{Б}^{2}}{\rho_{Б} G_{П}^{2}} < 1, \qquad (8)$$

where $G_{П}$ — capacity of a steam line with MSIV.

Criterion (8) actually reflects the relation of the hydrodynamic impact in the qualifying conditions of steam-water mixture, and the qualified (for the design and performance tests) impact of the steam-gas mixture on MSIV.

Determination of conditions and criteria for qualification in an unstable approach (water hammering) is based on the common approaches of thermal hydrodynamic instability [2] on the established emergency process formally imposed "small" fluctuation perturbation thermal-hydraulic parameters (δ), which, depending on the state of the system can either be "damped" or lead to a-periodic / low-frequency oscillatory instability of the water level in SG (water hammering).

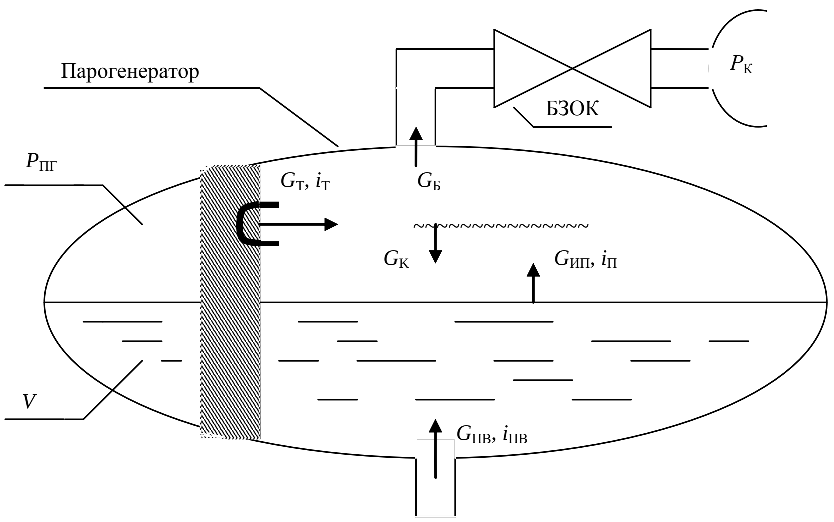

Fig. 1. Calculation model to the conditions of MSIV qualification on the conditions of steam-water flow

The mathematical model (1) - (5) in the small perturbations δ has the form:

$$\rho \frac{d\delta V}{dt} = \delta G_Т + \delta G_{ПВ} - \delta G_Б - \delta G_{ИП} + \delta G_К , \qquad (9)$$

$$\delta G_Т = \mu_Т F_Т \sqrt{\rho} \frac{\partial}{\partial P_{ПГ}} \left[\sqrt{\left(P_Р - P_{ПГ} \right)} \right] \frac{\partial P_{ПГ}}{\partial V} \delta V , \qquad (10)$$

$$\delta G_{ПВ} = \frac{\partial G_{ПВ}}{\partial P_{ПГ}} \frac{\partial P_{ПГ}}{\partial V} \delta V , \qquad (11)$$

$$\delta G_Б = \mu_{ПГ} F_Б \frac{\partial}{\partial P_{ПГ}} \left[\sqrt{\rho_Б \left(P_{ПГ} - P_К \right)} \right] \frac{\partial P_{ПГ}}{\partial V} \delta V , \qquad (12)$$

$$\delta G_К = \frac{\partial G_К}{\partial P_{ПГ}} \frac{\partial P_{ПГ}}{\partial V} \delta V , \qquad (13)$$

Then the solution of (9) - (13) with respect to the level of the disturbance of the level of steam-water volume in SG is reduced to the solution of the equation

$$\frac{d\delta V}{dt} = K_{ГУ} \delta V , \quad \delta V \sim \exp\left(K_{ГУ} t \right), \qquad (14)$$

where

$$K_{ГУ} = -\frac{\partial P_{ПГ}}{\partial V} \cdot \frac{\mu_Т F_Т}{\sqrt{\rho \left(P_Р - P_{ПГ} \right)}} +$$

$$+ \frac{\partial P_{ПГ}}{\partial V} \cdot \left[\frac{\mu_{ПГ} F_Б}{\sqrt{\rho_Б \left(P_{ПГ} - P_К \right)}} - \left| \frac{\partial G_{ПВ}}{\partial P_{ПГ}} \right| - \left| \frac{\partial G_К}{\partial P_{ПГ}} \right| \right] , \qquad (15)$$

Conservative condition of MSIV qualifying on water hammering:

$$K_{ГУ} < 0 . \qquad (16)$$

Preliminary analysis of the proposed methods and criteria for MSIV to the steam-water mixture showed that the conditions of the qualification are met. However, these results need to be clarified on the basis of design and operational documentation, and adequate simulation results of accidents with primary-to-secondary leakages; that is the subject of further researches.

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POSSIBILITY OF PERCOLATION DESCRIPTION OF BEHAVIOR OF NEUTRON MULTIPLICATION FACTOR

With the help of strict relations of percolation theory it is described the behavior of the neutron multiplication factor on the Bethe lattices at early stages of development of a self-sustaining fission chain reaction, corresponding to the percolation threshold. The behavior of the percolation probability, the probability of a chain reaction and its derivatives from this value is considered. The possibility of determining the boundaries of the critical region is indicated.

Keywords: percolation, percolation probability, the multiplication factor, the critical region

Problems associated with percolation (the word percolation means infiltration or leakage) occurred in the study of the flow of liquid or gas in a random labyrinth like passage of gas through the porous coal filter of a gas mask. Currently, the percolation theory is an extensive mathematical discipline [1-6] with numerous physical applications (magnetization, conductivity and other properties of various systems). Percolation theory describes the appearance of infinite connected structures (clusters), consisting of individual elements. Percolation is referred to the moment of occurrence of such a state of the lattice, in which there is at least one continuous path through the adjacent conductive components through the entire lattice. A collection of elements on which percolation occurs, is called the percolation cluster. Percolation theory deals with the formation of connected objects in disordered media. In terms of mathematics, percolation theory should be related to the theory of probability in graphs. From a physics standpoint, percolation is a phase transition related to phase geometry.

Percolation phenomena are closely related to fractality, phenomena of self-similarity and universality. Fractal models of different kinds of systems are capable of detecting new features of seemingly well-known phenomena. Many physical systems are either fractal or multifractal ones. In [7] the structure is called the fractal if it consists of parts that are in some ways similar to the whole. The fractal properties are especially clearly manifested in the phase transition point, in the critical region. Stationary operation of a nuclear reactor is being held at a critical point, and the fractal description should be important to characterize the operation of the reactor. [8]

In [2] a chain reaction is compared with spreading rumors in the percolation model. Equations of percolation theory [1, 4] are also valid in the general theory of phase transitions. Fractal concepts were used in the study of highly developed turbulence, inhomogeneous stellar clusters [9], the diffusion-limited aggregation, processes of destruction of matter, the structure of blood, etc. Description of the physical properties of systems with fractal structure led to the development of analytical methods in the fractal concept, based on the application of mathematical apparatus of the equations of fractional order, because the dimension of the space becomes fractional. The practical importance for the calculation of reactors may have the need to switch to the neutron transport equations in fractional derivatives [10], although often there is no sharp distinction between the percolation and diffusion processes [4]. In [11] it was noted that the transport processes in percolation clusters, fractal trees, and porous systems should be analyzed again in order to get the correct transport equation for such systems. In the branching fractal structures it can be implemented a "super-slow" transport process when a physical quantity changes more slowly than its first derivative. Indicator of fractional time derivative corresponds to the share of channels (branches), opened to the percolation. The dynamics of diffusion is determined by the random nature of particle motion: diffusing particle can reach any point in the medium. Percolation is associated with the fractal medium: below the percolation threshold the process of propagation of particles is limited to a finite region of the medium. A diffusion front having a fractal structure emerges at diffusion from the source. In [7] it is introduced the term "shell" of a percolation cluster. Below we consider the processes of the chain reaction in the reactor in the framework of the percolation theory.

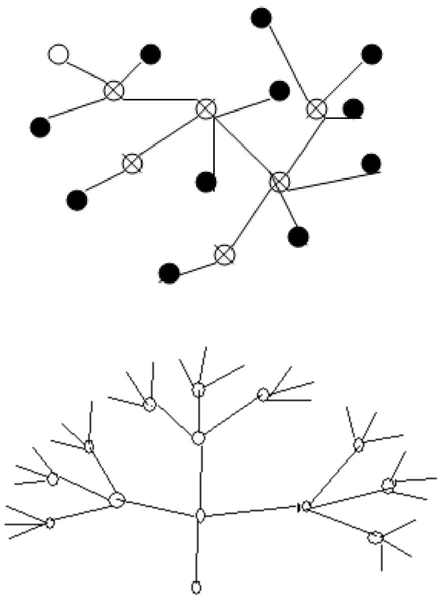
The importance of relations of percolation theory for neutron processes in the reactor is clear from the fact that they allow one to immediately get neutron multiplication equation, and the equation of the critical size of the reactor, interpreting the general relations of percolation theory, which shows the effectiveness of this approach in the theory of neutron processes in the reactor. It should be useful to have the relationships for the speed of propagation of the disturbance at the local supercriticality. It may be of interest to use many other relations of percolation theory in their application to reactors. This is, apparently, connected with the fact that the percolation itself is a critical process that requires the existence of a critical point, or a threshold. Near the percolation threshold processes occur according to the fractal scheme, which geometry is determined by the criticality. Geometric fractal characteristics are independent of the microscopic properties of the medium. Below the critical point the kinetic processes are limited by a finite region of the phase space, scattering, absorption and other neutron processes. At the critical point the fractal set becomes determining, which is formed at lowering the free energy of the statistical ensemble. System's behavior at slow action on it tends to self-organized criticality [12, 13]. Non-equilibrium steady states in fractal structures are chaotic, and turbulent. In [14, 15] for their research the Lorentz model is applied.

Kinetics and transport processes in the reactor fractal structures require a separate detailed study [9, 10, 15, and 16]. In the region of the critical point there are long-range correlation effects, manifested in the non-Gaussian behavior of the kinetic processes that determine the topological invariants of self-similar fractal sets. Transport processes at the percolation threshold are discussed in [9, 10]. The equations in fractional derivatives are used there, taking into account the effects of memory, non-locality, and intermittency.

There are few examples of exact self-similarity in nature; in other words, fractals with constant dimensions are rare, but the common are fractals with variable dimension - multifractals [4, 17]. Neutron processes in reactors are a good example.

Correlation of percolation theory on a Bethe lattices with neutron multiplication factor. Fission chains in a nuclear reactor have geometry of Cayley trees (a particular kind of Cayley graphs) [1-4]. Cayley tree, also known as the Bethe lattice is constructed starting from a central node from which radiate z branches of a unit length. They form the first shell of the Cayley tree. The end of each branch is also a node. Each node originates z-1 new branches forming z (z-1) nodes of the second shell. The process continues indefinitely. So, we can get infinite Cayley tree with z branches originated from each node. Any two nodes are connected by only one way. It should be taken into account the random nature of the branching. The theory of random graphs can also be applied. Knowledge of the properties of clusters allows one to explore their dynamic properties. There is a close relationship between the fractal phenomena and statistical distributions.

The processes represented by trees are associated with random branching processes [18], which describe the processes in neutron reactor [19]. We consider the aspect of the problem, which is determined by the magnitude and the nature of the behavior of clusters – nodes connected to each other. Under the node we understand the fissioning nucleus (or a neutron introduced into a system and being the tree's root [20]), and under a link - path of neutrons. Points of absorption of neutrons form the so-called hanging ends [20] (the vertices of degree 1) or the free ends.



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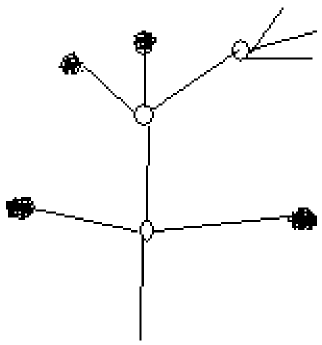

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Fig. 1. Trajectories of neutrons and their descendants
in the multiplying environment:
○ —start point of movement of initial neutron;
⊗ — point of neutrons fission;
● — points of absorption of neutrons.

If it were possible to trace the trajectory of movement of neutrons in a nuclear reactor, the observer would pay attention to the characteristic branching structure of the process for the total number of neutrons. Fig. 1 shows examples of the trajectories of a neutron entered in multiplying environment, taking into account the evolution events (of neutron fission and absorption), which lead to changes in the size of the neutron population. We can get the tree of type (*в*) similar to (*а*) by introducing hanging ends (dark dots). For larger subcriticality and larger negative values of reactivity $\rho=(k_{эф}-1)/k_{эф}$ (effective multiplication factor $k_{эф}<<1$) the system contains clusters of small size with a predominant number of hanging ends. If the intensity of the death of a neutron (absorption by medium or escape from the system) during $\Delta t\to 0$ designate as $\lambda_c\Delta t+0(\Delta t)$, and the intensity of neutron fission by $\lambda_f\Delta t+0(\Delta t)$ ($\lambda_f=v\Sigma_f$, where v – speed of neutrons; Σ_f - macroscopic cross section of fission), the probability of fission of atomic nucleus by a neutron is equal to:

$$c = p = \lambda_f \left(\lambda_f + \lambda_c\right)^{-1}. \qquad (1)$$

The effective neutron multiplication factor is $k_{эф}=p\bar{\nu}$, where $\bar{\nu}$ - the expectation value of number of secondary neutrons per single fission. At increase of p the size of clusters increases. For $p=1$, all the nuclei in the reactor fuel are fissioned and $k_{эф\ макс}=\bar{\nu}$ (in such conditions, there is an explosion). When $1-p<<1$, the system has an infinite cluster. There must be such a critical value p_c at which the transition from one mode to the other occurs – when an infinite cluster emerges for the first time. This corresponds to the case $k_{эф}=1$, $c_c=p_c=1/\bar{\nu}$. This result was obtained in the percolation model strictly mathematically [1-4,7]. The formation of an infinite cluster is a phase transition - the beginning of a self-sustaining chain fission reaction, the critical point of the system (in terms of the reactor theory). An important role in the theory of phase transitions plays the concept of the order parameter, or the physical quantity that has a key role in the processes that lead to the transformation. In theory of percolation clusters the order parameter is the power of the infinite cluster P_∞ - the probability that a node of the lattice belongs to the infinite cluster. Critical behavior of this physical quantity at $p\to p_c$, $p>p_c$ is determined by the relationship:

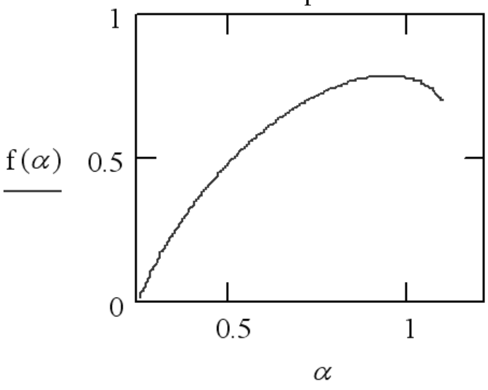
$$P_\infty = \left(p - p_c\right)^{\beta}, \qquad (2)$$

where β - one of the so-called critical indicators (scaling indices - in terms of the percolation theory) [1, 4]. The value β determines the critical behavior of the power of the infinite cluster P_∞. In the percolation theory the probability (2) is also called the probability of percolation. It serves as the main characteristic of a percolation system. Using percolation probability it can be expressed such properties of physical systems, depending on the topology of large clusters, as the spontaneous magnetization and conductivity. One can determine also such values as the average number of nodes of an end cluster, the correlation length ξ, the characteristic length scale of the cluster at $p<p_c$, and at $p>p_c$ - the characteristic size of the voids in it.

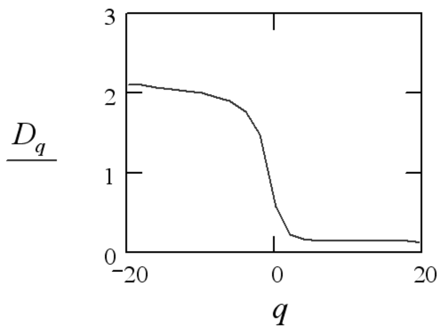
Formulae of percolation theory for the number of nodes, and the correlation length in the nuclear reactor theory (although they are obtained by another way there) correspond to the equation for the neutron multiplication $N=(1-k_{эф})^{-1}$, and the equation for the critical size $R_{эф}=\pi M(k_{эф}-1)^{-1/2}$, where $R_{эф}$ - effective size, a geometrical parameter; M - neutron migration length. In this case, the critical indicator $\nu=1/2$. The use of the percolation theory and constructions of fractal theory allows one to record some other relationships and consider, for example, the dynamic critical indices, the dimension of the skeleton of a cluster, spectral (fractions) dimension, etc.

To explore the multifractal properties of neutron processes in reactors, it is necessary to take into account the peculiarities of the process of division. If we plot the multifractal spectrum $f(\alpha)$ [17], using the approach of [4, 13], with a measure of multiplicative population, we obtain the dependence shown in Fig. 2*a*. A similar view has a function for $f(\alpha)$ of inhomogeneous Sierpinski triangle. [17] The range of generalized dimensions can be determined as well (Fig. 2*b*) [17].

The probability $c=p$ (1) is connected with important value of the percolation threshold. A collection of elements on which the flow is occurred, is called the percolation cluster. Being inherently a cohesive random graph, it may have a different shape depending on the particular realization. Therefore, it is common to characterize it by its general size. Percolation threshold is the number of elements of the percolation cluster, divided by the total number of elements of the considered medium. Because of the random nature of the switching states of the elements of the medium, there is no clearly determined threshold (the size of the critical cluster) in the target system, but there is a so-called critical area of values, in which with certain probability the values of the percolation threshold fall as a result of different random realizations. With the increase of the size of the system the area is narrowed to a point.



a



б

Fig. 2. The function of multifractal spectrum (a) and a range of generalized dimensions (b) for fission chains in the reactor with taking into account delayed neutrons

The processes on the Bethe lattice are considered, as a rule, for the case of an infinite lattice. In this paper we consider the case of a finite lattice, which corresponds to a finite number of neutrons in the reactor. Accounting for the finite number of neutrons is required, for example, during start-up of the reactor, or in critical assemblies. The results may be useful also for fast reactors, and transients.

In addition to the probability of percolation and percolation threshold, there are many other characteristics of the percolation process [1].

For neutron processes in a nuclear reactor the most important characteristics are the probability of percolation, which is interpreted as the probability of a self-sustaining chain fission reaction, and the values of the percolation threshold proportional to the neutron multiplication factor. In [21] it was obtained a recurrence relation for the probability of percolation of the root node, the probability that the connected component of the configuration comprising a root node (a starting point of the first appearance of a neutron in the system that initiates a chain reaction), reaches the opposite edges of the system. Conditional mathematical size of the system and the connected component tends to infinity, although the real system is finite. In [21], the value $P(n,c)$ denotes the probability of percolation of the root node on the distance n. The quantity n in our problem is interpreted as the number of generations of neutrons in a chain reaction. Number $c_{c\infty}=\inf\{c: P(c)>0\}$ is called in [21] the percolation threshold. In [4], this value is called the critical probability at which the first cluster emerges, extending over the entire array. Here, $P(c)=\lim_{n\to\infty}P(n,c)$, as in (2). Fig. 3, taken from [1] shows the behavior of the function $P(c=p)$. We assume that for finite values of n the percolation threshold exists:

$$c_{cn}=\inf\{c_n : P(n,c)>0\}. \qquad (3)$$

In general, the probability of percolation is as shown in Fig. 4 [1].

The recurrence relation obtained in [21] for the probability of percolation has the form

$$P(n+1,c)=c[1-(1-P(n,c))^s];$$
$$P(0,c)=c, \qquad (4)$$

where $s=\bar{\nu}$. The expressions for the derivatives obtained from (4) are of the form

$$f(n,c)=dP(n,c)/dc;$$
$$f(n+1,c)=1-(1-P(n,c))^{s-1}[1-P(n,c)-csf(n,c)];$$
$$f(0,c)=1, \qquad (5)$$

$$r(n+1,c)=s(1-P(n,c))^{s-2}[2(1-P(n,c))(dP(n,c)/dc)-$$
$$-c(s-1)(dP(n,c)/dc)^2+c(1-P(n,c))r(n,c)];$$
$$r(n,c)=d^2P(n,c)/dc^2;$$
$$r(0,c)=0. \qquad (6)$$

From (4) we obtain the probability of such a pattern of behavior for percolation for the Bethe lattice (Fig. 4), which differs from that one shown in Fig. 3 obtained for simple lattices. The probability $P(n,c)$ in Fig. 4 was calculated for n = 750. The vertical line shows the value $c_c=\bar{\nu}^{-1}$ when $n\to\infty$.

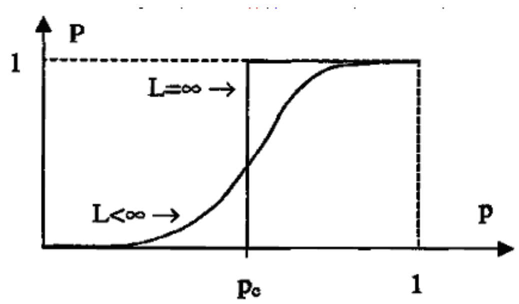
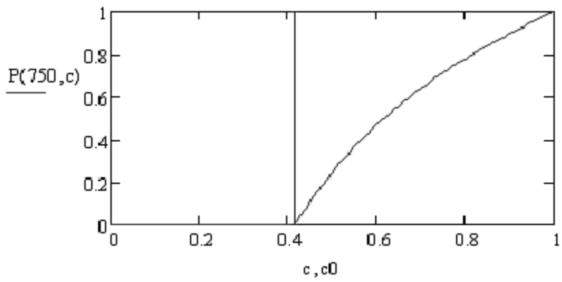


Fig. 3. The probability of percolation P according to the proportion of completed nodes $p=c$ (smooth curve corresponds to a lattice of finite size, step curve – to infinitely large lattice)



a

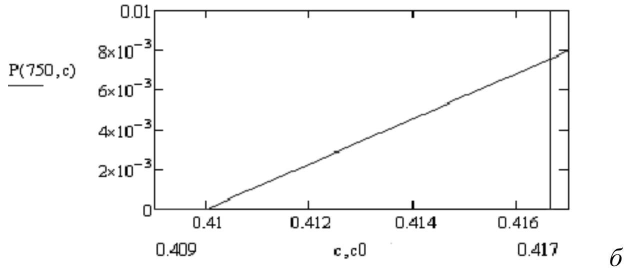


Fig. 4. The probability of percolation for the Bethe lattice, n = 750 (ranges of variation of c — 0…1 (a) и 0,409…0,417 (*б*)

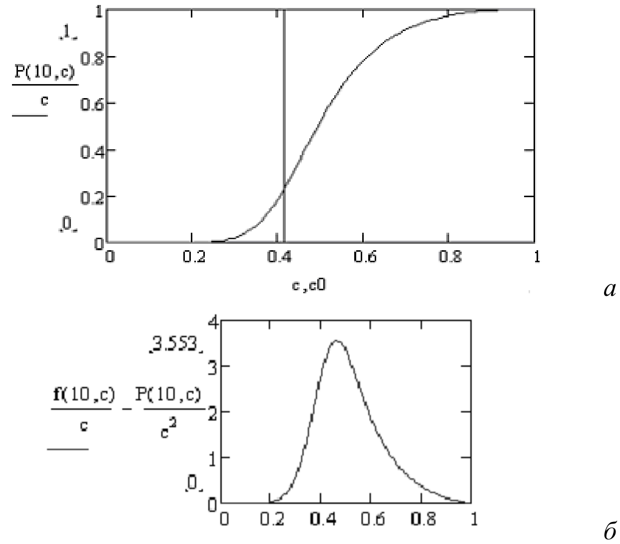


Fig. 5. The behavior of the conditional probability $P(10,c)/c$ (a) and the derivative with respect to c of the function $P(10,c)/c$ (*б*)

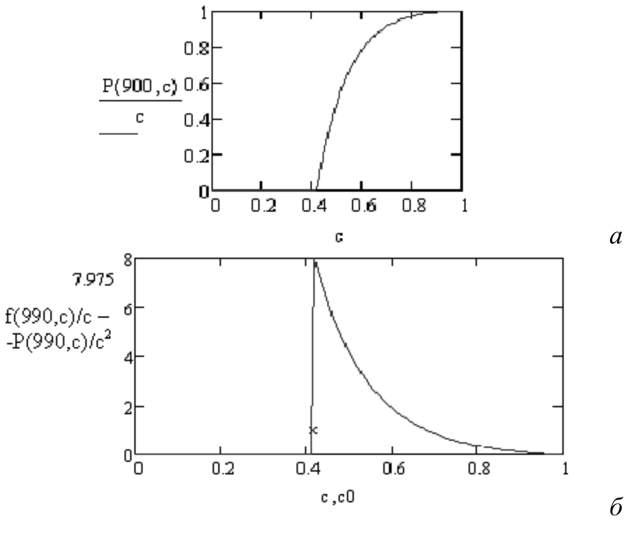


Fig. 6. The behavior of function $P(900,c)/c$ (a) and the derivative with respect to c of $P(990,c)/c$ (*б*)

Since the system is finite, the number of generations n = 750, then the critical probability does not equal to $c_c=\bar{\nu}^{-1}$. This can be seen from Fig. 4 *б*, where another variation range is shown from the value c — from 0.409 to 0.417, instead of the range from 0 to 1, as in Fig. 4, a. Fig. 4 *б* shows that the critical probability value for n = 750 is smaller than that for an infinite lattice where $c_c=\bar{\nu}^{-1}$, $c_{c750}\approx 0{,}41<\bar{\nu}^{-1}$. In the range of c=0.41 to $c_{c\infty}$ there exists nonzero probability, of the order $10^{-3}\ldots 8\cdot 10^{-3}$ of percolation, or, for reactors, the risk of origination of self-sustaining chain reaction of uranium fission. Thus, for the finite systems the percolation threshold and the multiplication factor are less than unity.

Fig. 3 differs from Fig. 4. In Fig. 3 (a similar Figure, which shows the derivative $dP(n,c)/dc$, can be found in [3]) shows the conditional probability $P(n,c)/c$, corresponding to our interpretation that the initial neutron hits the fissioning nucleus. Fig. 5 shows the behavior of function $P(10,c)/c$ and the derivative with respect to c of that function similar to Fig. 3 and the Fig. from [3]. However, this kind of behavior is typical for small values of n. At increase of n (Fig. 6) the pattern more closely resembles Fig. 4 and Fig. 7 with a derivative with respect to c of $P(n,c)$.

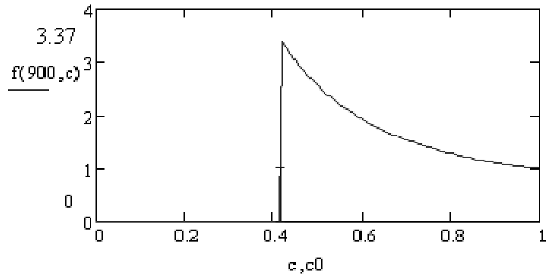


Fig. 7. Dependence of derivative with respect to c of $P(n,c)$, n=900

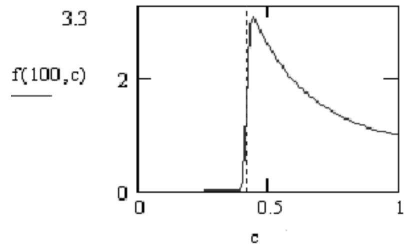


Fig. 8. The behavior of the derivative with respect to c of $P(n,c)$, n=100

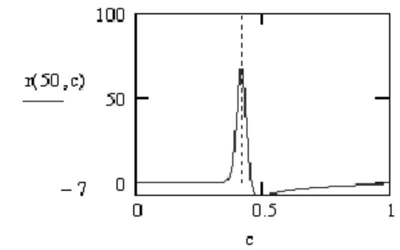


Fig. 9. Behavior of second derivative with respect to c of $P(n,c)$, n=50

Behavior of the functions (5) and (6) has the form shown in Fig. 8 and 9. It can be seen that the form of these functions is also associated with the position of the percolation threshold, shown by the vertical dashed line.

Fig. 10 shows the dependence $P(n,c_0)$ of n at fixed value $c=c_0=\nu^{-1}=c_{c\infty}$ in the variation range of n from 2 000 to 3 000. This function behaves similarly at other variation ranges of the value of the neutron generation n. This dependence is approximated by the function $1.43/n$. For other values different from $c=c_0$, this relationship is not satisfied.

In some studies (e.g., [3]), the value of the critical region is described as $c \approx c_c + B/L + ...$, where B - constant; L – dimension of the system. In [22] it is noted that the size of the Bethe lattice is proportional to ln N. Since $N=n$, this corresponds to the expression of $1.43/n$. We can estimate the time in which the values $c_0=c_{c\infty}$ reach some predetermined level. For example, the values 10^{-6} are achieved by $n=1{,}43 \cdot 10^6$generations of neutrons. For thermal neutron reactors, where the average lifetime of a neutrons generation taking into account the delayed neutrons is equal to 10^{-1} , this time is $1.43 \cdot 10^5$ s=1,655 days. For fast reactors, where the average lifetime of the generation of neutrons is equal to $10^{-4} \ldots 10^{-8}$, this time is reduced by 3…7 orders. The above methods of determining the critical point may be useful at the start-up of the reactor or at its transients, when due to manipulation of the absorbing rods the value of probability c varies.

Speed of changing the function $P(n,c)$ depending of n may be described by the derivative with respect to n, or more precisely, its discrete analogue $P(n+1,c_0)–P(n,c_0)$. Calculations show that this value taken with a negative sign, for $c_0=c_{c\infty}$ is well described by the relation $1.43/n^2$. The second derivative, the function

$P(n+1,c_0)–2P(n,c_0)+P(n–1,c_0)$ – is described by the relation $2.83/n^3$. The dependence of the *k*-th derivative with respect to *n* for $c_0=c_{c\infty}$ is proportional to $n–(k+1)$. Behavior of the discrete analogue of the dependence on *c* of the fourth derivative of $P(n,c)$ with respect to *n* is shown in Fig. 11. The behavior of the analogue of the second derivative on a smaller scale of the changes of *c* is shown in Fig. 12. The dependence on *n* of the difference between the second derivative at the point $c=0.42$ and $c=0.4$ is shown in Fig. 13.

Similar dependencies are recorded for derivatives with respect to *c* (5) and (6). Thus, the behavior of the discrete analog of the first derivative with respect to *n* of the second derivative of $P(n,c)$ with respect to *c* (6) is shown in Fig. 14, and the behavior of dependence of this value on *c* at fixed $n=50$ and $n=15$ is shown in Fig. 15*a* and Fig. 15*b*, respectively. Dependence on *c* of the third derivative with respect to *n* of the second derivative of $P(n,c)$ with respect to *c* (6) at n = 25 is shown in Fig. 16.

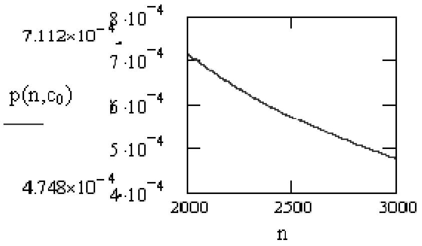


Fig. 10. The dependence $P(n,c_0)$ on *n* ($2000<n<3000$)
at a fixed value of $c=c_0=\nu^{-1}=c_{c\infty}$

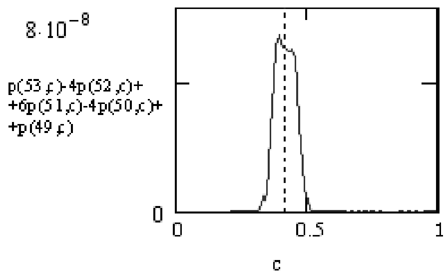


Fig. 11. Behavior of the discrete analogue of the dependence on *c* of the forth derivative with respect to *n* of $P(n,c)$

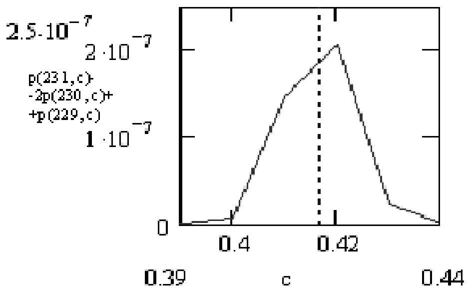


Fig. 12. Behavior of dependence on *c* of the second derivative with respect to *n* of $P(n,c)$ ($0,39<c<0,44$)

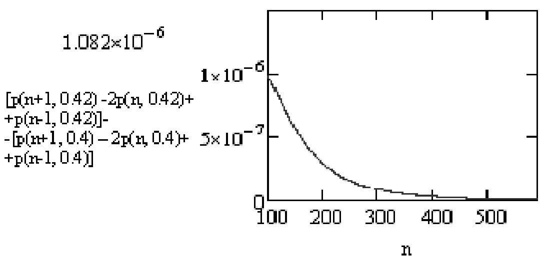


Fig. 13. Dependence on *n* of the difference between the second derivatives with respect to *n* of $P(n,c)$ at the point $c=0.42$ and $c=0.4$

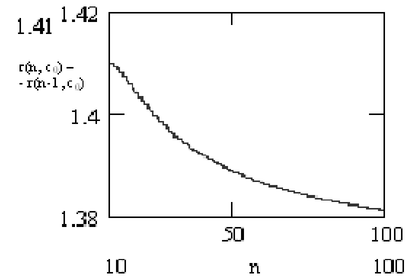
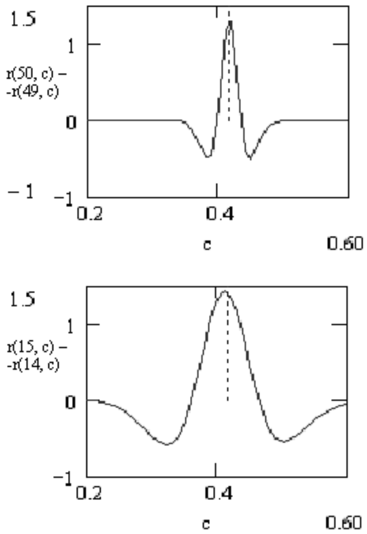


Fig. 14. Behavior of dependence on *n* of the discrete analogue of the first derivative with respect to *n* of the second derivative of *P*(*n*,*c*) with respect to *c*



а

б

Fig. 15. Behavior of dependence on *c* of the discrete analogue of the first derivative with respect to *n* of the second derivative of *P*(*n*,*c*) with respect to *c* at fixed *n*=50 (*а*) и *n*=15 (*б*)

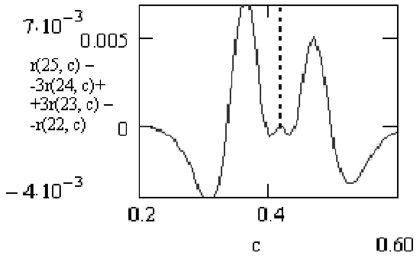


Fig. 16. Dependence on *c* of the third derivative with respect to *n* of the second derivative of *P*(*n*,*c*) with respect to *c* (6) at *n*= 25

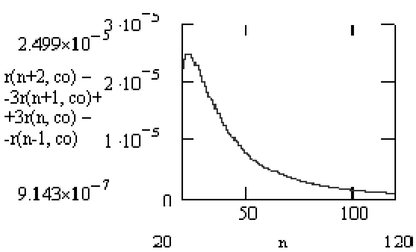


Fig. 17. Dependence on *n* of the third derivative with respect to *n* of *r*(*n*,*c*),
the second derivative of *P*(*n*,*c*) with respect to *c*

The dependence on *n* of the third derivative of *r*(*n*,*c*), with respect to *n*, and the second derivative *P*(*n*,*c*) with respect to *c* is shown in Fig. 17. The position of the maxima and minima in Fig. 16, is possibly related with the boundaries of the critical region. From Fig. 15 it is clear that the negative peaks of the first derivative with respect to *n* converge with increasing *n*.

Conclusion

Percolation and fractal properties of neutron processes in a nuclear reactor reflect the complex nature of the processes occurring in nuclear fission and neutrons movement. The use of exact relations of percolation theory obtained for the Bethe lattices, makes it possible to evaluate time behavior of such an important value for the reactor plants operating as the multiplication factor. The estimates show that the value of a single multiplication factor can be achieved only in the practically impossible case of an infinite number of generations of neutrons, corresponding to the infinite time, and infinitely large systems. But for the real-time operation, one can estimate the time required to achieve a very small intervals of the unit value of the multiplication factor.

The obtained results are important for the safety of reactor systems with a relatively small number of neutrons, both for start-up stages of the reactor or critical assembly. They should be useful for more detailed description of the transients in the reactor. Some general aspects of the problems raised in this paper, were considered in [23].

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SIMULATION OF DYNAMICS OF RADIOACTIVITY ACCUMULATION IN HIGHER AQUATIC PLANTS

A model of accumulation of ^{90}Sr, ^{95}Zr, ^{103,106}Ru, ^{137}Cs, and ^{141,144}Ce in higher water plants was developed. Five options of radionuclides entering into a water body were considered. It is shown that the content of radionuclides in higher aquatic plants can reach 10.6 % of the total content in the ecosystem.

Key words: modeling, aquatic ecosystems, higher aquatic plants, radionuclides

Nuclear energy is considered a promising source of energy to humans, but negative consequence of the use of nuclear energy is contamination of the environment. It is clear that the greatest danger is accidents at the nuclear enterprises in which uncontrollable contamination of the environment, including groundwater, may occur. In many scientific publications the authors note that higher water plants play a certain role in migration of radionuclides in aquatic ecosystems [1-4]. However, to date there were no quantitative assessment of the role of these plants in the process of distribution of radionuclides in aquatic ecosystems during accidental contamination of water. The purpose of our work was to develop a model of distribution of radionuclides in biotic (higher plants) and abiotic (water, bottom sediments) components of aquatic ecosystems, which would determine the role of the plant components in the migration of radioactive substances after accidental entering into water bodies.

Analysis of our own and referenced data [3, 5, 6] shows that during the first weeks after radionuclide contamination of water the plantsô radioactivity is determined by radionuclides of barium, lanthanum, cerium, ruthenium, iodine, zirconium and long-lived radionuclides cesium and strontium. Subsequently the content of radionuclides in aquatic plants is reduced by biological processes and radioactive decay. Reduction of ^{131}ɯand ^{140}I Θis mainly driven by radioactive decay. Therefore the simulation is topical for ^{90}Sr, ^{95}Zr, ^{103,106}Ru, ^{137}Cs and ^{141,144}Ce

Methods of simulation. Mathematical simulation of radionuclides content in the environment is based on the equations of the law of conservation of mass with taking into account radioactive decay. In radioecology the commonly used modes are the ñchamberò models in which components of the environment or living organisms are presented in the form of one or more chambers, and the speed of coming of a radionuclide into a chamber is proportional to the activity of other chambers [5-8]. Presentation of an object in the form of one or more chambers is based on the previous experience and allows us to apply the same mathematical tools for modeling of radionuclides both in abiotic and biotic components of ecosystems. In the simulation we considered the most important areas of migration observed in the water reservoirs after a single accidental intake of radionuclides. In such a case, the vast majority of radionuclides would be accumulated in the water masses, bottom sediments and in aquatic plants.

Simulation of radionuclides content in aquatic plants was carried out for the dominant ecological groups of plants, air and water ones, floating plants and plants with submerged leaves. It should be noted that aquatic plants can exist in 3 environments: soil (underground part), water and air (aerial part)

Migration of radionuclides from plants to take the sediments was taken into account in the chain "plant-water-bottom sediments." Calculations of activity of radionuclides in water masses were conducted in approaches of two-chamber (two-component) system. It was accepted that the activity of radionuclides in a chamber did not depend on their activity in another chamber. Calculations of specific activity of a particular radionuclide in the water at time $t+\Delta t$ ($A_w(t+\Delta t)$, Bq/l) were performed step by step, and for each chamber separately:

$$A_w(t+\Delta t) = \sum_{i=1,2} A_w^i(t+\Delta t) =$$

$$= \sum_{i=1,2} \left[A_w^i(t) e^{-p\Delta t} e^{-p_i \Delta t} + \frac{\Delta A_{ps}(t+\Delta t) A_w^i}{V} \right], \qquad (1)$$

where Δt is the step of simulation, day; $A_w^i(t)$ ð specific activity of a radionuclide in the •-th chamber, Bq/l

$\left(A_{\text{w}}^{i}(0)=A_{\text{w}}^{i}A_0\cdot\left(1-\sum_{j=1}^{3}k_jx_j\right)\cdot V^{-1}\right)$; A_{w}^{i} ð the part of radionuclides that come to i-th chamber, shares $\left(\sum_{i=1,2}A_{\text{w}}^{i}=1\right)$; A_0 ð density of radioactive fallout, Bq/m^2; k_j ð coefficient of holding radionuclides by plants of j-th ecological group; x_j ð average value of overgrowing of the water body by j-th ecological group of plants; V ð average volume of water mass per unit area l/m^2; λ=ln2/$T_{1/2}$ ð radioactive decay constant, day^{-1}; p_i=ln2/$T_{1/2\,i}$ ð rate of removal of radionuclide from i-th camera; day^{-1}; $T_{1/2}$, $T_{1/2\,i}$ ð period of the half-life and half-removal of a radionuclide, respectively, days, $\Delta A_{\text{ps}}(t+\Delta t)$ ð the average over the water body removal and accumulation of a radionuclide by plants per unit area during the time Δt, Bq/m^2.

The content of radionuclides in plants was counted at each step of the simulation. In the simulation of radionuclides in submerged plants a single-chamber system was used; in air-aquatic plants and plants with floating leaves ï the double chamber system similar to the chosen for water masses:

$$A_{\text{p}\,j}(t+\Delta t)=\sum_{i=1,2}A_{\text{p}\,ji}(t+\Delta t)=$$
$$=\sum_{i=1,2}\left[\frac{A_{\text{p}\,ji}(t)e^{-p\Delta t}e^{-p_{ji}\Delta t}m_j(t)}{m_j(t+\Delta t)}+Z_jA_{\text{p}\,ji}A_{\text{w}}(t)\Delta t\right], \quad (2)$$

where $A_{\text{p}\,j}(t+\Delta t)$ ð specific content of a radionuclide in the plants of the j-th ecological group in the moment of time $t+\Delta t$, Bq/kg; $A_{\text{p}\,ji}(t)$ ð specific content of a radionuclide in i-th chamber of j-th ecological group of plants, Bq/kg; p_{ji}=ln2/$T_{1/2\,ji}$ ð speed of radionuclide removal from i-th chamber of j-th ecological group of plants, day^{-1}; $m_j(t)$ ð biomass of plants of j-th ecological group, kg/m^2 (multiplier $\frac{m_j(t)}{m_j(t+\Delta t)}$ accounts changing of biomass); $Z_j=K_{\text{i}\,j}\ln 2\left(\sum_{i=1,2}A_{\text{p}ji}T_{1/2\,ji}\right)^{-1}$ ð fallout of a radionuclide to plants of j-th ecological group, day^{-1}; $A_{\text{p}ji}$ ð a part of a radionuclide, which comes to the i-th chamber of j-th ecological group, shares $\left(\sum_{i=1,2}A_{\text{p}\,ji}=1\right)$; $K_{\text{dz}j}$ ð equilibrum koefficient of radionuclide accumulation by the plants of j-th ecological group; $T_{1/2\,ji}$ ð period of half-removal of a radionuclide from i-th chamber of j-th ecological group of plants, day.

Calculations of redistribution of radionuclides were performed for the model reservoir in general, which is equivalent to calculation per unit area at a constant space density of contamination of aquatic plants. The density of plant contamination was calculated by multiplying the average biomass [kg/m^2] and specific activity of plants. Radionuclide contamination of components of aquatic ecosystems can be described by the following indicators: specific activity [Bq/kg] volume activity [Bq/m^3] activity per unit area [Bq/m^2] and the total [Bq] or relative [%] activity of a radionuclide; coefficients of accumulation (K_{dz}). It is distinguished the equilibrium (see. (2)) and instant coefficients of accumulation, i.e the values that show the ratio of specific activity of radionuclides in plants [Bq/kg] and in water [Bq/l] in equilibrium state, and in selected moment, respectively. According to the work objective we studied the behavior over time of the value of the part of a radionuclide activity in plants (of particular environmental groups and in general) to the total activity of radionuclides in the ecosystem. In the future we will use the term relative activity of the radionuclide in the ecological group of plants or in plants.

Parameters of the model. Parameters of migration of ^{90}Sr and ^{137}Cs in the water masses were selected based on the balance of radionuclides in water of the Dniepr reservoirs taking into account modeling of processes of irreversible fixing of radionuclides in bottom sediments [7]: ^{90}Sr ð A_{w}^{1}=0.2, $T_{1/2\,1}$=134 days, A_{w}^{2}=0.8, $T_{1/2\,2}$=828 days; for ^{137}Cs ð A_{w}^{1}=0.97, $T_{1/2\,1}$=111 days, A_{w}^{2}=0,03, $T_{1/2\,2}$=7,5 years. Based on the behavior of cesium, cerium, zirconium and ruthenium in aquatic ecosystems [1, 2, 6] it was assumed that migration parameters in the ñwater-bottom sedimentsò system of these radionuclides are the same.

For the air-aquatic plants and plants with floating leaves the parameters of radionuclides exchange were taken according to [8]. With taking into consideration processing of the primary data of [6] for these groups, the chosen parameters of exchange of separate nuclides were the same. For the submerged plants we calculated the migration parameters according to [1, 2]. Dynamics of aquatic plants phytomass formation we chose after [9] and our own observations. It was taken that the value of the coefficient of hold of the radionuclide k_j for air-aquatic plants and plants with floating leaves equals to one, and for submerged plants ð zero. It was taken, that after finishing the vegetation and before its start phytomass of aquatic plants equals to zero. At simulation we took into account only the above-ground phytomass; the share of radionuclides that were accumulated in the underground mass, was accounted as a part of bottom sediments.

It was decided that at the end of the growing season and the beginning of the biomass of aquatic plants is zero. In the simulation took into account only aboveground biomass; contribution activity radionuclides are concentrated in underground mass, counted as a fraction of the radioactivity of bottom sediments.

Water bodies of Ukraine are characterized by an extraordinary high variety of hydrobiological and hydro-morphological indicators. E.g., the water depth varies from 1é 2 meters to several tens of meters, and overgrowth of air-water plants varies from 0 to 100%. It was chosen that the average depth of the model reservoir is 4.0 m and the vegetation development coincides with the indicators that are specific to the Kiev reservoir (Table 1).

Table 1. Parameters of the model reservoir

The ecological group of plants	Increase, %	Maximal phytomass g/m^2
Air-aquatic	9,9	107,0
With floating leaves	0,7	1,1
Submerged	3,7	6,2

Accidental release of radionuclides can occur at any time of the growing season. Therefore, assuming that vegetation of higher aquatic plants begins April 15th, we simulated the distribution of radionuclides that fell on the surface of a water body in several scenarios, namely: *Scenario 1* - radioactive substances fall into the reservoir 2 months before the beginning of vegetation; *Scenario 2* - for 1 month before the growing season; *Scenario 3* - the beginning of the growing season; *Scenario 4* - a month after the start of the growing season; *Scenario 5* ï in the peak of the growing season (1 August).

It was assumed that the surface of the water body was instantly and uniformly contaminated with other investigated radionuclides. The density of contamination was 40 kBq /m^2. Such contamination in the absence of vegetation provides primary contamination of water masses at 10 Bq/l. For *scenarios 1* and *2* we assumed lack of ice cover.

Simulation results. There are two fundamentally different cases of the formation of radioactive contamination of aquatic ecosystems. Radionuclides that fell on the surface of the water body before the growing season (*scenarios 1-3*) will be accumulated by vegetation chronically from water masses, and in case of falling on the vegetating plants (*scenarios 4-5*), they will be absorbed by the plants, not only chronically from water masses but also from air at the time of fallout.

For *scenarios 1 ï 3* behavior of the value of relative activity of each radionuclide in plants differs only by amplitude (Table 2). At the same time accumulation of different radionuclides by plants differs by amplitude and speed of accumulation or removal, as evidenced by the various inclinations of dynamics curve (Fig. 1).

For the second case (*scenarios 4ï5*) value of the maximum relative activity of plants, excluding submerged ones, is determined by design-basis overlap (see Table 1, and 2), and temporal characteristics of behavior of relative values of radionuclide activity coincide in general (Fig. 2). Only for radioisotopes of cerium according *scenario 4* of accumulation processes in air-water plants prevail over removal processes (Fig. 2, ***н***).

In the case of contamination of a water body by ^{95}Zr according to *scenario 3* the plants from the start of the growing season will actively accumulate it. Relative activity of ^{95}Zr in phytomass of submerged plants will reach a maximum approximately 2.5 months after the start of the growing season and will be 0.36% of the general amount in the ecosystem (Fig. 1, a), and later, 3 months after the start of the growing season the relative radionuclide activity reach maximum in phytomass of air-water plants ~ 0.3 %. The total maximum relative activity of ^{95}Zr in plants be ~0.65 % of the total value.

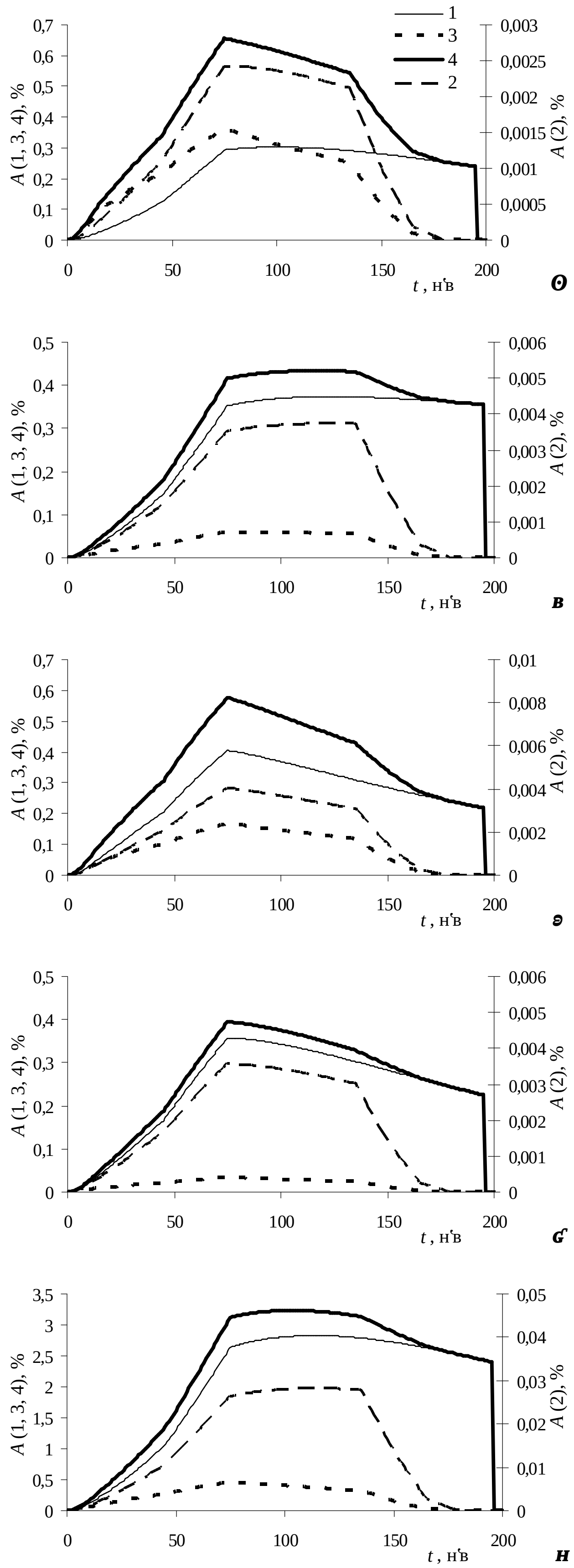


Fig. 1. Dynamics of the relative activity of ^{95}Zr (Θ), ^{90}Sr (в), ^{106}Ru (э), ^{137}Cs (ɕ) and ^{144}Ce (н) according *Scenario 3*
In higher aquatic plants: *1* ð air-aquatic, *2* ð with floating leaves, *3* ð submerged, *4* ð total content in plants

It should be noted that the total radionuclide content in phytomass increase both due to the increase of specific radionuclide content in it, and by increase of the biomass itself. Thus, the specific activity of ^{95}Zr in submerged plants will grow during 16é 17 days after the start of the growing season, and the relative content of radionuclides in plants of this group will grow over 2.5 months, i.e. the time to achieve maximum weight.

Fundamentally different picture of the dynamics of relative activity in plants of ^{95}Zr is observed in case of its fallout on vegetating surface biomass, i.e. in *scenario 4 and 5* (Fig. 2a). Here, for air-water plants in case of fallout after 1 month after the start of the growing season, this value will be 5.9%, in the peak growing season - 9.9%; and for the plants with floating leaves ï 0.42% and 0.7%, respectively. Relative activity of ^{95}Zr in air-water plants and plants with floating leaves will decrease during the growing season. Instant K_{dz} in these groups during the growing season will be several times larger than the equilibrium ones. It should be noted that such processes were observed in 1986 in the upper Dnieper reservoirs [5, 6].

In case of fallout of ^{90}Sr in different terms before or at the beginning of vegetation the dynamics of its distribution between biotic and abiotic components according to *scenarios 1 ї 3*, will coincide, only the amplitude will slightly differ (Table 2).

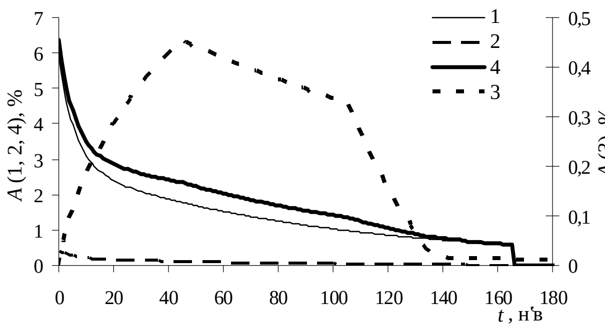
After the start of the growing season the amount of accumulated ^{90}Sr in plants will increase. Intensive growth of content of ^{90}Sr will be observed for about 2.5 months after the start of the growing season, then increasing of the activity of air-aquatic plants and plants with floating leaves will slow, and its relative activity in submerged plants will begin to decline (Fig. 1 ***в***).

In general, in *scenarios 1 ї 3* the relative activity of ^{90}Sr in plants of different ecological groups will correlate with their phytomass. Plants will concentrate about 0.4% of ^{90}Sr in the ecosystem.

For *scenarios 4 and 5*, the relative activity of ^{90}Sr in the air-aquatic plants and plants with floating leaves during the growing season will decrease (Fig. 2b) and instant values of K_{dz} in these plants will 2.5 times exceed the equilibrium.

At fallout of ^{103}Ru and ^{106}Ru before the start of vegetation their active accumulation in phytomass was observed in the first 2.5 months after the start of the growing season, then the relative activity of each radionuclide in plants decrease (Fig. 1, c), due to a decrease in the specific activity of plants.

As with other radionuclides, for *Scenarios 1ї3* relative activity of ^{137}Cs in plants will be the same, only the amplitude will be different (Table. 2).



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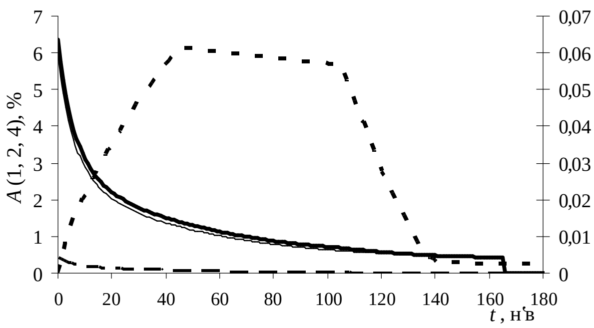

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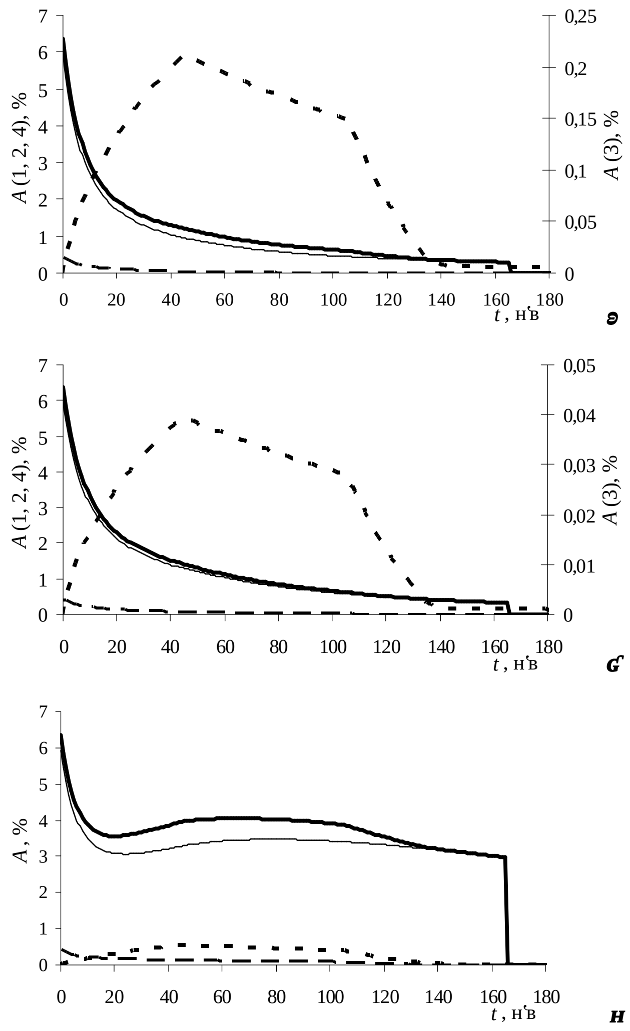

Fig. 2. Dynamics of the relative activity of ^{95}Zr (**Ɵ**), ^{90}Sr (**в**), ^{106}Ru (**ɵ**), ^{137}Cs (**ɢ**) and ^{144}Ce (**ʜ**) according to *Scenario 4 in* higher aquatic plants: *1* ð air-aquatic, *2* ð with floating leaves, *3* ð submerged, *4* ð total content in plants

Table 2. Maximum relative activity of certain radionuclides in higher aquatic plants in % of their total amount in the ecosystem

Ecological group of plants	Scenario											
	1						2					
	^{90}Sr	^{103}Ru	^{106}Ru	^{137}Cs	^{141}ʉȷ	^{144}ʉȷ	^{90}Sr	^{103}Ru	^{106}Ru	^{137}Cs	^{141}ʉȷ	^{144}ʉȷ
Air-aquatic	0,343	0,287	0,283	0,250	1,97	1,98	0,356	0,343	0,349	0,300	2,35	2,36
With floating leaves	0,003	0,003	0,003	0,003	0,02	0,02	0,004	0,003	0,003	0,003	0,02	0,02
Submerged	0,055	0,119	0,117	0,023	0,32	0,32	0,057	0,143	0,142	0,028	0,39	0,39
TOTAL	0,400	0,409	0,404	0,276	2,26	2,26	0,410	0,490	0,484	0,330	2,70	2,70

Table 2 (contõd)

Ecological group of plants	Scenario																	
	3						4						5					
	^{90}Sr	^{103}Ru	^{106}Ru	^{137}Cs	^{141}ʉȷ	^{144}ʉȷ	^{90}Sr	^{103}Ru	^{106}Ru	^{137}Cs	^{141}ʉȷ	^{144}ʉȷ	^{90}Sr	^{103}Ru	^{106}Ru	^{137}Cs	^{141}ʉȷ	^{144}ʉȷ
Air-aquatic	0,374	0,410	0,405	0,360	2,82	2,83	5,94	5,94	5,94	5,94	5,94	5,94	9,90	9,9	9,9	9,90	9,9	9,9
With floating leaves	0,004	0,004	0,004	0,004	0,03	0,03	0,42	0,42	0,42	0,42	0,42	0,42	0,70	0,7	0,7	0,70	0,7	0,7
Submerged	0,060	0,170	0,168	0,033	0,46	0,46	0,06	0,22	0,21	0,04	0,56	0,54	0,06	0,2	0,2	0,04	0,5	0,47
TOTAL	0,430	0,584	0,577	0,394	3,23	3,23	6,36	6,36	6,36	6,36	6,36	6,36	10,6	10,6	10,6	10,6	10,6	10,6

Intensive accumulation of ^{137}Cs by air-aquatic plants and plants with floating leaves will continue during the first 2.5 months after the start of the growing season (Fig. 1, d), due to the increase in biomass and specific activity. After reaching the maximum phytomass by plants, the rate of removal of radionuclides exceeds the speed of its income, so the total activity of ^{137}Cs in plants begins to decrease due to the decrease of specific activity. In submerged plants specific activity of ^{137}Cs will grow within 22 days after the start of the growing season, then its specific activity will decrease, but due to increase of the total biomass of submerged plants the activity will grow (Fig. 1, [illegible]). The relative activity of ^{137}Cs in the aquatic plants for *Scenarios 1 – 3* will not exceed 0.4% of its amount in the ecosystem.

For *Scenarios 4 – 5* relative activity of ^{137}Cs of the air-aquatic plants and plants with floating leaves during the growing season will decrease, and for the submerged ones it will increase within 1.5 months, than it will be reduced first by reducing the specific activity, then - because of the withering away of biomass (Fig. 2, [illegible])

Dynamics of relative activity ^{141}Ce and ^{144}Ce in plants mostly coincides. It is clear, that the absolute values of specific activity for short-lived ^{141}Ce over time will be lower on the value of its decay. For *Scenarios 1 – 3* the maximum value of the relative activity of radionuclides in plants cerium will be 2-5 times greater than for ^{137}Cs (Table 2).

The dynamics of the relative activity of cerium radioisotopes in plants computed by *Scenario 4* is significantly different from the dynamics of other radionuclides (Fig. 2, [illegible]). During the first 20 days after radioactive fallout, the same as for other radionuclides, relative content of ^{141,144}Ce in the air-aquatic plants and plants with floating leaves will decline, but later this value will increase. According to the *Scenario 5*, the same as for other radionuclides, relative activity of ^{141,144}Ce in air-aquatic plants and plants with floating leaves will gradually decrease.

Conclusions

In the case of a single accidental fallout of ^{95}Zr, ^{90}Sr, ^{103,106}Ru, ^{137}Cs and ^{141,144}Ce on aquatic ecosystems during the early growing season of the higher aquatic plants, the relative activity of radionuclides in phytomass increases by increasing the specific activity and the mass of the plants. Maximum relative activity of a radionuclide in the case of fallouts before the beginning of the growing season or early in the growing season for ^{95}Zr, ^{90}Sr, ^{103,106}Ru and ^{137}Cs will not exceed 0.7% of the total content of a radioisotope in the ecosystem, and for ^{141,144}Ce – 3,4 %. In the event of radioactive fallout on vegetating plants relative activity of radionuclides in phytomass defined by design overgrowth of a pond by plants. During the growing season the relative content of radionuclides in phytomass will decrease except the *scenario 4* for ^{141,144}Ce, when radioactive substances fall into the water body a month after the start of the growing season.

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DEPENDENCE BETWEEN THE PARAMETERS OF TRANSPARENCY AND DEVELOPMENT OF PLANKTONIC ALGAE IN THE KHMELNITSKY NPP COOLING POND

The results of studies of phytoplankton and water transparency of Khmelnitsky NPP cooling pond were represented. The dependence of the indicators of the water transparency from phytoplankton biomass was shown, which allows one to roughly determine the trophic status of the cooling pond and water quality indicators. Method of determining of water transparency by Secchi disk was recommended for hydrobiological monitoring of NPP cooling ponds.

Key words: phytoplankton, water transparency, Secchi disk, NPP cooling pond, water body trophicity

Water transparency is an important hydro-physical parameter used to determine the quality of water. Transparency is one of the elements determining the ecological status of water bodies under the Water Framework Directive [1], and it is also included in the list of indicators for the hydro-biological monitoring of water bodies in Ukraine [2].

Water transparency is caused by suspended solids of organic and inorganic origin. In other words, the main factor that determines the transparency value is its turbidity, i.e. the number of suspended substances in the water. These characteristics are inversely proportional [3].

Suspended solids in the industrial cooling ponds are formed mainly by autochthonous mechanisms by stirring up bottom sediments and by aquatic life activity [4].

Research of turbidity and transparency of water have their own history. The first records of regular measurements of natural water transparency were made by German naturalist A. Chamisso during the expedition on the Russian ship "Rurik" in the years 1815-1818. The measurements were performed by submersion to the certaing depth of a white plate suspended on a rope. The method based on immersion of a white-painted disk into water to a depth of visibility, was described by an Italian physicist P. Secchi in 1865. In the early twentieth century, the definition of the transparency of water, using white disk was named the Secchi disk method [5]. According to modern requirements [6] measuring disk or the Secchi disk is a white disk with a diameter of 20 cm; it may have some black sectors, which helps to more precisely determine the depth of visibility (Fig. 1).

The measure of water transparency is the measure of the height of water column, through which you can still observe the Secchi disk or read a typographic symbol of a certain size [7]. In addition to this, in researches of aquatic ecosystems the spectrophotometric method is currently applied, which allows to determine turbidity of water at different depths. [3] There may be situations when different depths are characterized by different levels of turbidity. In particular, if at the bottom of a pond there are large populations of shellfish (e.g. zebra mussel) that filters water, the transparency of water at the bottom can be much better than the near-surface transparency.

Data on water transparency measurements using the Secchi disk have been accumulated for a large number of water bodies. For example, in the continental water bodies there are observations, with the use of Secchi disk, of water transparency for the depths from 0.2 to 40 m. The depth of penetration of solar radiation is directly related to water transparency, and thus by knowing the water transparency one can determine the power of the so-called trophogenic layer, i.e. the layer of water, in which the main processes of photosynthesis by algae plankton occur [8].

The techniques for environmental monitoring in the cooling ponds of Ukrainian NPPs use the method of determining the transparency by typographic fonts. In reality, however, at sufficiently low turbidity, and thus high transparency, it is very difficult to determine transparency by this method. The method is more suitable for working with wastewater where turbidity is usually high.

Determination of transparency of water, including reservoirs and cooling ponds, is important not only as finding of one of hydro-physical parameters, but also as identification of ecological state and trophic status of the ecosystem. This is due to the fact that the main component of the vegetation period of the totality (the pool) of suspended substances is usually consist of water planktonic organisms (phytoplankton and zooplankton) and with increasing the amount of algae in water the primary products, i.e. the water body trophicity is increased as well.

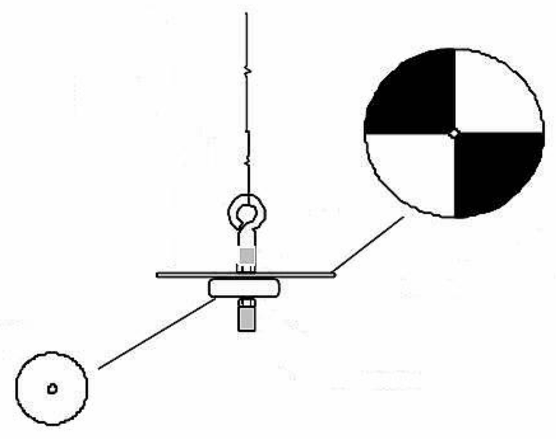

Fig. 1. Disk to determine water transparency (Secchi disk)

In the history of the ecosystem of Khmelnitsky nuclear power plant (KhNPP) cooling pond one can underline several periods, accompanied by changes in water transparency. This periodicity is related with the commissioning of the second unit, general increase in technogenic pressure on the water body, and also by moving in of an active mollusc-filter, zebra mussel (*Dreissena polymorpha* Pall.).

At the first stage (the study was conducted in the 1998-2001) during operation of one NPP unit, water transparency by Secchi disk (white disc of 30 cm in diameter) in the summer-autumn period, the average for the number of measurements at different points of the reservoir was (1,23 ± 0.05) m. Indicators of abundance of phytoplankton were quite high: number (42,50 ± 10,43) million cells/dm^3, biomass (13,78 ± 2,19) mg/dm^3. According to the ecological classification of surface water [2] the value of transparency index corresponded to class II (mesotrophic water). At the same time, phytoplankton biomass ranged from typical for III (eutrophic) and IV (poly-trophyc) classes.

The beginning of operation of the second unit (2004) and immigration of zebra mussel has decreased the quantitative indices of phytoplankton - (8.73 ± 2.79) million cells/dm^3 and (0.64 ± 0.12) mg/dm^3 (number and biomass, respectively), which naturally led to an increase in transparency to (2.62 ± 0.08) m (average data for the summer-autumn period of 2006-2010). Starting from October 2006, when in the benthos and periphyton a peak of zebra mussel growth was observed, the trophicity of the cooling pond by water transparency and by biomass of phytoplankton corresponded to class I (oligotrophic water). It should be noted separately that the life activity of invasive species *D. polymorpha* not only significantly limited the quantitative development of phytoplankton, but also negatively affect its species diversity. Thus, in July 2006, in the KhNPP cooling pond phytoplankton there were 71 lowest detectable taxons (in transliteration - NOT) of algae, in September 2008 there were only 9 ones, though in September 2010, phytoplankton has been presented by 26 NOT.

At the present stage (2012-2014) under the conditions of the two nuclear power units operation, and under significant reduction of quantitative indicators of zebra mussel [9] there observed a decrease in water transparency to (1,94 ± 0,05) m, respectively, an increase in the abundance of phytoplankton (number - (19 21 ± 2,34) million cells/dm^3, biomass - (3,20 ± 0,35) mg/dm^3). Thus, in recent years of the studies, water trophicity of the cooling pond based on the values of transparency, remained at the same level ï the oligotrophic one, while the values of phytoplankton biomass increased to the level of the year 2001 and corresponded to class III of water quality - eutrophic water. It should be noted that in this particular case an assessment of trophic status and water quality is provided only in terms of the development of phytoplankton and water clarity. For a full assessment of the environmental status of water bodies more different parameters should be analyzed [2].

Indicators of water transparency and phytoplankton biomass, as well as chlorophyll concentration are inversely related [8, 10-13]. Long-term studies on the cooling pond of Khmelnitsky NPP, confirmed the described pattern (Fig. 2).

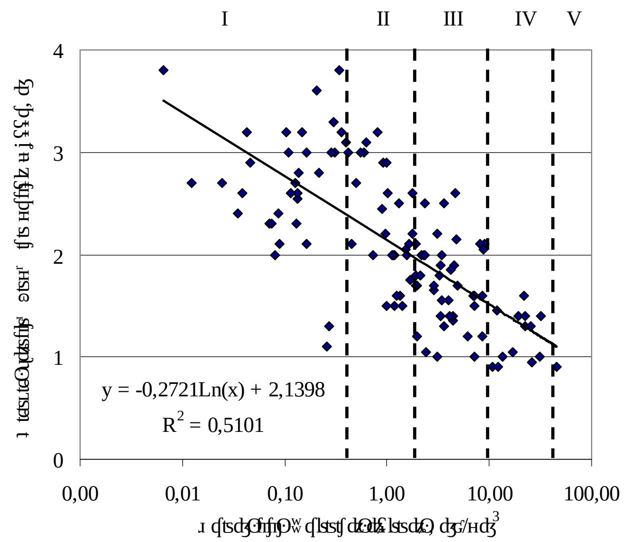

Fig. 2. The relationship of changes in the water transparency and phytoplankton biomass of KhNPP cooling pond in regard to the boundaries of trophic classes and water quality (dashed line) (according to [2]). Trophic types and classes of water quality:
I - oligotrophic, "very clean"; II - mesotrophic, "clean"; III - eutrophic, "contaminated"; IV - polythrophic, "dirty"; V - hypertrophic, "very dirty"

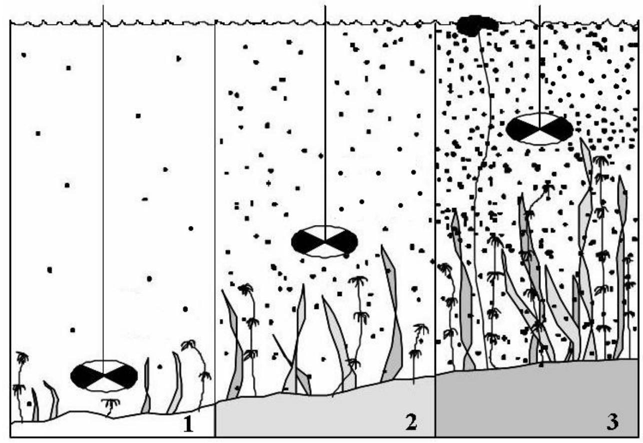

Fig. 3. Various grades of trophicity and conditional development of aquatic organisms in waters with different transparency ([14]). Trophic types:
1 - oligotrophic; 2 - mesotrophic; 3 - eutrophic

Exploring the relationship between transparency and quantitative characteristics of phytoplankton, it is possible based on the operational data on transparency to establish with some certainty the trophic status of the aquatic ecosystems and to judge the probable changes in the ecosystem.

So, if one takes the graph shown in Fig. 2, and divides the scale with indices of phytoplankton biomass to the respective classes of trophicity, it is possible, knowing the water transparency, to determine the zones of a particular trophicity. These relationships are visually shown in Fig. 3 (scale of separation of trophic zones given as in the original [14]).

Thereby, the index of transparency of the water being determined using a measuring disc (the Secchi disk) is very informative and provides data not only on hydro-physical characteristics of a water body, but also the degree of development of plankton. However, it should be taken into consideration that the pond should have no sources of mineral suspended matter, and factors of stirring up the sediments. It was accumulated a large number of measurements of water transparency using this method in different reservoirs. Many of those measurements dealt with the study of plankton and comparative evaluation of the trophic status and the ecological state.

Based on the analysis, the authors consider it appropriate to include the method of measuring the turbidity (water transparency), according to [6] to the regulations of hydrobiological monitoring of the NPP cooling ponds, which is being developed in accordance with [15].

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ZOOPLANKTON OF CHANNELS OF KHMELNITSKY NPP COOLING SYSTEM

Composition and quantitative characteristics of zooplankton of the inflow and outflow channels of the Khmelnitsky NPP cooling system were investigated. It was shown that changes of number of species and their abundance in the channels were connected with intensity of turbulence of the stream, income of waste waters from treatment facilities into the outflow channels, interrelation with water masses of the cooling pond and a season. Sometimes pass through the channels leads to decrease of zooplankton abundance, decrease of Illoricata numbers, and eggs abortion in cladocerans. In order to reveal impact (mechanical and thermal) of the NPP facilities on death of zooplankton, investigations is needed to be carried out with application of methods, enabling to differentiate recently died specimens.

Keywords: zooplankton, supply channel, outlet channel, NPP cooling system, species richness, abundance, structure.

Water-supplying part of the techno-ecosystems of power plants has complex biotopical structure, an important place in which occupy different lothic habitats [1, 2]. In case of water recirculation with involvement of cooling ponds, the last ones, as a rule are usually connected with nuclear power plants (NPP) and thermal power plants (TPP) by inlet and outlet channels. From lenthic conditions of cooling ponds plankton organisms fall into lothic conditions (channels), and then into extremely lothic conditions in cooling systems and technical water supply systems.

Unlike natural lothic ecosystems, techno-ecosystems have not only such important environmental factors, as flow and turbulence, but also the temperature factor in addition to them. It is this factor that varies significantly in the inlet and outlet channels forming the difference in their conditions.

Many publications give evidence of significant mortality of zooplankton under the impact of thermal and mechanical effects of cooling systems. Losses of total number of zooplankton during the season can range from 23.4 to 80%. For example, when passing through the cooling system of Lukoml TPP the average loss of zooplankton per season is about 40-54% (up to 1.2 tones of zooplankton dies per day). [3] Studies of zooplankton of Ladyzhynskaya TPP revealed a five time reduction of quantitative indicators after the passage of the cooling system [4]. Mechanical and thermal effects of cooling system of Konakovskaya TPP led to the death of 34.5% crustacean plankton at 26 °ʉ and 53.6% - at in the 32ð 33 °ʉ [5]. Average daily loss of zooplankton biomass in the summer period were 5-10 tones of wet weight [6]. After passing through the cooling system of Tripolskaya TPP the copepod abundance was reduced by 51%, Cladocera - by 71%, rotifers ï by 24%, and zebra mussel veligers ï by 3% [7]. Thus, the passing through the cooling system adversely affects the state and abundance of zooplankton. It is necessary to draw attention to the fact that different groups of zooplankton respond differently to a technological impact.

If we consider that up to 9.5 million m^3 of water per day runs through the installations at Khmelnitsky NPP (KhNPP), and average biomass of zooplankton in the channels of KhNPP during the growing period is about 3 g/m^3, we can expect the dying out of about 11 tons of plankton per day if we take mortality of 40% [3].

Thermal impacts on zooplankton is observed also in certain areas of cooling ponds. In areas of significant impact of technogenic heating of water (up to 40°ʉ), zooplankton abundance decreases dramatically [7]. It is noted the negative impact of heated waste water on the number of species and diversity of zooplankton species [8]. This effect of water temperature on zooplankton is evidently manifested in the summer and winter seasons. [9] Particularly affected are the major forms of Cladocera and adult Cyclopoida, among which the number of ovigerous females reduce, and eggs are aborted from the brood chambers of cladocerans [3, 5, 9-13]. At the same time, high temperatures are better tolerated by eurytopic and eurythermal types (*Chydorus sphaericus* (O.F. Müller), *Bosmina longirostris* (O.F. Müller), *Diaphanosoma brachyurum* (Liévin)), which often increasing their numbers. As a result, the natural balance of species peculiar to the natural water bodies is disturbed.

Some authors [10, 14] point out the depressing effect of high flow rate and its changes, as well as turbulence of the flow, on the development of major forms of crustacean zooplankton. In the areas of high turbulence the decrease in number of plankton invertebrates is observed, which is related, among other factors, with the increase in water turbidity. There are evidences that zooplankton biomass in certain parts of the channel depends on water consumption [10].

The aim of this work was to study the characteristics of zooplankton in the supply and discharge water channels of the KhNPP, as well as possible impact of anthropogenic factors on its composition and abundance.

Materials and methods. The KhNPP cooling system consists of a cooling pond, the supplying (inlet) channel (SC) and a discharge (outlet) channel (DC) (Fig. 1). The length of the SC is about 1.6 km, depth - 8…9 m, water surface width - 90 m, width at the bottom - 35 m. The banks are lined with concrete, with sand and gravel bottom. The length of the DC is about 4 km, depth - about 4 m, and width - 50 m. Over 700 meters from the start of the channel coasts are lined with concrete, further strengthened with rubble. In the upper part of DC through pipelines waste water is discharged from treatment plants and from Neteshin NPP site [1]. The flow rate in the SC at operation of one NPP unit is 0.1 m/s, two - 0.2 m/s, in the DC ï up to 0.6 m/s. Differences of temperature conditions at entering the SC and when exiting the DC is 0…8,5 °ɥ.

In our work we used the materials of hydrobiological database WaCo of technical laboratory of the Institute for Hydrobiology of NAS of Ukraine which were partially published in [1, 15-18]. The conclusions are based on the analysis of 76 samples of zooplankton, which were taken in 1998, 1999, 2001, 2005-2010, 2012-2014, and which cover all seasons in some years. Sampling stations were located at the entrance to the inlet channel, at the exit from the outlet channel and, in some years in the channels themselves. Zooplankton sampling was performed by filtering 100 liters of water, mainly from the near-surface layer (depth - 0.5 m) through an Epstein plankton net (mesh number 70); in the period of VII.2007, VIII.2008, IX.2008, VII.2009, IX.2012, IX.2014 (Roman numerals denote months, Arab - years) by the method of total vertical plankton net catches, followed by formalin fixation. In the DC due to the high flow rate the samples were taken at a distance of 2.5-3.0 m from the shore. The samples were treated in the laboratory according to standard procedures [19]. To calculate the similarity in species composition of zooplankton we used Sorensen coefficient [20] .

The results of research. The species composition of the zooplankton, entering the channels and coming out of them was characterized by high degree of similarity. Sorensen index values between the study sites during the NPPs operation were 0.53-0.91.

Changes in zooplankton species abundance during the passage of the channel were not unidirectional. The number of the lowest detectable taxon (in transliteration ï NOT) of zooplankton captured at the exit of the outlet channel, in some cases was lower than for the coming one, but in the others it was higher (Fig. 2). The decrease in species abundance was observed in the DC in 47% of cases. The noted increase in several cases, of the number of species of zooplankton in the DC can be explained by possible underestimation of certain small species in the SC, and then detected in the DC, as well as by presence of specific species associated with the outlet channel. In any case, it was observed no significant reduction in the number of zooplankton NOT in the DC including the zone of discharge of circulating water, relative to the SC values.

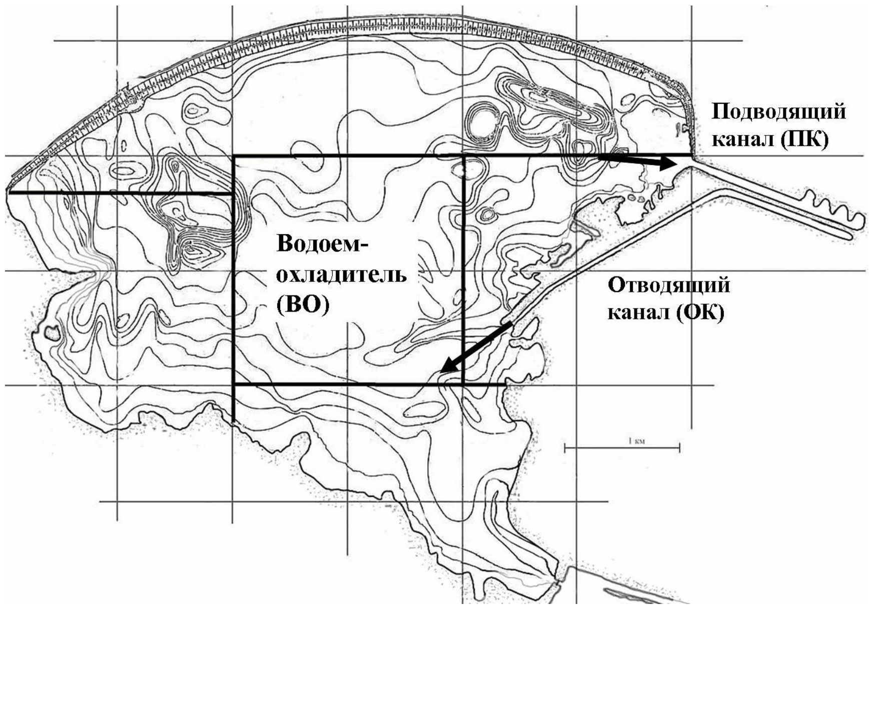


Fig. 1. The scheme of KhNPP cooling system: cooling pond, supplying channel, and discharge channel. The district borders at 1-kilometer map are outlined. The arrows indicate the direction of movement of water from the discharge channel and into the supply channel

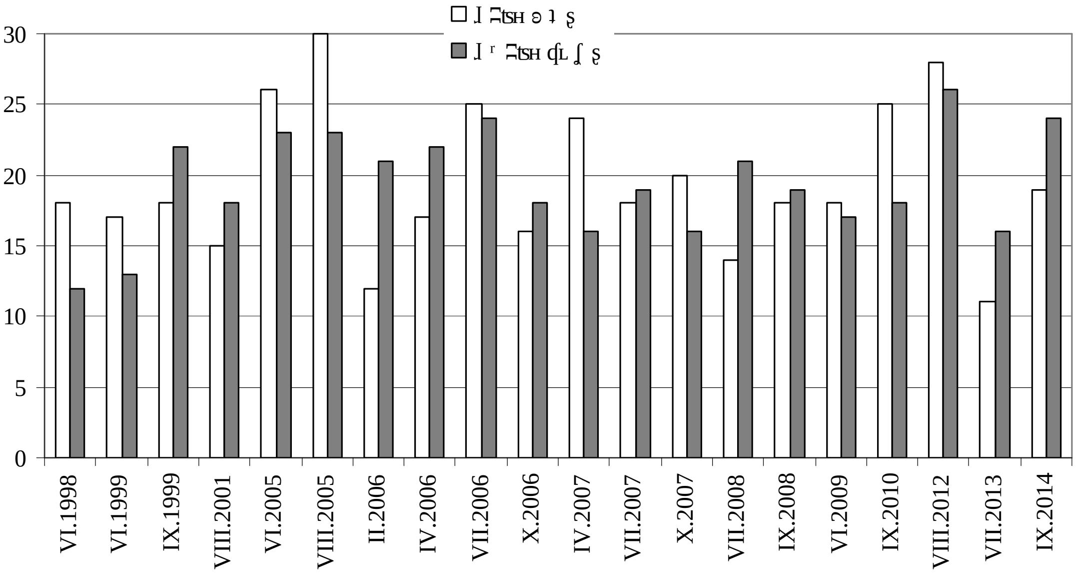
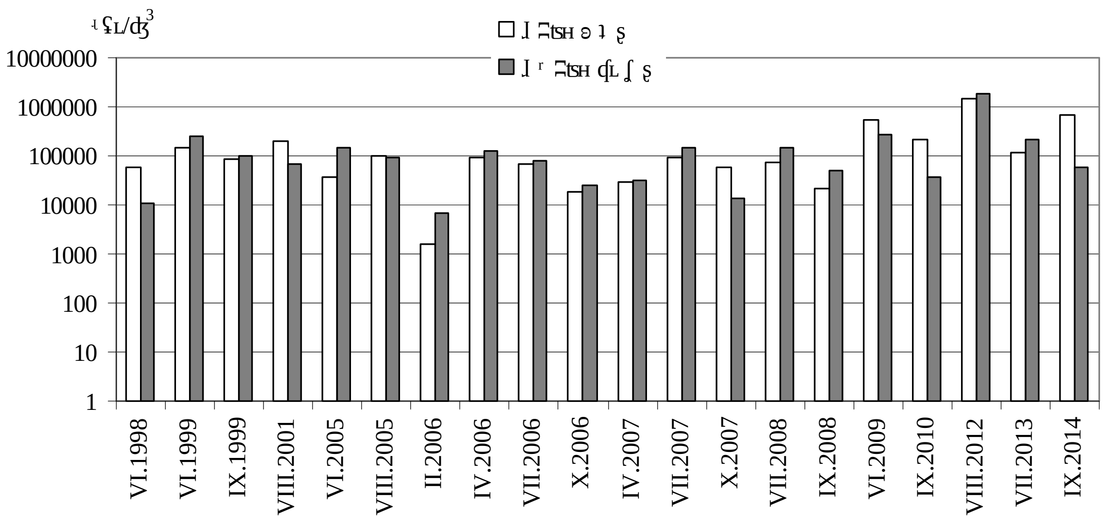


Fig. 2. The number of NOT of zooplankton flowing into and out of the SC (during the study period of VI.1998, VI.1999, and VII.2008 power units were shutdown)



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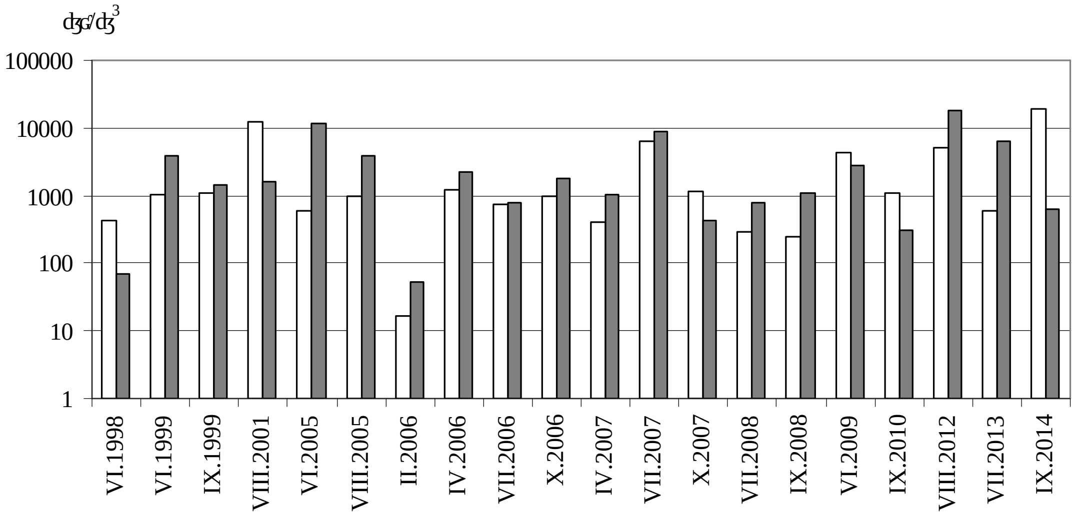
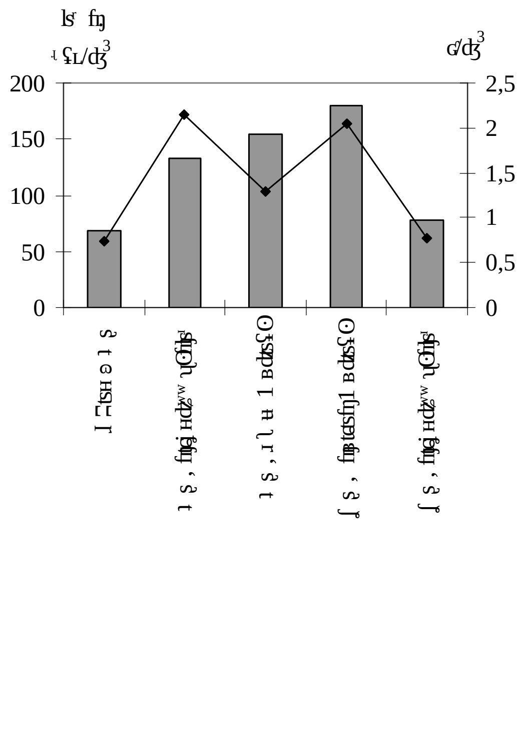


b

Fig. 3. Changes in the number of (a) and biomass of zooplankton (b) in the channels of the KhNPP in different years.

Zooplankton abundance, as well as richness of species, in some cases was higher when exiting the discharge channel in relation to that coming to the supplying channel, while in other cases it was lower (Fig. 3), which may be due to several factors. Lower rates of zooplankton population when exiting the discharge channel was observed in 35% of cases, and for the biomass ï in 29% of cases. The most significant decrease in the abundance of zooplankton flowing through the channels was observed in September 2014, when their number dropped by an order (Fig. 3a), and biomass - by almost 3 orders of magnitude (Fig. 3b).

The data we have on zooplankton in the middle sections of SC and DC do not reveal a clear relationship between the amounts of zooplankton in these sections. There has been some tendency of increase in the zooplankton abundance in the DC. At the same time, we observed significant direct relationship between the abundance and biomass of zooplankton in the supplying channel (the middle part of the channel) and the abundance of zooplankton at the outlet of the discharge channel. This suggests that zooplankton in the channels is heterogeneous in terms of abundance, and the channels themselves are not simply transit Lothic techno-elements of the ecosystem. To understand the causes of these irregularities the detailed studies of different parts of the channels are needed. In any case, in general, according to the available data there is no regular decrease in the abundance of zooplankton in the direction from SC to DC in the KhNPP channels.



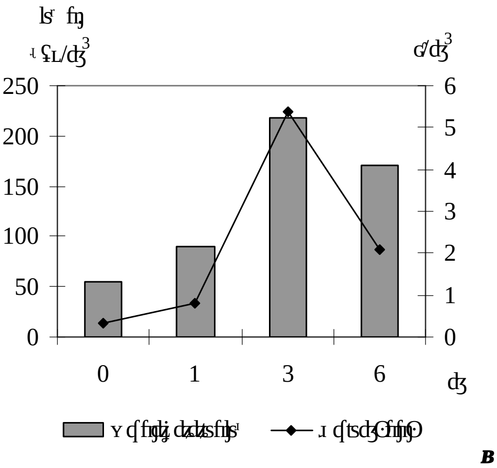


Fig. 4. Changes in zooplankton abundance and biomass in the near-surface layer along the length of the SC and the DC (a) and on the depth in the middle of SCs (b), in July 2006

One of the reasons for such difference in the number of NOT, abundance and biomass of zooplankton at the inlet to the SC and outlet from the DC, is probably the fact that in conditions of high turbulence in the channels there were permanent changes in concentration zones of zooplankton. So, as an example, in July 2006, the number of NOT of zooplankton at the inlet to the SC and outlet from the DC was almost the same (25 and 24 NOT, respectively) but within the channels the abundance of NOT varied widely: 15-23 along the length of the SC, 15 -27 vertically (in the middle part of the SC), 16-28 along the DC. The distribution of zooplankton abundance was inhomogeneous as well (Fig. 4). Changes in the abundance and, especially, in biomass of zooplankton in the channels was often determined by the dynamics of large crustaceans, e.g., *Daphnia longispina* O.F. Müller, whose abundance in different parts of the SC and the DC could differ by 1-2 orders of magnitude.

There were cases when reduction or increase in the number of NOT, and abundance of zooplankton occurred directly in the area of exit from DC (IV.2006, IV.2007, VIII.2012), which can be caused by the interaction of water masses of the channel and the cooling pond, in particular, by coming of plankton from the bottom layers of water. In February 2006, the number of NOT in the area out of the DC was almost doubled (Fig. 1), mainly due to emerge of demersal species. The observed high abundance of plankton in this area may be due to favorable thermal regime in winter.

Zooplankton in the discharge channel was probably influenced by ingress into the upper part of the channel of wastewater from sewage treatment plants, which was more apparent in the absence of flow when there was an accumulation of phosphates, nitrates and other substances in the water of the channel that resulted in significant development of the phytoplankton [1]. In July 2008, when there were no technogenic circulation and entry of heated water, in the DC in the area of dumping of sewage from treatment plants there was a sharp increase in the taxonomic abundance of zooplankton: the number of NOT in the SC was 14, in the DC lower the point of dumping facilities - 25, at the exit from the DC - 21. Similar differences were observed in the distribution, abundance and biomass of zooplankton: 71.16 thousand. ind/m^3 and 0.29 g/m^3 in the SC; 287.59 thousand ind/m^3 and 1.94 g/m^3, in the DC; 145.10 thousand. ind/m^3 and 0.80 g/m^3 at the outlet of the DC (Fig. 4a). In the SC sharp decline of diversity and abundance of both phytoplankton and zooplankton was due to zebra mussel filtration activity [1]. In the zooplankton of the DC a lot of rotifers were observed (78.5% of the number and 70.5% of zooplankton biomass), including 5 species of the Brachionus, which is typical for wastewater and sewage [21]. The most numerous among them *Brachionus calyciflorus* Pallas (137.93 thousand ind/m^3) was 48% of the population of the entire community. Mass development of rotifers *B. calyciflorus* (up to 536 thousand ind/m^3) was also noted in the areas of rivers, which were influenced by wastewater [22]. On this part of the DC eurytopic the species *B. longirostris* and *Moina rectirostris* (Leydig) were developed. When exiting the DC the structure of zooplankton again changed into the predominance of copepods, which dominated in the SC.

It was noted that quantitative characteristics of development of zooplankton directly below the dumping points of the power units were higher than in the supplying channel. Such a phenomenon was observed also by other researchers, whose explainaitions were that in the vicinity of dumping point there was accumulation of still, traumatized and decaying crustaceans that in the processing of samples were often had no difference from living ones [5]. Another reason for the increase in amount of zooplankton in dumping water as compared to intake water is the possible accumulation and subsequent flushing of plankton away of rotating flat screens in the moment of their start. [7] Many authors have noted that the standard fixed samples of zooplankton contain dead organisms with no visible signs of deterioration, mistakenly recorded as alive ones. Their share ranges from a few percent in areas with favorable conditions for zooplankton to 100% in extreme conditions [14]. In this paper we did not use the techniques which enables us to identify dead, but morphologically unchanged plankton organisms. Probably for this reason, indicators of zooplankton abundance immediately below the dumping points of the power units were higher than those at the inlet. Thus; for example, in July 2006 (Fig. 4a) below the discharge point of KhNPP Unit 1 the measured values of zooplankton abundance (179.65 thousand ind/m^3 and 2.04 g/m^3) were slightly higher, compared with those in the area of water intake (154.37 thousand ind/m^3 and 1.3 g/m^3). In September 2010, the DC below the discharge point of the second unit the total number of zooplankton decreased, while the number of large cladocerans and calanids was higher, resulting in two-time increase in zooplankton biomass.

Unlike crustaceans, non-crust forms of rotifers are destroyed faster. Reduction of the number of non-crust forms of rotifers (Synchaeta, Polyarthra etc.) as a result of the passage of the channels was registered in most cases. Most notable is the decline recorded in June 2009, when the rotifer, which amount in the SC was about 87.00 thousand ind/m^3, was absent in the plankton when exiting the DC.

As the negative impact of the plant on zooplankton the abortions of eggs of cladocerans was observed. Their number in the cooling pond in September 2014 reached 11.64 thousand ind/m^3.

Among the taxonomic groups of zooplankton in the KhNPP channels copepods often dominated by number, cladocerans ï by biomass, (more rarely ï copepods). In some periods taxonomic adjustment was observed within the channels, with increase of the share of rotifer. In the DC it was probably caused by the influence of the sewage treatment plants. Despite this, the ratio of the taxonomic groups of zooplankton at the entrance of the channels and at their exit was generally similar.

Differences in the composition and abundance of zooplankton of the studying sections of the channels during periods when power units were not in operation (VI.1998, VI.1999, VII.2008), reflect the conditions in the surrounding areas of the cooling pond.

Conclusions

As a result of the passage of KhNPP channels quantitative indicators of zooplankton development were changed differently, and, in most cases, in small range. This may indicate that specific factors of circulating water in KhNPP channels (flow rate, turbulence, water temperature, the length of the channel, and others) adversely affect on the composition and structure of zooplankton only in cases of a particular combination of unfavorable conditions, the study of which is the task of future researches.

The research results show that in the channels there is no simple mechanical transit of zooplankton, and its amount ranges, varying in time and space. Differences in the number of NOT and abundance of zooplankton at the entrance to the SC and when exiting the DC, were mainly caused by the turbulence of flow that leads to inhomogeneous distribution of zooplankton in the channels, the impact of wastewater from treatment facilities on the zooplankton in the outlet channel, and the interaction with water masses of the cooling pond in the areas adjacent to the channels.

In some periods, as a result of passage of the KhNPP channels and circulation system there were observed decline in zooplankton abundance and size of non-crust rotifers, as well as the abortion of eggs from the brood chambers of cladocerans. To determine the impact of plant units operation (mechanical and thermal) on death of zooplankton, further studies are needed using techniques that identify the dead organisms of morphologically unchanged plankton.

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PHYTOPLANKTON OF WATER BODIES OF KHMELNITSKY NPP TECHNO-ECOSYSTEM AND ITS BACKGROUND WATER BODIES

The results of studies of phytoplankton in background water bodies of Khmelnitsky NPP techno-ecosystem are presented. It is shown that study of background water reservoirs is an important constituent of hydrobiological and environmental monitoring. In this case the mutual negative influence between NPP techno-ecosystems and background reservoirs was not observed.

Key words: phytoplankton, NPP techno-ecosystem, cooling pond, background water bodies.

Hydrobiological and ecological monitoring of ecosystems, directly related to the production cycle of nuclear power plants, is the basis for conclusions about the possible or actual negative impact of a nuclear power plant (NPP) on the environment. However, the external ecosystems may be the cause of various biological interferences with an NPP. According to the "Regulations of hydrobiological monitoring ..." [1], in the hydrobiological observations and the more general environmental monitoring of NPP techno-ecosystem one should focus on observing the background of water bodies and their ecosystems. These are water bodies or waterways which are located on the territory adjacent to the plant, hydraulically connected to the water part of the NPP techno-ecosystem and having no direct effect of the system of technical water supply of the NPP.

Some background water bodies serve as water sources external to the NPP cooling pond and, accordingly, they are the sources of biomass coming into the pond. A water source can introduce invasive species that do not have clearly negative impact within the natural habitat or natural bodies of water, but can cause serious ecological and economic damage in terms of techno-ecosystem of an NPP [2]. And effect of the cooling pond on the biota of background reservoirs is also possible. In this case, it is the monitoring of background water bodies that gives information about the influence of an NPP techno-ecosystem on the environment.

Phytoplankton (a community of algae that live in the water column) is highly sensitive to environmental conditions and it dynamically respond to their changing. Change of algae community can occur within a short time after the conditions have changed. Thus, we can use the condition of the plankton algae as an indicator of the condition of the main parameters of the biotic component of the aquatic ecosystem. Because of the need to obtain information on populations of species, unwanted for nuclear power plants operation, it is recommended to carry out monitoring of phytoplankton in the background reservoirs both at routing monitoring and at the extreme and the expanded monitoring [1].

These studies were carried out to investigate possible mutual influence of NPP techno-ecosystem and background water bodies on the example of the techno-ecosystem and background water bodies of Khmelnitsky NPP (KhNPP).

Objects and methods of research. Among the water bodies mentioned below, only the cooling pond and slurry tank are involved in the KhNPP production cycle. All other water bodies are the background ones in their relation to the KhNPP techno-ecosystem. These water bodies are:

The Goryn river (the Pripyat River basin) refers to the waterways of flat land type, within the 30-km zone of KhNPP the channel segment is 157 km. In the studied area the river has a width of 30-40 m, depth 0.6-2.5 m, with a sharp increase from the shore, the flow velocity is 0.45-0.60 m / sec. For the cooling pond it is the water source of feeding make-up water;

The Gniloy Rog river (the left bank second order tributary of the river Gorin) has 28 km length, the entire drainage basin is within a 30-km zone of KhNPP. Water yield of the river is fully accumulated in the cooling pond. In the lower part of the stream a part of the river is artificially straightened (channeled). Wellhead section of the river is the bay, which was formed due to the backwater of the dam before the river inflow into the water reservoir. The bay is separated from the cooling pond with a dam;

The drainage canal, designed to intercept the flow of water drainage and supply it to the pumping station of seepage water, through which the drainage water is returned back to the cooling pond. Power drain channel is fed by water precipitation and drainage of groundwater, including those from the cooling pond through the dam. Due to this, the temperature of water in the drainage channel in the summer-autumn period, in average figures, is 5°ᵾ lower than in the other background water bodies, and 13°ᵾ lower than in the cooling pond (Table 1).

The flowing water open pit, located on the river Gorin 5.4 km along the riverbed (including meanders) from the place of confluence of the channel connecting the cooling pond to the river Gorin;

The open pit of make-up water linked by channels with the Gorin and the cooling pond;

The channel on which the additional water from the river Gorin through the open pit enters the pond. The channelôs length is 2.4 km.

As it was noted above, the KhNPP techno-ecosystem includes the cooling pond and the slurry reservoir. The cooling pond is a water reservoir on the river Gniloy Rog with the area of 20 km^2 and a volume of more than 100 million m^3. Slurry reservoir is intended for receiving purge water of clarifiers of chemical water treatment. Excess of water from the slurry reservoir can be discharged into the cooling pond.

Investigations of phytoplankton were carried out in summer and autumn of 2012 and 2013. Samples were taken on the river Gorin at the site within the 30-kilometer zone of KhNPP, on the river Gniloy Rog ï on the natural area in the downstream, on the canalized section and on the outfall before flowing into the cooling pond. Phytoplankton sampling was carried out on clean water from the surface horizon. Collection, preservation and processing of the material was carried out by conventional methods in hydrobiology [3]. The species composition of planktonic algae of different water bodies were compared by calculating the Sorensen coefficient of floristic community [4]. For description of the taxonomic composition the term Lowest Detectable Taxon (NOT - in Ukr. transliteration) is used.

The results of research. In the years 2012 and 2013 in phytoplankton of the river Gorin 16 and 39 NOT of algae were discovered, respectively. Taxonomic composition was quite different (47% by Serensen). In both years as in relation to floristic and quantitatively the green algae dominated. They were mostly *Pseudodidymocystis planctonica* (Korsch.) Hegew. et Deason, species of the genus Crucigenia, *Kirchneriella lunaris* (Kirchn.) Möb., and on biomass as subdominants there were diatoms *Cyclotella sp.*, *Aulacoseira granulata* (Ehrenb.) Sim. High values of the Shannon index (Table 1) and uniformity indicate the absence of a pronounced dominant.

Phytoplankton of the Gniloy Rog river (NOT = 43 in 2012 and 75 in 2013) was formed mainly by diatoms. In different sections of the river it was joined by green, cryptophytae and Euglenophyta as subdominants. It should be noted here that blue-green algae, particularly of the genus Microcystis, was presented more broadly in quantity both in the species composition and in dominant complexes than the phytoplankton of the Gorin river. As for green chlorococcales, the basis of their quantity was formed by the same types as in the Goryn river, as well as by *Monoraphidium contortum* (Thur.) Kom.-Legn., *Coelastrum microporum* Näggeli. Diatoms *Cocconeis placentula* Ehrenb. were part of the composition of leading systems on their biomass. Indicators of taxonomic diversity (the Shannon index) and evenness were similar to those for phytoplankton of the Gorin river.

The species composition of phytoplankton in the drainage channel was extremely poor (7 NOT, with 6 of them - diatoms, and 1 - cryptophytae). The population and biomass was formed mainly due to large-cell diatom algae *Synedra ulna* (Nitz.) Ehrenb, which caused low values of diversity and evenness.

The flowing water open pit on the river Gorin was characterized by qualitatively rich phytoplankton.

Table 1. Structural indicators of phytoplankton (averaged values) of the background ponds, the slurry reservoir and the cooling pond of Khmelnitsky NPP (2012-2013).

Name of the water body	Temperature *t*, °ᵾ	Number *N*, mil cells/dm^3	Biomass ɹ, mg/dm^3	Diversity (the Shennon index)		Evenness	
				On number ɿ $_N$, bit/ specimen	On biomass ɿ $_ɹ$, bit/mg	On number J_N	On biomass J_B
the river Goryn	20,3	10,70	1,29	3,50	3,50	0,80	0,80
the river Gniloy Rog	19,5	14,16	1,87	3,00	3,14	0,74	0,77
The Drainage channel	15,8	1,03	4,25	2,08	0,50	0,74	0,20
The flowing water open pit on the Goryn	20,8	6,76	1,36	3,78	3,87	0,72	0,74
The make-up water open pit	21,0	356,24	41,29	1,24	2,01	0,26	0,43
The channel of additional water open pit	20,8	4,95	63,71	2,64	0,35	0,68	0,09
The slurry	21,0	4,51	0,68	3,21	3,05	0,87	0,82

accumulation reservoir							
Cooling pond	28,6	12,37	3,67	2,42	2,58	0,57	0,61

There were registered 38 NOT of algae from 7 phylums. In the floristic spectrum the green (57.9% of the total number of species) and diatom species (23.7%) were dominated. The composition of the dominant complex population consisted of blue-green *Hydrococcus rivularis* Kütz., Green Ps. *planctonica*, cryptophytae *Rhodomonas pusilla* (Bachm.) Javorn. Biomass was formed mainly by diatoms *A. granulata, Cyclotella meneghiniana* Kütz., and Ps. *planctonica*. High values of the Shannon index and evenness show uniform distribution of species in the community.

The floristic spectrum of phytoplankton in the open pit of make-up water, there were 26 NOT of algae from 6 phylums. The green (30.8%), blue-green (26.9%) and diatoms (23.1%) algae were dominated. High values of the number (356.240 000 cells/dm^3) were caused by massive development of cyanobacteria, particularly *Aphanizomenon isatchenkoi* (Ussatsch.) Pr.-Lavr. The basis of the biomass (41.29 mg / dm^3) was formed by large-dinoflagellates *Ceratium hirundinella* (O. Müll.) Schrank *and Aph. isatchenkoi* as subdominant. Monodomination of *Aph. isatchenkoi* on numer (78.9% of overall indexes) has resulted in low value of the Shannon index and the evenness.

The phytoplankton of the channel connecting the open pit of make-up water and the cooling pond, amounted 15 NOT of algae belonging to 6 phylums. There the decline of blue-green algae has resulted in reduction in the total number to 4.95 million cells /dm3, which, however, did not affect the level of biomass (63.71 mg/dm3). The *Aphanizomenon flos-aquae* (L.) Ralfs. were dominated in number, and *C. Hirundinella* **ї** in biomass, which ensured the extremely low values of the Shannon index and the evenness.

Phytoplankton of the slurry reservoir was consisted mainly of the green algae: 10 NOT among 13, or 82.1% of the total population, or 86.8% of the total biomass. The dominant complex numbers were *Ps. planctonica, Tetraedron caudatum* (Corda) Hansg., *K. lunaris*, and on biomass - *Ps. planctonica, Cosmarium sp., Pediastrum boryanum* (Turp.) Menegh. The values of the Shannon index and evenness are characteristic of polydominant community/

In 2012 and 2013 the phytoplankton in the cooling pond consisted of 84 and 59 NOT of algae, respectively. In general, the ratio of systematic groups in both years was similar, but in 2013 in each group the number of its component species was substantially decreased. Taxonomic composition data were quite different (50% similarity on the Sorensen index). In both years in relation to floristic green algae predominated (58.3% and 55.9% of the total value, respectively). The level of population is determined mainly by the development of *M. aeruginosa*, and in 2012 the subdominants were *Binuclearia lauterbornii* (Schmidle) Pr.-Lavr., *Rh. pusilla, Cryptomonas* sp. Biomass in both years was determined by domination of *A. granulata and Cryptomonas sp*. The average value of the Shannon index and evenness in 2013 were lower due to the mass of *M. Aeruginosa.*

The calculated Serensen values of the similarity rate of NOT of the phytoplankton content in the background water bodies, the cooling pond and the slurry reservoir were fluctuated in a wide range: from the complete lack of similarity to a value of 0.47. Out of 7 NOT (Lowest Detectable Taxons) of phytoplankton in the drainage channel, only 3 were met in other water bodies, and that led to a low average value of the similarity rate with other lists (0.08). Of all the investigated water bodies the average values of pairwise similarities were the highest in phytoplankton of the cooling pond (0.28) due to its high species richness. The cooling pond and the river Gniloy Rog having constant fluid communication were characterized by maximum value of the similarity of species composition (0.47) and a similar level of quantitative development of phytoplankton. It should be noted that the open pits, one of which is located directly on the river Goryn, and the other one is in constant connection with it, on the composition of phytoplankton had a few more similarities with the cooling pond (0.32 and 0.27, respectively) than with the river (0.23 and 0.24). Thus, the growth of phytoplankton in the open pits was influenced rather by hydrodynamic than by thermal conditions.

No species were revealed that could be potentially dangerous if caught in the techno-ecosystem of KhNPP in the sense of creating biological noise in the background reservoirs

Discussion of the results. Plankton algae are one of the important biological elements determining the ecological status of water bodies under the Water Framework Directive [5]. Phytoplankton is also included in the list of recommended biological objects during hydrobiological monitoring of a cooling pond, cooling systems and NPP technical water supply systems [1]. The importance of characteristics of the state of phytoplankton at studying aquatic ecosystems is determined by its high production characteristics and speed of response to changes in the environment parameters. Background ponds are either sporadically or permanently in fluid communication with the cooling pond and therefore, as noted above, may pose a threat as a source of biota, causing biological interference in power and significantly affects the state of the cooling pond

For example, during our research in the open pit of back-up water the biomass of blue-green algae (19.3 mg/dm^3) corresponded to the fourth degree of water "flowering" (strong). These are environmentally hazardous levels, causing considerable biological pollution and killing phenomena. At the same time directly in the cooling pond the recorded biomass of cyanobacteria did not reach dangerous values (maximum 1.71 mg/dm^3) and mainly was caused by the development of *M. aeruginosa*. Also, along with the water from this open pit the dinoflagellates *C. hirundinella* came in the cooling pond, which has a large individual mass and, therefore, even in small amounts substantially affects the value of the total biomass of phytoplankton and thus the quality of water. The phytoplankton in the open pit water at the number of 0.18 million kl./dm^3, which amounted to 0.1% of common indicators, *C. hirundinella* formed 44.0% of the biomass or 18.16 mg/dm^3. On this indicator, the water quality in the open pit reservoir corresponded to 6 category of the 4th grade of quality, or "dirty." In the phytoplankton in the channel connecting the open pit reservoir and back-up water cooling pond, *C. hirundinella* formed biomass, which corresponded to 7 category of the 5th grade of quality - "very dirty". In the years 2012 and 2013 the water quality of the cooling pond by phytoplankton biomass corresponded to the category 4 of the 3rd grade - "slightly contaminated" water

Conclusions

As a summary, no negative impact of NPP techno-ecosystem on background ponds was observed, and their bio-funds currently do not have any significant impact on hydrobiological state of the cooling pond. Nevertheless, some types of algae coming from the open pit reservoir water, for example, *C. Hirundinella,* can create a significant biomass of phytoplankton in the cooling pond. The carried researches have shown the reasonability of the monitoring studies of background water bodies, particularly on phytoplankton, but while monitoring it is necessary to constantly adjust the selection of water bodies and the volume of research in each of them.

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ASSESSMENT OF ENVIRONMENTAL RISK TO THE PUBLIC AT COMBUSTION OF COAL AT THERMAL POWER PLANTS IN UKRAINE

In this article the conceptual approach to assessment of ecological risks to the public from chemical and radioactive substances during normal operation of thermal power plants (TPP) of Ukraine is used. The data on non-carcinogenic, carcinogenic and radioactive substances emissions in air of thermal power plants are analyzed and comprehensive assessment of ecological risk to the public from chemical and radioactive emissions into the atmosphere by coal combustion at TPP is provided.

Keywords: thermal power plant; non-carcinogenic, carcinogenic and radioactive substances; environmental risk

Thermal power plants (TPP) impact on the public is caused by air emissions at the stage of coal firing, and depends on the type and amount of fuel consumed, ways of its use and effectiveness of purification of emissions [1, 2].

TPP discharge into the environment ash, volatile matter, benzo(a)pyrene (the most toxic among the polycyclic aromatic hydrocarbons), as well as gaseous substances (sulfur dioxide, nitrogen oxides and carbon monoxide) [3]. Volatile ash contains heavy metals (vanadium, zinc, lead, copper, mercury, cadmium, chromium, nickel, arsenic) [4], as well as natural radionuclides (NRN) of uranium and thorium family. [5]

Of particular danger to health are heavy metals and NRN, which are carcinogenic and can cause cancer, and gaseous substances toxic to the human body [6].

For the environmental risk assessment it is important to take into account the contribution due to the action of both carcinogenic and non-carcinogenic substances which are toxic by nature.

The main potential of thermal power industry in Ukraine are large thermal power plants of capacity over 300 MW, such as Uglegorskaya, Starobeshevskaya, Kurakhovskaya, Slavianskaya, Zuevskaya (Donetsk region); Prydnieprovskaya, Kryvorozhskaya (Dnipropetrovsk region); Luganskaya (Lugansk region) Dobrotvorskaya (Lviv region), Burshtynskaya (Ivano-Frankivsk region), Zaporizhzhskaya (Zaporozhye region), Ladyzhinskaya (Vinnytsia region), Tripolskaya (Kiev region), and Zmiivska (Kharkiv region) that used coal as the main fuel.

All thermal power plants are the source of environmental pollution and the object of high-risk to the ecology [7, 8].

Assessing the environmental risk to the public health is widely recognized around the world. It should be noted that the health of the population is considered as a system-forming factor of social and economic development of the society, and the risk index characterizes the degree of damage to the environment and human health by harmful factors of different nature [9-13]. This article examines the environmental risks for the population under the influence of chemical and radioactive discharges of TPP [14, 15].

The lack of studies on the impact of full component composition of TPP emissions into the atmosphere from the coal firing makes it necessary to assess the environmental risk.

The article uses the term "environmental risk" as the probability of adverse effects on the public health due to contamination of the environment by chemical and radioactive substances [14, 15].

Methodological approach to the environmental risk assessment. Currently in Ukraine there is no method of assessing environmental risk to the public during normal operation of thermal power industry generally accepted and approved at the legislative level.

The conceptual approach to environmental risk assessment involves two elements - the risk assessment and risk management [11, 13, 16, 17].

The main steps in the process of environmental risk assessment for the population during normal operation of TPP are [14-18]:

The first stage ï identification of hazard - includes hazard identification, identification of sources and environmental risk factors (chemical and radiation), as well as areas of risk dissemination;

the second phase - exposure assessment - is evaluating the real impact of environmental risk factors on the population;

the third stage - evaluation of "dose-response" dependence is linked with the analysis of impact of risk factors and determination of environmental sustainability against impact of chemical and radiation factors;

the fourth or the final stage ï risk characterization - includes the analysis and generalization of information on the qualitative and quantitative parameters used in the previous stages, as well as identifying a source of occurrence and severity of risks in specific scenarios and routes of exposure to environmental risk factors.

The main purpose of managing environmental risks hazards to the public health in normal TPP operation is to identify ways to reduce the risk of the given constraints on time and resources.

The probabilistic approach of integrated assessment of environmental risks to the public health, proposed by the authors in this article is used to determine the expected number of additional cases of stochastic effects at actual emissions of chemical and radioactive substances from thermal power plants, with the data taken from [19, 20].

According to the Haber law [21], the risk of long-term consequences to human health, i.e. seriousness of the disease emerged, is proportional to the concentration of the chemical *c*, and the time of exposure to the chemical *t*.

According to this law, the concentration of chemicals, calculated over definite period of time can be used for evaluation of exposure to chemicals [22].

It is believed that the environmental risk *r*, due to the impact on the population of non-carcinogenic, carcinogenic and radioactive substances in the environment, depends on their amount, entered into the human body:

$$r = f(D), \qquad (1)$$

where $f(D)$ ð a function of dose of a substance entered the human body.

It is assumed that at low doses the ratio between the dose of the chemical reaction D_{ch} and reaction to it is linear [22], and effect of non-carcinogenic and carcinogenic chemicals does not have a threshold. Then the additional risk established for the entire duration of an individualôs life, or the number of additional cases of diseases, leading to the death of the population, can be calculated taking into account the coefficients of non-carcinogenic risk per unit dose to the population permanently living in the area of operation of thermal power plants.

If one accepts the hypothesis on the linear no-threshold nature of the "dose-effect" dependence at low doses, the formula (1) to estimate the additional risk [21] can be written as follows:

$$r(D_{\text{ch}}) = F_{D_{\text{ch}}} \cdot c \cdot \nu \cdot t, \qquad (2)$$

where D_{ch} ð dose of a chemical, mg; $F_{D_{\text{ch}}}$ ð coefficient of risk, proportional to the slope of the curve "dose-effect", as shown in [14, 15, 21, 22], which reflects the degree of risk increase with increasing exposure dose of the chemical per unit dose, mg^{-1}; c ð concentration of the chemical, mg/m^3; $\nu = 8{,}10 \cdot 10^3$ ð the intensity of the receipt of the carcinogens-containing air inhaled by a person, m^3/year; t ð the time during which non-carcinogenic and carcinogenic chemicals were ingested/inhaled, years.

In [11, 13, 16, 21] it was founded, and now is accepted by the authors the reasonable level of risk for non-carcinogenic chemicals is 10^{-6} per year, for carcinogenic chemicals and NRN ð 10^{-5} per year [17, 24ð 27].

On the assumption that, in relation to the average daily maximum permissible concentrations (ɟ ɼ ş ffȷŋ or MPCs) [23], the annual intake of a chemical into the body gives a certain increase of additional cases of serious consequences for public health [22], the formula for the calculation of the risk coefficient $F_{D_{\text{ch}}}^{\text{ncanc}}$ to non-carcinogenic chemicals per dose unit can be written as follows:

$$F_{D_{\text{ch}}}^{\text{ncanc}} = \frac{10^{-6}}{\text{ɟ ɼ ş ffȷŋ} \cdot \nu}, \qquad (3)$$

where ɟ ɼ ş ffȷŋ ð average daily maximum permissible concentration, mg/m^3

The coefficients for environmental risk for the investigated non-carcinogenic chemicals were calculated by the authors of this article using the formula (3). Risk factors for the cancer-causing chemicals $F_{D_{\text{ch}}}^{\text{canc}}$ were taken from [16, 23] and recalculated for the dimension of [mg^{-1}] (Table 1).

Table 1. Coefficients of environmental risk under impact of chemicals

For non-carcinogenic substances

Substance	$F_{D_{ch}}^{ncanc}$, mg^{-1}
SO_2	$1{,}54\cdot10^{-9}$
NO_x	$3{,}09\cdot10^{-9}$
CO	$4{,}11\cdot10^{-11}$
Solid particles	$8{,}23\cdot10^{-10}$
Hg	$4{,}11\cdot10^{-8}$
Zn	$1{,}37\cdot10^{-6}$
Cu	$6{,}17\cdot10^{-6}$
V	$1{,}76\cdot10^{-6}$
Pb	$8{,}23\cdot10^{-7}$

For carcinogenic substances

Substance	$F_{D_{ch}}^{canc}$, mg^{-1}
Ni	$5{,}09\cdot10^{-7}$
As	$8{,}39\cdot10^{-6}$
Benz (a)pyrene	$1{,}73\cdot10^{-6}$
Cr	$2{,}35\cdot10^{-5}$
Cd	$3{,}52\cdot10^{-6}$

Individual dose at exposure to chemicals is determined by the product of the chemical concentration c, the intensity of the receipt of the inhaled air by a person ν, and the total time of its receipt t. In view of the foregoing, one can rewrite the formula (2) for calculating environmental risk as

$$r_{ch} = F_{D_{ch}} \cdot D_{ch}^{èíä}, \qquad (4)$$

where r_{ch} ð the probability of stochastic effects when exposed to non-carcinogenic and carcinogenic chemicals, reduced to one year exposure.

The expected number of extra cases of stochastic effects for the population under the influence of chemical R_{ch} is defined as:

$$R_{ch} = F_{D_{ch}} \cdot D_{ch}^{êîë}, \qquad (5)$$

where $D_{ch}^{êîë} = D_{ch}^{èíä} \cdot \rho \cdot S$ ð collective dose at exposure to chemicals, man-mg; ρ ð population density, man/km^2; S ð population area, km^2.

International Commission on Radiological Protection (ICRP) [25] and the United Nations Scientific Committee on the Effects of Atomic Radiation (UN SCEAR) [26], taking into account the concept of a linear no-threshold model, believe that any dose different from zero, is associated with risk.

Radiation risk r_r, as the probability of induction of stochastic effects (occurrence of oncological diseases and serious hereditary effects of radiation exposure) per unit dose NRN, is given by formulae [24-26]

$$r_r = F_{D_r} \cdot D_r^{èíä}, \qquad (6)$$

where $D_r^{èíä}$ ð individual effective equivalent dose, Sv; F_{D_r} ð proportionality factor, which determines the slope of the "dose-response" curve due to the effects of ionizing radiation, which reflects the degree of risk rise with increase of exposure dose per unit, Sv^{-1}.

The expected number of cases of stochastic effects from the exposure to ionizing radiation in the population is given by [24ð 26]

$$R_r = F_{D_r} \cdot D_r^{êîë}, \qquad (7)$$

where $D_{\text{r}}^{\hat{e}\hat{i}\ddot{e}} = D_{\text{r}}^{\grave{e}\acute{i}\ddot{a}}$ ĀрĀS ð collective effective equivalent dose, man-Sv.

In accordance with the ICRP publication [25] the total damage is a complex value, which indicates the probability of developing cancer and severe hereditary effects in the population in general.

Risk factor of stochastic effects for the population $F_{D_{\text{r}}}$ is equal to 5,7Ā10^{-2} Sv^{-1} (for cancer ï 5.5Ā10^{-2} Sv^{-1}, for serious hereditary effects ï 0.2Ā10^{-2} Sv^{-1}) [25].

The above approach of evaluation of environmental risk will enable to assess integrally the radiological and chemical components of environmental risk in unified indices of probability of stochastic effects per unit of individual dose, and the number of cases of stochastic effects for the population per unit of collective dose using conversion factors for chemicals (see. Table . 1) and radioactive substances [25].

Indicators of environmental risk to the population under the impact of thermal power plant emissions. Based on the data about the number of non-carcinogenic chemicals in emissions of TPP in Ukraine for 2004-2012 years [19] it was determined that particulate emissions are in the range of 1.22 for Uglegorskaya TPP to 157 thousand tons/(GW (e.)·year) for Kurakhovskaya TPP; NO_x - from 1.97 on Uglegorskaya to 226 of the Krivoy Rog TPP; SO_2 - from 13.3 at the Krivoy Rog TPP to 1130 for Ladyzhynskaya TPP; CO - from 0.41 on Dobrotvorskaya TPP to 5.55 at the Krivoy Rog TPP (Fig. 1).

The average annual gas emissions are: SO_2 - 95,4; NO_x - 14,18; CO - 0,96 thousand t/(GW (e.)·year); solids - 33.7 thousand t/(GW (e.)·year).

The average annual concentration of gaseous emissions at a distance of 1 km (minimum distance to the nearest town) per 1 GW (e) for TPP are: SO_2 - 6,23·10^{-1} mg / m3 NO_x - 9,69·10-2 mg/m^3, CO - 6,24·10^{-3} mg/ m^3; particulate - 2,20·10^{-1} mg/m^3. Individual dose when exposed to a chemical for a septuagenarian period are: solids - 1,25 Ā10^5 ; for SO_2 - 3,53 Ā105, NO_x - 5,49Ā10^4, solids - 3,54Ā10^3 mg/(GW (e.)·year).

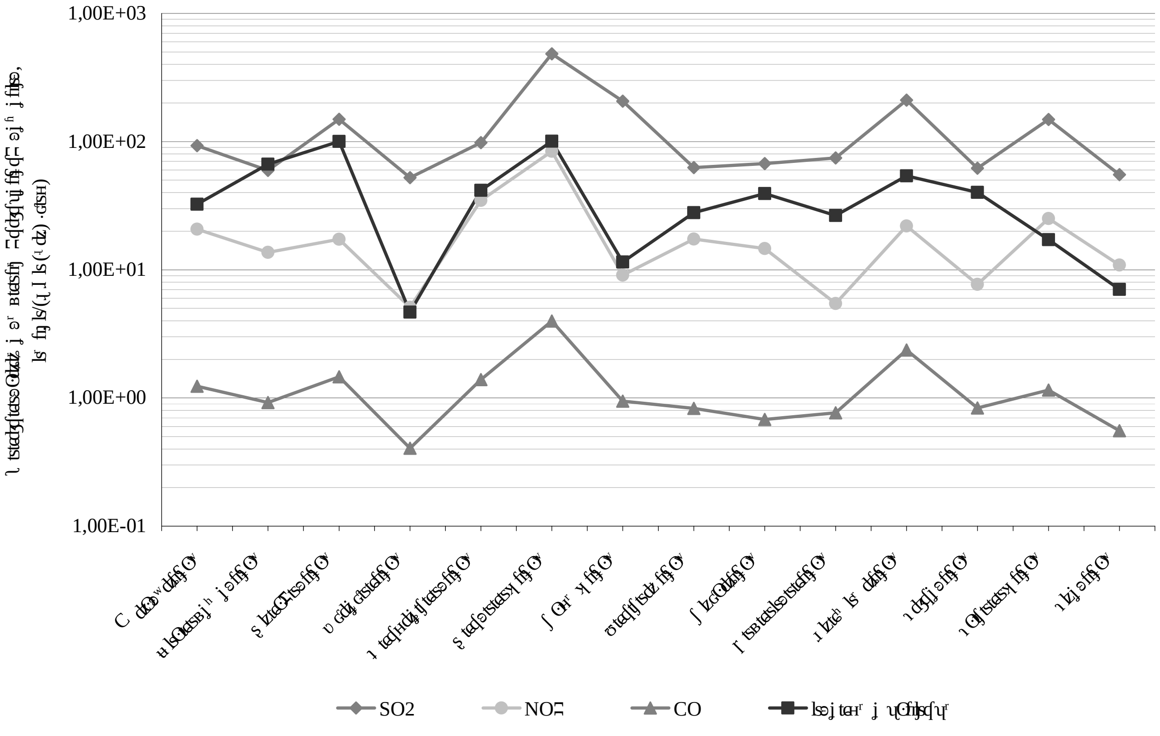

Fig. 1. The average emissions of gases and solids at TPP in Ukraine

The probability of stochastic effects for the population from releases of carcinogenic chemicals calculated on 1 GW (e.)·year of energy produced by these TPP in Ukraine is: for SO_2 ï 5.44 Ā10^{-4}, for NO_x ï 1.70Ā10^{-4}, for ɐʃ ï 1.45Ā10^{-7}; and for solids ï 1.03Ā10^{-4}.

The number of cases of stochastic effects for the population caused by the impact of emissions of non-carcinogenic chemicals at 1 GW (e.)·year for the mentioned TPP in Ukraine is: for SO_2 ï 6.78; NO_x ï 2.11; ɐʃ ï 1.81Ā10^{-3}; solids - 1.28.

Table 2. Indicators of environmental risk to the population under the influence of chemicals in the flying ash

emissions at thermal power plant 1 GW (e.)·year

Substance	Release, thousand tones	Average annual ƒŋ at 1km distance, mg/m^3	r_{ch}	R_{ch}
Non-carcinogenic				
Pb	4,12	$2{,}85 \cdot 10^{-5}$	$1{,}33 \cdot 10^{-5}$	$3{,}29 \cdot 10^{-1}$
V	3,91	$2{,}70 \cdot 10^{-5}$	$1{,}37 \cdot 10^{-6}$	$3{,}39 \cdot 10^{-2}$
Hg	13,58	$9{,}39 \cdot 10^{-5}$	$6{,}03 \cdot 10^{-8}$	$1{,}49 \cdot 10^{-3}$
Cu	0,37	$2{,}59 \cdot 10^{-6}$	$9{,}46 \cdot 10^{-5}$	2,34
Zn	0,20	$1{,}37 \cdot 10^{-6}$	$7{,}30 \cdot 10^{-5}$	1,81
Carcinogenic				
Ni	4,45	$3{,}08 \cdot 10^{-5}$	$8{,}88 \cdot 10^{-6}$	$2{,}20 \cdot 10^{-1}$
ɥr	5,86	$4{,}06 \cdot 10^{-5}$	$5{,}41 \cdot 10^{-4}$	13,4
As	0,16	$1{,}07 \cdot 10^{-6}$	$5{,}11 \cdot 10^{-6}$	$1{,}27 \cdot 10^{-1}$
ɥd	2,20	$1{,}52 \cdot 10^{-5}$	$3{,}04 \cdot 10^{-5}$	$7{,}52 \cdot 10^{-1}$
Benz (a)pyrene	0,01	$4{,}45 \cdot 10^{-8}$	$4{,}37 \cdot 10^{-8}$	$1{,}08 \cdot 10^{-3}$

Based on the data taken from [20], we determined the content of releases of benzo(a)pyrene and heavy metals (carcinogens - Cd, Cr, Ni, As; non-carcinogenic - Pb, Cu, V, Zn, Hg) in the fly ash releases of TPP on 1 GW (e.)·year (Table 2).

Individual and collective effective doses of irradiation of the population under the impact of releases of NRN composed of fly ash (see Fig. 1, *solid particles* -ỵ́-) are calculated based on the data given in [27], and by application of software package CAP-88, developed by the US Environmental Protection Agency [28].

Expected individual effective doses to the public at a distance of 1 km are: the maximum values - for the areas of accommodation of Zmievska TPP (83.6 mSv/year), Dobrotvorska TPP (51.5 mSv/year), Luganska TPP (49.9 mSv/year), and Burshtynska TPP (48.3 mSv/year); minimum - for Ladyzhynska TPP (4.10 mSv/year) and Uglegorska TPP (4.54 mSv/year). The values of individual doses to the public from exposure to releases of NRN from Ukraine TPP differ more than ten times.

The value of the total collective effective dose to the population for the year was 26.3 man-Sv. During the study period the thermal power plants in Ukraine produced 9.12 GW (e.)Āyear, which led to an average collective effective dose of the population of 2.92 man-Sv per 1 GW (e.)Āyear.

The probability and the number of stochastic effects for the population under the impact of gases and solids for a seventy-year period for these thermal power plants of Ukraine are given in Table 3.

Table 3. Probability and the number of cases of stochastic effects for population under the impact of chemicals and radioactive substances from releases of thermal power plants in Ukraine on 1 GW (e)Āyear

TPP	r_{ch}					r_r	R_{ch}					R_r
	SO_2	NO_2	ɥO	Solids	Ɇ	NRN	SO_2	NO_2	ɥO	Solids	Ɇ	NRN
Burshtynska	6,20Ā0^{-4}	1,18Ā0^{-4}	1,70Ā0^{-8}	8,01Ā0^{-5}	8,18Ā0^{-4}	1,54Ā0^{-4}	15,2	2,88	4,16Ā0^{-3}	1,96	20,0	10,1
Dobrotvorska	2,35Ā0^{-4}	3,45Ā0^{-5}	6,48Ā0^{-8}	4,46Ā0^{-5}	3,15Ā0^{-4}	5,58Ā0^{-4}	5,75	8,44Ā0^{-1}	1,58Ā0^{-3}	1,09	7,68	79,1
Zaporizhska	2,99Ā0^{-4}	9,83Ā0^{-5}	8,00Ā0^{-8}	2,05Ā0^{-5}	4,18Ā0^{-4}	2,39Ā0^{-5}	7,3	2,40	1,96Ā0^{-3}	5,01Ā0^{-1}	10,2	2,46
Zmievska	3,16Ā0^{-4}	7,75Ā0^{-5}	1,12Ā0^{-7}	1,06Ā0^{-4}	4,99Ā0^{-4}	2,64Ā0^{-4}	7,7	1,89	2,74Ā0^{-3}	2,58	12,2	19,4
Zuevska	3,74Ā0^{-4}	1,48Ā0^{-4}	8,17Ā0^{-8}	2,54Ā0^{-5}	5,47Ā0^{-4}	2,01Ā0^{-4}	9,1	3,62	2,74Ā0^{-3}	6,21Ā0^{-1}	13,1	15,7
Krivorizhska	5,11Ā0^{-4}	1,86Ā0^{-4}	1,21Ā0^{-7}	5,92Ā0^{-5}	7,56Ā0^{-4}	7,53Ā0^{-5}	12,5	4,55	2,00Ā0^{-3}	1,45	18,5	6,51
Kurahovska	4,38Ā0^{-4}	1,01Ā0^{-4}	1,13Ā0^{-7}	1,48Ā0^{-4}	6,86Ā0^{-4}	2,60Ā0^{-4}	10,7	2,46	2,75Ā0^{-3}	3,62	16,8	20,6
Ladyzhynska	4,53Ā0^{-4}	5,81Ā0^{-5}	7,71Ā0^{-8}	2,11Ā0^{-5}	5,32Ā0^{-4}	8,99Ā0^{-5}	11,1	1,42	1,88Ā0^{-3}	5,16Ā0^{-1}	13,0	9,34
Luganska	4,14Ā0^{-4}	1,77Ā0^{-4}	1,09Ā0^{-7}	1,24Ā0^{-4}	7,15Ā0^{-4}	3,03Ā0^{-4}	10,1	4,32	2,68Ā0^{-3}	3,03	17,5	23,8
Pridneprovska	2,43Ā0^{-4}	1,61Ā0^{-4}	8,56Ā0^{-8}	5,00Ā0^{-5}	4,54Ā0^{-4}	9,20Ā0^{-5}	5,9	3,94	2,09Ā0^{-3}	1,22	11,1	20,9
Slavianska	1,61Ā0^{-4}	7,07Ā0^{-5}	5,65Ā0^{-8}	3,00Ā0^{-5}	2,61Ā0^{-4}	1,58Ā0^{-4}	3,9	1,73	1,38Ā0^{-3}	7,33Ā0^{-1}	6,39	12,6
Starobeshevska	2,40Ā0^{-4}	1,06Ā0^{-4}	9,53Ā0^{-8}	1,37Ā0^{-4}	4,83Ā0^{-4}	1,92Ā0^{-4}	5,9	2,59	2,33Ā0^{-3}	3,34	11,8	15,2
Tripolska	2,76Ā0^{-4}	1,36Ā0^{-4}	7,77Ā0^{-8}	5,79Ā0^{-5}	4,70Ā0^{-4}	9,76Ā0^{-5}	6,75	3,32	1,90Ā0^{-3}	1,41	11,5	13,2
Uglegorska	3,85Ā0^{-4}	7,56Ā0^{-5}	8,17Ā0^{-8}	1,81Ā0^{-5}	4,79Ā0^{-4}	2,01Ā0^{-5}	9,4	1,85	2,00Ā0^{-3}	4,41Ā0^{-1}	11,7	1,62

We estimate that the number of stochastic effect cases due to the average annual releases of gaseous and particulate substances, at 1 GW (e.)·year will amount to 10.2 (average value for thermal power plants).

The probability values and the number of stochastic effects for the population exposed to carcinogenic and non-carcinogenic substances contained in flying ash from thermal power plant releases, were calculated for the seventy-year period as well (see. Table. 2).

It should be emphasized that the number of stochastic effects at 1 GW (e.)·year, average annual releases caused by NRN, and by carcinogenic and non-carcinogenic substances contained in fling ash emissions of thermal power plants in Ukraine, will be 32.2 (average value for thermal power plants).

Conclusions

Application of comprehensive assessment of environmental risks for the population made it possible to estimate the contribution of both individual and complex risk factors, including non-carcinogenic and carcinogenic chemicals as well as radioactive substances, under the impact of releases from thermal power plants into estimated value of individual risk and the number of stochastic effects.

It should be noted that the contribution of the environmental risk to the public health due to radioactive emissions of TPP in Ukraine is almost ten times smaller than the contribution due to the gaseous and particulate carcinogenic and non-carcinogenic substances.

To sum up, the forecast on the total number of stochastic effects for the population for the period of seventy years under the influence of chemical and radioactive substances releases from thermal power plants in Ukraine will be 387 cases.

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