Праці Одеського політехнічного університету, 2022. Вип. 2(66)
ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

UDC 621.039.58:502/504

V. Skalozubov[1]**,** DSc., Prof.,
I. Kozlov[1]**,** DSc., Prof.,
Hani Hayo[1]**,**
O. Kozlov[1]**,**
I. Dudarev[2]**,** PhD, Assoc. Prof.,
G. Yarotskaya[3]**,** DSc., Prof.
[1] Odessa Polytechnic National University, 1 Shevchenko Ave., Odessa, Ukraine, 65044; e-mail: kozlov_i.l_@ukr.net
[2] Odessa State Agrarian University, 13 Panteleymonovskaya Str., Odessa, Ukraine, 65012; e-mail:247531@ukr.net
[3] Odessa I.I. Mechnikov National University, 2 Dvoryanskaya Str., Odessa, Ukraine, 65082; e-mail: g.yarotskaya@gmail.com

ISSUES OF PREDICTINGTHE IMPACT OF NUCLEAR POWER FACILITIES ACCIDENTS' RADIATION CONSEQUENCES

В. Скалозубов, І. Козлов, Хані Хайо, О. Козлов, І. Дударев, Г. Яроцька. **Питання прогнозування впливу радіаційних наслідків аварій на об'єктах ядерної енергетики.** Аналіз наслідків найбільших за історію ядерної енергетики аварій на Чорнобильській атомній електростанції (АЕС) та АЕС Fukushima-Daiichi визначив велику різноманітність радіаційних дозових навантажень на ліквідаторів, населення та довкілля. Прогнозування подальшого впливу радіаційних наслідків на біологічні та екологічні об'єкти суттєво залежить не тільки від діапазону отриманих внаслідок аварій радіаційних навантажень, а й від інших численних факторів, які безпосередньо не пов'язані з радіаційними наслідками аварій. Аналіз стохастичних підходів прогнозування впливу радіаційних наслідків визначив їх обмежені можливості через відсутність достатньо адекватних та обґрунтованих статистичних баз даних щодо негативних ефектів в наслідок аварійних радіаційних навантажень. Аналіз детерміністських методів прогнозування впливу радіаційних наслідків визначив їх обмежені можливості внаслідок суттєвих кількісних та якісних розбіжностей з різних методів. Ці розбіжності можуть бути викликані різницею як нейтронно-фізичних моделей «доза – ефект», і умов експериментальної верифікації різних методів. Для прогнозування впливу радіаційних наслідків аварій на АЕС актуально розробити альтернативний ризик-орієнтований підхід, що ґрунтується на комплексному використанні як стохастичних, так і детерміністських методів з урахуванням обмежень їх застосування. «Верхня» межа області ймовірності виникнення неприпустимої негативної події в залежності від отриманих у процесі аварій доз опромінення визначається стохастичними методами, а «нижня» межа області ймовірності виникнення неприпустимого негативного ефекту визначається детерміністичними методами. Граничне (максимальне) значення ймовірності неприпустимої негативної події визначається гранично допустимою дозою початку променевої хвороби. Отримані результати можуть бути основою об'єктивних оцінок інформування громадянського населення про наслідки радіаційних аварій на АЕС.
Ключові слова: радіаційні викиди, дозові навантаження, іонізуюче випромінювання, біологічний ефект, нейтронно-фізична модель

V. Skalozubo, I.Kozlov, Hani Hayo, O. Kozlov, I. Dudarev, G. Yarotskaya. **Issuesof predictingthe impact of nuclear power facilities accidents' radiation consequences.** The analysis for history's biggest nuclear accidents consequences, at Chernobyl Nuclear Power Plant (NPP) and Fukushima-Daihichi NPP, identified various radiation dose loads on liquidators, civilians and environment. Predicting the radiation subsequent effects on biological and ecological objects depends both on the radiation loads range and various other factors not related directly to the accidents' radiation consequences. The analysis of stochastic approaches to predicting the radiation impact revealed their limited applicability cause of sufficiently adequate and substantiated statistical databases about the accidents-produced radiation doses negative effects. The analysis of deterministic methods to predicting that impact determined their limitation due to significant quantitative and qualitative discrepancies between methods caused by the difference in neutron-physical "dose – effect" models and those methods experimental verification conditions difference. To predict the NPP accidents radiation impact, important is to develop an alternative risk-oriented approach based on the integrated use of stochastic and deterministic methods, taking into account their applicability limitations. The unacceptable negative event "upper" limit probability area depending on the radiation doses from the accidents, is determined by stochastic methods, and the "lower" limit probability area is determined by deterministic ones. Such event probability maximum value is determined by the maximum allowed dose at radiation sickness onset. The obtained results can serve in a basis for objective assessments of civilians informing about the consequences of radiation accidents at NPPs.
Keywords: radiation emissions, dose loads, ionizing radiation, biological effect, neutron-physical model

1. Introduction

The largest accidents in the history of nuclear energy at the Chernobyl NPP and the Fukushima-Daiichi NPP have determined large-scale catastrophic radiational and environmental repercussions. The lessons of preventing and overcoming the repercussions of these accidents determined the limit of applications of known approaches and methods for predicting the impact of the radiation effects of accidents on personnel, the population, and the environment. In fact, it was possible to predict and, to a certain extent, confirm an increase in thyroid cancer in children who received relatively high dose

DOI: 10.15276/opu.2.66.2022.08

loads. However, many issues of predicting the impact of a wide range of doses during accidents on personnel, population, and the environment remain unresolved.

Therefore, an urgent issue is the analysis of the adequacy and validity of methods for predicting the impact of radiational effects of accidents at nuclear power facilities on personnel, population, and the environment.

2. Analysis of Literary Sources and Problem Statement

Many studies have been devoted to the radiational and environmental impacts of the Chernobyl accident in 1986 [1 – 6, etc.]. The main results of these studies allow us to draw the following general conclusions.

1. The largest radiation fallout of cesium-137 was on the territory of the northern part of Ukraine (more than 40 kBq/m^2), as well as in the 30-kilometer exclusion zone (more than 1500 kBq/m^2). Approximately 30 MCi of radioactive substances fell on the territory of the exclusion zone. Part of the coniferous forests died, and a significant amount of hazardous radioactive waste, which could lead to secondary air pollution, was formed. The radionuclides released during the accident contaminated forests with an area of over 1.5 million hectares in Zhytomyr, Kiev, Chernigov, and Rivne regions.

Immediately after the accident, significant radioactive contamination of river ecosystems was recorded – 10 kBq/L in the Pripyat River, 5 kBq/L in the Uzh River, 4 kBq/L in the Dnieper River.

2. On the territory of other states, the greatest radiational impact was recorded in the southern part of Belarus, the southwestern part of Russia, the Baltic states, and in the Scandinavian countries. Thus, in Sweden in 1987, in 14000 lakes, the concentration of radio-cesium was more than 1500 Bq/kg.

In total, because of the Chernobyl accident, 1.1 million hectares of agricultural land were exposed to radioactive contamination with cesium-137 with a density of more than 1 Ci/km^2.

3. The population of the 30-kilometer exclusion zone received significant doses of thyroid irradiation – from 70 mSv in adults and up to 1 mSv in children. For residents of Pripyat, within two days after the accident, the average thyroid dose was 0.47 Gy.

4. The average value of the individual radiation dose for the plant employees, medical staff, and firefighters was 0.31 Gy. The presence of acute radiation sickness was confirmed in 134 people. The average registered effective dose of external exposure found in evacuators during post-accident events (about 600 thousand people) was 170 mSv in 1986.

5. It was found that for the development of acute radiation sickness the minimum radiation dose is more than 1 Gy, and for leukemia and oncology – 0.3 Gy.

In general, because of the accident, the deaths of 31 evacuators of the accident were registered and more than 100 people suffered from radiation sickness and other health problems to varying degrees.

6. In medical examinations for 20 years after the accident, a significant increase in cases of thyroid cancer among children living in contaminated areas was recorded.

After the Chernobyl accident, the World Health Organization established a special international program to study the effects of ionizing radiation on human health. The projected estimates of the World Health Organization for a noticeable increase in thyroid cancer were justified only for children living in contaminated areas and receiving high doses of radiation. General predictive estimates of the impact of the radiational consequences of the Chernobyl accident on the environment and human health are insufficient.

The radiational and environmental consequences of the major accident at the Fukushima-Daiichi NPP were also considered in numerous studies (for example, [7 – 18, etc.]) and summarized in the report of the IAEA Director General in 2014 [18].

1. Inert gases account for a significant portion of the initial emissions from the Fukushima-Daiichi NPP; emissions were estimated [12] to be between about 6.000…12.000 PBq of ^{133}Xe (initially 500…15.000 PBq). The average total activity of the released ^{131}I was approximately 100…400 PBq, and the activity of ^{137}Cs was approximately 20 PBq (according to initial estimates, 90…700 PBq and 7…50 PBq). Emissions from this accident are estimated to be about one tenth of those associated with the Chernobyl accident in 1986. Most of the emissions into the atmosphere were dispersed over the North Pacific Ocean onto the surface layer of the water. There were direct discharges, as well as discharges into the sea from the site, with the main source of highly radioactive water being a trough near the Fukushima-Daiichi NPP. The peak level of radioactive releases was observed in early April 2011. The volume of direct releases and discharges of ^{131}I into the sea was estimated at 10…20 PBq [13].

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

Direct emissions and discharges of ^{137}Cs were estimated as 1…6 PBq as a result of most analyses, but some estimates reported values from 23 to 26.9 PBq.

2. The largest deposition of long-lived ^{137}Cs was found northwest of the Fukushima-Daiichi NPP: the total deposition of ^{137}Cs was estimated at about 2…3 PBq [14]. To the northwest of the Fukushima-Daiichi NPP, significantly higher levels of ^{137}Cs deposition were recorded, up to 1000000 Bq/m^2. The maximum deposition of ^{131}I exceeded 3 000000 Bq/m^2 immediately after the accident, but due to the short half-life of ^{131}I, the levels declined rapidly, and are currently not measurable.

3. In the affected areas, radionuclides such as ^{131}I, ^{134}Cs, and ^{137}Cs have been detected in some consumer goods and other items that are used on a daily basis by the population for personal or domestic purposes, such as food, drinking water and some non-food items [15].

4. In the first four months, a number of estimates of individual effective doses resulting from external exposure in the "evacuation zone" and "planned evacuation area" were published. These doses were below 5 mSv in 98.7 % of residents (with a maximum effective dose of 25 mSv). In Fukushima Prefecture as a whole, including the evacuation zone and the planned evacuation area, doses were less than 3 mSv in 99.4 % of the residents participating in the survey.

The analysis again confirmed that the annual individual dose equivalents are low with an average effective dose of less than 1 mSv per year, which gives 95 % confidence that the value of effective doses received by residents is below 5 mSv. Since the accident, more than 200000 residents have been monitored in various areas of Fukushima Prefecture. Levels were generally below the lowest detection limits for whole body radiometry, indicating little or no exposure to radionuclides.

5. When nuclear accidents occur with significant releases of ^{131}I, thyroid gland exposure in children is of great importance in terms of protecting public health. The main potential route of thyroid gland exposure in children is usually through the consumption of milk containing ^{131}I. However, the typical exposure of ^{131}I through cow's milk after the accident was very low due to a number of factors. Estimates of the equivalent dose in the thyroid gland in children were carried out by monitoring the levels of external exposure based on the action of ^{131}I in the gland. These levels were measured on the skin near the thyroid gland in children from areas where high thyroid doses were predicted. The highest ambient dose equivalent recorded near the thyroid gland of one-year-old children was 0.0001 mSv per hour, which is consistent with an absorbed thyroid dose of about 50 mGy (namely, a thyroid equivalent dose of 50 mSv).

6. Between March 2011 and March 2012 174 out of almost 23000 workers on site exceeded the primary criterion for an effective dose during an accident, which was 100 mSv, while six of them exceeded the indicator of (temporarily revised) work during accident, which was 250 mSv. None of the workers exceeded the effective dose of 100 mSv in subsequent years. One worker exceeded the annual effective dose limit of 50 mSv between April 2012 and March 2013. Internal doses are mainly thyroid equivalent doses resulting from inhalation of ^{131}I. Even though the overwhelming majority of Fukushima-Daiichi workers received equivalent thyroid doses of less than 100 mSv, 1757 workers received equivalent thyroid doses higher than this level, 17 workers received equivalent thyroid doses more than 2000 mSv, and two workers received more than 12000 mSv [16, 17].

7. Neither the workers nor the public had any early radiation-induced health effects that could be attributed to the accident. However, the latency period for the long-term health effects of exposure to radiation can last for decades.

In the period immediately after the accident, there were some limited observations, but no direct radiation-induced effects on plants and animals were recorded.

3. Purpose of the presented work

The above known results of studies of the consequences of accidents in Chernobyl and Fukushima may be the necessary initial data for predicting radiational consequences for the future of environmental safety. However, to date, the actual issue remains, more specifically, the issue of determining adequate and sufficiently substantiated methods for predicting the impact of radiational consequences on objects of biosystems and the environment.

The aim of our study is to analyze the known methods of predicting radiational consequences of the largest accidents at the Chernobyl NPP and the Fukushima-Daiichi NPP for the future of environmental safety.

4. Methods for predicting the impact of radiational consequences

Prediction of the impact of radiational consequences can be carried out by risk-oriented and deterministic methods. Risk-based methods consist of determining the probabilistic indicators of the influence of radiational consequences on “negative effects” in biosystems and the environment. The main problem of the implementation of risk-oriented approaches is the need for representative and adequate statistics among the registered consequences of the radiational impact of accidents that have occurred. However, the creation of such a statistical database is associated with many difficulties, among which the main one is the need to “cut off” the influence of numerous factors not related to the Chernobyl and Fukushima accidents from their radiational consequences: changes in climatic and technogenic conditions, pathological and hereditary diseases, lifestyle, and others.

The deterministic approach is based on the study of ionizing radiation direct influence at both biosystems and the environment microlevel and is considered in the works by Rusov V.D. and Zelentsova T.N. [19, 20].

A diagram of the primary physicochemical processes from initial ionization to the final biological effect is shown in Fig. 1 [21]. Radiolysis products, primarily free radicals containing unpaired electrons, are characterized by extremely high reactivity, so that their lifetime ranges from 10^{-10} to fractions of a second. During this period, they either recombine with each other, or react with nearby organic compounds.

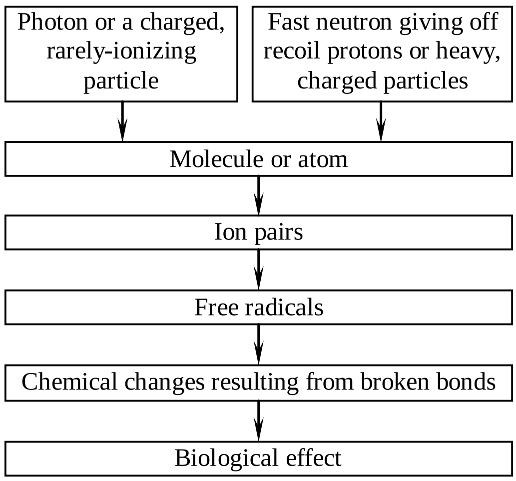

Fig. 1. Diagram of primary physical and chemical processes from initial ionization to the final biological effect [21]

The effects of different types of radiation on biosystems and the environment also differ.

Alpha particles, when passing through matter and colliding with atoms, ionize them, knocking out electrons. Under certain conditions, these particles are absorbed by the nuclei of atoms, transforming them into a state with higher energy, and the excess energy contributes to the occurrence of various chemical reactions. Alpha radiation can have a strong effect on organic matter (fats, proteins, and carbohydrates).

Under the influence of β-radiation, radiolysis (decomposition) of water occurs with the formation of hydrogen, oxygen, hydrogen peroxide (H_2O_2), and charged particles (ions, OH_2^- and HO_2^-). The decomposition products of water have oxidizing properties and cause the destruction of many organic substances.

The action of γ- and X-ray radiation is mainly due to generated free electrons. Neutrons, passing through a substance, produce the biggest changes in the substance as compared to other ionizing radiation.

The biological effect of ionizing radiation comes down to a change in the structure or destruction of substances (molecules), which leads to disruption of the biochemical processes occurring in cells, or even cell death. Ionizing radiation causes “breakage” of chromosomes – chromosomal aberrations, after which the torn ends form new combinations, called chromosomal translocations. This leads to a change in the gene apparatus and the formation of daughter cells that differ from the mother cell. If persistent chromosomal aberrations occur in germ cells, then this leads to mutations, i.e., the appearance of offspring with other characteristics in irradiated individuals.

The presence, and hence influence, of ionizing radiation in the body disrupts the function of hematopoietic organs, causes an increase in the permeability and fragility of blood vessels, upsets the gastrointestinal tract, decreases the body's resistance, increases its depletion, induces the degeneration

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

of normal cells into malignant cells, etc. The effects develop over different periods: from fractions of a second up to many years.

The damaging effects of radiation manifest themselves in various forms on the body and are collectively called radiation sickness. The variety of these manifestations depends on the following factors: type of exposure – general or local, external or from incorporated radioactive substances; time factor – single, repeated, prolonged, chronic irradiation; spatial factor – uniform or uneven irradiation; volume and localization of the irradiated segment of the body and skin surface, etc. Low degree development of a mild form of radiation sickness occurs at a radiation dose equivalent to approximately 1 Gy; a severe form of radiation sickness, in which half of all exposed people die, occurs at a radiation dose equivalent to 4.5 Gy. 100 % death from radiation sickness corresponds to a radiation dose equivalent to 5.5…7.0 Gy [22].

Chronic radiation sickness develops when the total dose reaches 0.7…1 Sv. The recovery process is very slow after the cessation of irradiation. The essence of the recovery process, both in acute and in chronic radiation sickness, is the process of reproduction of cells that have retained their viability, and on this basis, the restoration of the functional activity of organs occurs. However, even the complete restoration of the organism does not guarantee the absence of danger from future manifestations of long-term consequences of the action of nuclear radiation, and its offspring, namely it does not guarantee the absence of hereditary or congenital disorders. These effects can be observed for several years after acute exposure. Their severity mainly depends on the dose, dose rate, age at the time of exposure, and the state of health of the victim.

In the long term (in mice and rats after a few months, in humans – after many years and decades) after irradiation and, it would seem, in an organism that has completely recovered from radiation damage, various changes occur, which are called long-term effects of radiation. It is customary to distinguish between two types of long-term consequences – somatic, developing in the irradiated individuals themselves, and genetic – hereditary diseases that develop in the offspring of irradiated parents. The somatic effect of ionizing radiation is a direct effect on the body. It results in radiation sickness, local damage to individual organs and tissues, and other negative consequences.

Genetic effects are the result of irradiation of the germ cell genome. Such effects are manifested in the offspring of irradiated individuals in the form of inherited disorders. Genetic long-term consequences or hereditary diseases belong to the second group of stochastic effects of radiation, which are manifested not in the exposed people themselves, but in their offspring. They are the result of radiation mutations in the germ cells of irradiated parents, in contrast to malignant neoplasms that arise as a result of mutations in the somatic cells of the irradiated individuals themselves.

5. Research results

Deterministic methods for predicting the impact of radiational consequences are based on various neutron-physical models of the effect of ionizing radiation on the molecules of matter [23 – 28].

One of the first theoretical models was the “target” model [27, 28]. Its essence is as follows: energy absorption is a process that obeys statistical laws, a principle. This means that the observed effect, for example cell death, occurs only when the particles enter the sensitive volume inside the cell (target). The calculated dose-effect curve for this interaction model was consistent with individual experiments. The calculation results also showed that small portions of the energy of ionizing radiation could only give a strong effect when they fall on a small target. The critical structure in the cell is the chromatin of the cell nucleus, chromosomes, and DNA molecules. Later, with the help of microbeams of ionizing particles with a diameter of less than 0.1 microns, it was possible to show that the lethal dose for a cell nucleus is 10…100 times less than when other parts of it are irradiated [29].

In the course of the development of radiobiology, studies were carried out that significantly complicated the picture of radiation damage to a cell. It turns out that the primary damage that has arisen in the cell under the influence of radiation can intensify and deepen over time. The structures on which the actions of these mechanisms for enhancing radiation injury are played out are cell membranes. As a result of these studies, the next step has been taken in understanding the mechanism of radiational damage to cells. It was concluded that, along with the main target, DNA, the second most important target is the membrane. Many of the advances in the radiobiology of radiation injury have been studied only qualitatively.

A report from the National Academy of Sciences’ Committee on the Biological Effects of Ionizing Radiation notes “most of the available data does not suggest any “dose-response” model [30]. For most cancers of radiation origin, the “dose-response” relationship is best described as a linearly-quadratic function with a non-negative degree. However, there are arguments in favor of other models, especially linear and quadratic, although they lead to a large discrepancy in the estimates.”

The qualitative relationship “dose-effect” for various models is shown in Fig. 2 [31]. When considering the effects of stimulating vital activity (hormesis), the curve first descends into the area of “beneficial effects”, before changing direction and rising to the area of detrimental effects. The part of this curve that is to the left of the minimum represents radiational deficit (shortage) conditions.

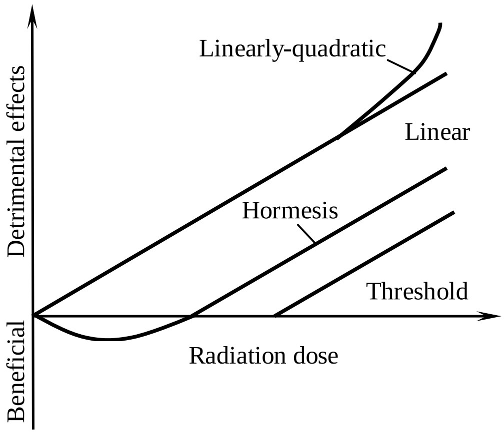

Fig. 2. Plots representative of various theories of radiation exposure [31]

Due to the lack of convincing evidence of the existence of a threshold model, the ICRP publications recommend accepting the assumption that any action of ionizing radiation may carry some risk of developing somatic or genetic effects [32]. Therefore, for stochastic effects, a linear, threshold-free relationship between dose and the likelihood of an effect is recommended. Nevertheless, the application of the concept of a threshold-less linear dose-effect relationship significantly overestimates the real danger.

The following results of long-term observations can be arguments in favor of the “threshold” model:

1. Among the consequences of the adverse effect of ionizing radiation, it is possible unambiguously to establish a connection between health damage and the effect of radiation only in relation to radiation sickness, which is characterized by symptoms exclusive to only radiation sickness.

The characteristic signs of radiation sickness under conditions of acute irradiation can be reliably recorded starting from a dose of 1 Gy. Therefore, in human radiobiology, doses over 1 Gy are considered high, which are certainly accompanied by transient or permanent damage to health.

2. At lower doses of irradiation, there are no injuries arising from the action of an exclusively radiational agent. As a result, diseases which humanity suffers without any connection to an increased irradiation (in relation to the background level) are recorded. It is possible to reveal an increase in the incidence rate at doses less than 1 Gy only by statistical methods, by comparing the frequency of manifestation of the studied deviation from the norm in the irradiated and control groups.

Conclusions

1. Analysis of the consequences of the largest accidents in the history of nuclear power engineering at the Chernobyl NPP and the Fukushima-Daiichi NPP determined a wide range of radiation dose loads on the evacuators, the population, and the environment. Predicting the influence of radiational consequences on subsequent biological and ecological states essentially depends not only on the spectrum of radiation loads obtained as a result of accidents, but also on numerous other factors that are not directly related to the radiational consequences of accidents.

2. Analysis of stochastic approaches for predicting the impact of radiational consequences determined their limited capabilities due to the lack of sufficiently adequate and substantiated statistical databases on negative effects of only emergency radiation loads.

3. Analysis of deterministic methods for predicting the impact of radiational consequences determined their limited capabilities due to significant quantitative and qualitative discrepancies in dif-

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

ferent methods. These discrepancies can be caused by differences in both the neutron-physical dose-effect models and the conditions of experimental verification of different methods.

4. To predict the impact of radiational consequences of accidents at nuclear power facilities, it is important to develop an alternative risk-oriented approach based on the integrated use of both stochastic and deterministic methods, while taking into account the limitations of their applicability.

5. Despite the high level of safety achieved and lessons learned from radiational consequences, there is a gap between scientific knowledge about the severity of medical consequences, factual evidence, and public opinion, which presents a serious problem. The idea of deadly danger related to nuclear energy is the main reason that people perceive information about nuclear energy with great apprehension. For example, people are apprehensive about the thought of construction of nuclear power plants near their residence. A state that plans to develop nuclear energy must ensure that the population is provided with timely, thoroughly verified, and scientifically confirmed information. However, it is important to note that using the advantages of social networks and new media (free access to them, the ability to exchange quickly resources and information) carries certain risks. Social networks are practically not regulated, which casts doubt on the accuracy and reliability of the information provided, and therefore contributes to the spread of rumors and myths about threats that nuclear energy can pose.

Література

1. Носовский А.В., Васильченко В.Н., Ключников А.А., Пристер Б.С. Авария на Чернобыльской АЭС. Опыт преодоления. Извлеченные уроки. Київ : Техніка, 2006. 264 с.
2. Барьяхтар В.Г. Чернобыльская катастрофа. Київ : Наук. думка, 1995. 568 с.
3. UNSCEAR 2000 REPORT, Vol. II (2000). Annex J: Exposures and effects of the Chernobyl accident. UNITED NATIONS New York, 2000. P. 453–551. URL: https://www.unscear.org/docs/publications/2000/UNSCEAR_2000_Annex-J.pdf.
4. The Chernobyl accident : updating of INSAG-1 : INSAG-7 (1992) A report by the International Nuclear Safety Advisory Group. Vienna : International Atomic Energy Agency, 1992. 136 p. URL: https://www-pub.iaea. org /MTCD/publications/PDF/Pub913e_web.pdf.
5. Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Report, Volume II (2011). Annex D: Health effects due to radiation from the Chernobyl accident. UNITED NATIONS New York, 2011. 47–206. URL: https://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_D.pdf.
6. World Health Organization. (2006). Health effects of the Chernobyl accident and special health care programmes. World Health Organization. Geneva, 160 p. URL: https://apps.who.int/iris/handle/10665/43447.
7. Скалозубов В.И., Ключников А.А., Ващенко В.Н., Яровой С.С. Анализ причин и последствий аварии на АЭС Fukushima как фактор предотвращения тяжелых аварий в корпусных реакторах : монография / за ред. В.И. Скалозубова. Чернобыль : Ин-т проблем безопасности АЭС, 2012. 280 с.
8. Evaluation of Meteorological Analyses for the Radionuclide Dispersion and Deposition from the Fukushima Daiichi Nuclear Power Plant Accident. Geneva : WMO, 2013. 68 p.
9. Оперативный анализ аварии на АЭС “Фукусима-1” (Япония) и прогнозирование ее последствий / Р.В. Арутюнян, Л.А. Большов, А.Е. Киселев и др. *Атомная энергия*. 2012. 112(3). С. 151–159. URL: https://dlib.eastview.com/browse/doc/27115482.
10. (2012) Оценка выброса радионуклидов при аварии на АЭС “Фукусима-1” (Япония) 15 марта 2011 г. / Р.В. Арутюнян, Л.А. Большов, Д.А. Припачкин и др. *Атомная энергия*. 2012. 112(3). С. 159–163. URL: https://dlib.eastview.com/browse/doc/27115472.
11. Козлов И.Л. Анализ экологических последствий и уроков Фукусимской аварии. *Праці Одеського політехнічного університету*. 2014. 1(43). С. 112–120. URL: http://nbuv.gov.ua/UJRN/Popu_2014_1_20.
12. Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami. World Health Organization. Geneva : WHO, 2012. 120 p.
13. Preliminary estimation of release amounts of 131I and 137Cs accidentally discharged from the Fukushima Daiichi nuclear power plant into the atmosphere / M. Chino, H. Nakayama, H. Nagai, et al. *Journal of Nuclear Science and Technology*. 2011. 48(7). P. 1129−1134. URL: https://doi.org/10.1080/18811248.2011.9711799.
14. Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition / A. Stohl, P. Seibert, G. Wotawa, et al. *Atmospheric Chemistry and Physics.* 2011. 11. P. 28319–28394. URL: http://www.atmos-chem-phys.net/12/2313/2012/acp-12-2313-2012.pdf.

15. UNSCEAR 2013 Report. Sources, Effects and Risks of Ionizing Radiation. Report to the General Assembly of United Nations. Vol. I. Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation. New York : UNSCEAR, 2014. 289 p. URL: https://www.unscear.org/docs/reports/2013/13-85418_Report_2013_Annex_A.pdf.
16. Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, Based on a Preliminary Dose Estimation. World Health Organization. Geneva : WHO, 2013. 168 p. URL: https://www.who.int/publications/i/item/978924150513.
17. Kai M. Some lessons on radiological protection learned from the accident of the Fukushima Dai-ichi nuclear power plant. *J. Radiol. Prot.* 2012. 32(1), P. 101−105.
18. The Fukushima Daiichi Accident. Report by the Director General, IAEA, Austria, Vienna : 2015. 208 p. URL: https://www-pub.iaea.org/mtcd/publications/pdf/pub1710-reportbythedg-web.pdf.
19. Rusov V.D., Zelentsova T.N. Thermodynamic theory of phase transition in biosubstance from exposure to low doses of ionizing radiation, Proc of Intern. Conf. on «Low doses of ionizing radiation: biological effects and regulatory control. Seville (Spain). Publ. IAEA-CN-67/156, 1997. P. 491–495.
20. Rusov V.D., Zelentsova T.N., Tarasov V.A. Precision method for the determination of neutrino mixing angle. *Problems of Atomic Science and Technology, Ser. General and Nuclear Phys.* 2001. 6(1), P. 157–160. URL: http://dspace.nbuv.gov.ua/handle/123456789/79476.
21. Баранова А.А. Б24 Радиационная биофизика : лабораторный практикум. Екатеринбург : Изд-во Урал. ун-та, 2018. 100 с.
22. Гребенюк А.Н., Легеза В.И., Евдокимов В.И. и др. Радиационная медицина. Часть 1. Основы биологического действия радиации. СПб. : Политехника-сервис, 2013. 124 с.
23. Калистратова В.С., Беляев И.К., Жорова Е.С. и др. Радиобиология инкорпорированных радионуклидов. М. : Изд-во ФМБЦ им. А.И. Бурназяна, 2012. 464 с.
24. Козлов И.Л., Скалозубов В.И., Оборский Г.А. Развитие методов переоценки ядерной безопасности с учетом уроков большой аварии на АЭС Fukushima-Daiichi: монографія : LAP Lambert Academic Publishing, 2014. 448 с.
25. Смагин А.И. Биологическое действие и защита от ионизирующих излучений: учебное пособие. Челябинск : Издательский центр ЮУр ГУ, 2018. 117 с.
26. Губин А.Т., Сакович В.А. Методические проблемы практических оценок радиогенного риска. *Радиационная гигиена*, 2014. 7(1). С. 16–22.
27. Bodgi L., Canet A., Pujo-Menjouet L., et al. Mathematical models of radiation action on living cells: From the target theory to the modern approaches. A historical and critical review / L. Bodgi, A. Canet, L. Pujo-Menjouet, et al. *Journal of theoretical biology*. 2016. Vol. 394. P. 93–101.
28. Филимонов М.М., Новиков Д.А. Радиобиология: учебное пособие. Минск : БГУ, 2015. 132 с. URL: http://elib.bsu.by/handle/123456789/123247.
29. Алексахин Р.М., Гераськин С.А., Удалова А.А. Новейшие результаты исследований в области радиоэкологии. *Вестник Российской академии наук*. 2015. 85(4). P. 373–376.
30. Morgan W.F., Sowa M.B. Effects of ionizing radiation in nonirradiated cells. *Proc. Natl. Acad. Sci. USA.* 2005. 102(40). P. 14127–14128. URL: https://www.ncbi.nlm.nih.gov/pubmed/16186485.
31. Вопросы дозиметрии и радиационная безопасность на атомных электрических станциях, учебное пособие / за ред. Носовского А.В. Славутич : Укратомиздат, 1998. 405 с.
32. Рюм В., Волощак Г., Шор Р. Эффекты дозы и мощности дозы ионизирующего излучения-дискусия с позиции радиологической защиты. *Медицинская радиология и радиационная безопасность.* 2017. 62(3). P. 50−76.

References

1. Nosovskiy, A. V., Vasilchenko, V. N., Klyuchnikov, A. A., & Prister, B. S. (2006). *Chernobyl NPP accident. Overcoming experience. Acquired lessons.* Kyiv: Engineering.
2. Baryakhtar, V. G. (1995). The Chernobyl disaster. Kyiv: *Science. Dumka*, 568 p.
3. UNSCEAR 2000 REPORT, Vol. II (2000). *Annex J:Exposures and effects of the Chernobyl accident.* UNITED NATIONS New York, 453-551. Retrieved from https://www.unscear.org/docs/publications/2000/UNSCEAR_2000_Annex-J.pdf.
4. The Chernobyl accident: updating of INSAG-1 : INSAG-7 (1992). *A report by the International Nuclear Safety Advisory Group.* Vienna, International Atomic Energy Agency, 136 p. Retrieved from https://www-pub.iaea. org /MTCD/publications/PDF/Pub913e_web.pdf.
5. Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Report, Volume II. (2011). *Annex D: Health effects due to radiation from the*

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

Chernobyl accident. UNITED NATIONS New York, 47–206. Retrieved from https://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_D.pdf.

6. World Health Organization. (2006). *Health effects of the Chernobyl accident and special health care programmes.* World Health Organization. Geneva, 160 p. Retrieved from https://apps.who.int/iris/handle/10665/43447.
7. Skalozubov, V. I. Klyuchnikov, A.A. & Vashchenko, V. N., et al. (2012). *The analysis of the reasons and accident consequences on the nuclear power plant Fukushima-Daiichi as a factor of overcoming of severe accidents in case reactors.* Chernobyl: NAN of Ukraine, IPB nuclear power plant NANU.
8. Evaluation of Meteorological Analyses for the Radionuclide Dispersion and Deposition from the Fukushima Daiichi Nuclear Power Plant Accident. (2013). *World Meteorological Organization.* Geneva: WMO, 68 p.
9. Arutyunyan, R.V., Bolshov, L.A., & Kiselev, A.E., et al. (2012). Efficient Analysis of Fukushima-1 (Japan) Nuclear Power Accident and its Consequences Prognosis. *Atomnaia energiia, 112(3)*, 151–159. Retrieved from https://dlib.eastview.com/browse/doc/27115482.
10. Arutyunyan, R.V., Bolshov, L.A., & Pripachkin, D.A., et al. (2012). Assessment of the Radionuclides Release at the Severe Accidents on the Fukushima-1 NPP (Japan) 15 March 2011. *Atomnaia energiia,* 112(3), 159–163. Retrieved from https://dlib.eastview.com/browse/doc/27115472.
11. Kozlov I. L. (2014). Analysis of ecological consequences and lessons of the Fukushima accident, *Proceedings of Odessa Polytechnic University, 1(43*), 112–120. Retrieved from http://nbuv.gov.ua/UJRN/Popu_2014_1_20.
12. Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami. (2012). *World Health Organization. Geneva: WHO*, 120 p.
13. Chino, M., Nakayama, H., & Nagai, H., et al. (2011). Preliminary estimation of release amounts of 131I and 137Cs accidentally discharged from the Fukushima Daiichi nuclear power plant into the atmosphere. *Journal of Nuclear Science and Technology, 48(7)*, 1129−1134. Retrieved from https://doi.org/10.1080/18811248.2011.9711799.
14. Stohl, A., Seibert, P., & Wotawa, G., et al. (2011). Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition. *Atmospheric Chemistry and Physics,* 11, 28319–28394. Retrieved from http://www.atmos-chem-phys.net/12/2313/2012/acp-12-2313-2012.pdf.
15. UNSCEAR 2013 Report. (2014). *Sources, Effects and Risks of Ionizing Radiation*. Report to the General Assembly of United Nations. Vol. I. Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation. New York: UNSCEAR, 289 p. Retrieved from https://www.unscear.org/docs/reports/2013/13-85418_Report_2013_Annex_A.pdf.
16. Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, Based on a Preliminary Dose Estimation. (2013). *World Health Organization. Geneva: WHO*, 168 p. Retrieved from https://www.who.int/publications/i/item/978924150513.
17. Kai, M. (2012). Some lessons on radiological protection learned from the accident of the Fukushima Dai-ichi nuclear power plant. *J. Radiol. Prot., 32(1)*, 101−105.
18. The Fukushima Daiichi Accident. (2015). *Report by the Director General*. Austria, Vienna: IAEA, 208 p. Retrieved from https://www-pub.iaea.org/mtcd/publications/pdf/pub1710-reportbythedg-web.pdf.
19. Rusov, V.D., & Zelentsova, T.N. (1997). Thermodynamic theory of phase transition in biosubstance from exposure to low doses of ionizing radiation, Proc. of Intern. Conf. on Low doses of ionizing radiation: biological effects and regulatory control. *Seville(Spain). Publ. IAEA-CN-67/156*, 491–495.
20. Rusov, V.D., Zelentsova, T.N., & Tarasov V.A. (2001). Precision method for the determination of neutrino mixing angle. *Problems of Atomic Science and Technology, Ser. General and Nuclear Phys., 6(1)*, 157–160. Retrieved from http://dspace.nbuv.gov.ua/handle/123456789/79476.
21. Baranova, A.A. (2018). *B24 Radiation biophysics: laboratory practice.* Yekaterinburg: Ural Federal University.
22. Grebenyuk, A.N., Legeza, V.I., & Evdokimov, V.I., et al. (2013). *Radiation medicine: textbook. allowance – Part I: Fundamentals of the biological effects of radiation.* St. Petersburg: Polytechnic-service, 124 p.
23. Kalistratova, V.S., Belyaev, I.K., & Zhorova, E.S., et al. (2012). *Radiobiology of incorporated radionuclides.* Publisher Burnasyan FMBC of the FMBA of Russia, 464 p.
24. Kozlov, I., Skalozubov, V., & Oborsky, G. (2014). Development of methods for reassessment of nuclear safety taking into account the lessons of a major accident at the Fukushima-Daiichi nuclear power plant. *monograph. Lambert Academic Publishing,* 448 p.
25. Smagin, A.I. (2018). *Biological action and protection against ionizing radiation: study guide.* Chelyabinsk: Publishing Center SUSU.

26. Gubin, A.T., & Sakovich, V.A. (2014). Methodological problems of practical radiological risk assessments. *RadiatsionnayaGygiena = Radiation Hygiene*, *7(1)*, 16–22.
27. Bodgi, L., Canet, A., & Pujo-Menjouet, L., et al. (2016). Mathematical models of radiation action on living cells: From the target theory to the modern approaches. A historical and critical review. *Journal of theoretical biology, 394*, 93–101.
28. Filimonov, M.M., & Novikov, D.A. (2015). *Radiobiology: manual.* Minsk: Belarusian State University. Retrieved from http://elib.bsu.by/handle/123456789/123247.
29. Alexakhin, R.M., Geras'kin, S.A., & Udalova, A.A., et al. (2015). The Latest Research Results in the Field of Radiology. *Herald of the Russian Academy of Sciences*, *85(4)*, 373–376.
30. Morgan, W.F., & Sowa, M.B. (2005). Effects of ionizing radiation in nonirradiated cells. *Proc. Natl. Acad. Sci. USA*, 102(40), 14127–14128. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/16186485.
31. Nosovskiy, A. V. (Ed.), (1998). *Dosimetry Issues and Radiation Safety at Nuclear Power Plants*, Slavutich: Ukratomizdat.
32. Werner R., Gayle E.W., & Roy E.S. (2017). Dose and dose-rate effects of ionizing radiation: a discussion in the light of radiological protection. *Medical Radiology and Radiation Safety*, *62(3)*, 50−76.

Скалозубов Володимир Іванович; Volodymyr Skalozubov, ORCID: https://orcid.org/0000-0003-2361-223X
Козлов Ігор Леонідович; Igor Kozlov, ORCID: https://orcid.org/0000-0003-0435-6373
Хані Хайо; Hani Hayo, ORCID: https://orcid.org/0000-0002-5471-5496
Козлов Олексій Ігоревич; Olexiy Kozlov, ORCID: https://orcid.org/0000-0002-1834-6902
Дударев Ігор Іванович; Igor Dudarev, ORCID: htts//orcid.org/0000-0001-95-6970
Яроцька Галина Сергіївна; Galina Yarotskaya, ORCID: https://orcid.org/0000-003-4456-3852

Received October 11, 2022

Accepted November 26, 2022