ECOLOGICA

UDC:502.7

ISSN 0354 - 3285

No - 116 • Beograd, 2024. • Godina XXXI

Samo u pretplati

ISSN 0354-3285
UDC: 502.7
COBISS.SR – ID 80263175

ECOLOGICA

Godina XXXI, Broj 116, Beograd 2024.

NAUČNO-STRUČNO DRUŠTVO ZA ZAŠTITU ŽIVOTNE SREDINE SRBIJE
ECOLOGICA

Osnivač i izdavač
NAUČNO-STRUČNO DRUŠTVO ZA ZAŠTITU ŽIVOTNE SREDINE SRBIJE ECOLOGICA
Adresa: Beograd, Kneza Miloša 7a, tel/fax (011) 32 44 248; e-mail: ecologica.drustvo@gmail.com;
URL: www.ecologica.org.rs; Tekući račun: 200 – 2718500101033 – 84, Banka Poštanska Štedionica;
PIB - 101600071; Matični broj – 17057057.
Za izdavača: Emeritus prof. dr Larisa Jovanović, Predsednik Društva ECOLOGICA

Publisher
SCIENTIFIC PROFESSIONAL SOCIETY FOR ENVIRONMENTAL PROTECTION OF SERBIA - ECOLOGICA

Suizdavači:
Institut za opštu i fizičku hemiju, Beograd
Institut za ekonomiku poljoprivrede, Beograd

Co-publishers:
Institute of General and Physical Chemistry, Belgrade
Institute of Agricultural Economics, Belgrade

Glavni urednik / Editor in chief: Emeritus prof. dr Larisa Jovanović

Štampa: Akademska izdanja, d.o.o., Zemun

Slika na koricama: Kopaonik, Foto: Aleksandra Stojkov Pavlović

Kompjuterska grafička obrada: ms Dejan Anđelković

Korektura i lektura: doc. dr Milan Brkljač

URL časopisa ECOLOGICA: www.ecologica.org.rs/?page_id=21

Uputstvo za pripremu radova: www.ecologica.org.rs/?page_id=219

CIP - Katalogizacija u publikaciji
Narodna biblioteka Srbije, Beograd

502.7

ECOLOGICA / glavni urednik Larisa Jovanović, God. 1, broj 1 (1994) – Beograd (Kneza Miloša 7a): Naučno-stručno društvo za zaštitu životne sredine Srbije – Ecologica, 1994 – (Zemun : Akademska izdanja) - 28 cm

Tromesečno

ISSN 0354 – 3285 = Ecologica

COBISS.SR – ID 80263175

Štampanje časopisa pomaže
Ministarstvo nauke, tehnološkog razvoja i inovacija Republike Srbije

Posebnu zahvalnost Upravni odbor Naučno-stručnog društva „Ecologica“ izražava organima, rukovodstvu i Stručnoj službi Saveza inženjera i tehničara Srbije za podršku u realizaciji Programa rada Društva „Ecologica“

Naučna politika časopisa ECOLOGICA

Časopis „ECOLOGICA“ nalazi se u kategoriji vrhunskih nacionalnih časopisa (M51) Ministarstva nauke, tehnološkog razvoja i inovacija Republike Srbije.
Izdavač časopisa Naučno-stručno društvo „ECOLOGICA“ objavilo je prvi broj časopisa 1994. godine, i od tada časopis izlazi u kontinuitetu četiri puta godišnje.
Časopis ECOLOGICA opremljen je svim neophodnim elementima i oznakama, u skladu sa zakonom, kojim se uređuje izdavačka delatnost (ISSN, CIP katalogizacija, UDK klasifikacija, Cobiss - ID).
Svakom naučnom radu primljenom za objavljivanje u časopisu ECOLOGICA dodeljuje se DOI broj i međunarodni standardni UDK broj a za svakog autora se navodi ORCID identifikator.
Časopis objavljuje radove koji se bave kvalitetom životne sredine i zaštitom i unapređenjem kvaliteta životne sredine. Zbog interdisciplinarnog i multidisciplinarnog karaktera tematike u zaštiti životne sredine, radovi objavljeni u časopisu pripadaju Društveno-humanističkom, Prirodno-matematičkom i Tehničko-tehnološkom polju i sledećim naučnim oblastima:
Nauke o zaštiti životne sredine, Hemijske nauke, Biotehničke nauke,Inženjerstvo zaštite životne sredine i zaštite na radu, Ekonomske nauke, Menadžment i biznis, Pravne nauke, Sociološke nauke, a takođe užim naučnim oblastima: Ekološki menadžment, Geohemijske osnove ekološkog menadžmenta, Biogeohemija životne sredine, Fizička hemija, Menadžment prirodnih resursa, Održivi razvoj, Indikatori održivog razvoja, Zelena ekonomija, Ekoturizam, Cirkularna ekonomija, Ekološko inženjerstvo, Tehnologije primene obnovljivih izvora energije, Biotehnologije u zaštiti životne sredine, Socijalna korporativna odgovornost, Socijalni aspekti zaštite životne sredine, Ekonomska politika, Ekološko pravo, Finansiranje zaštite životne sredine, Kvalitet i bezbednost proizvoda, Standardi zaštite životne sredine, Integrisani standardi zaštite kvaliteta i bezbednosti proizvoda. Unapređenje kvaliteta vodnih i zemljišnih resursa, Unapređenje kvaliteta vazduha, Ublažavanje klimatskih promena itd.
Časopis „ECOLOGICA“ objavljuje radove u kojima se istražuju različiti teorijski i empirijski problemi iz navedenih oblasti.
Časopis „ECOLOGICA“ objavljuje radove zasnovane na fundamentalnim, primenjenim i razvojnim istraživanjima koja se odvijaju u različitim zemljama sveta i u Srbiji.
Naučna saradnja sa predstavnicima Međunarodnog uređivačkog odbora iz 15 zemalja sveta: Ruske Federacije, Španije, Nemačke, Austrije, Francuske, Slovenije, Hrvatske, Bosne i Hercegovine, Bugarske, Rumunije, Kirgistana, Kazahstana, Severne Makedonije, Grčke i SAD, daje mogućnost razmene iskustava u odabiru i pripremi radova za objavljivanje u časopisu „ECOLOGICA“.
Naši autori crpe inspiraciju za naučne radove na međunarodnim naučnim konferencijam posvećenim svetskom Danu planete Zemlje, koje Naučno Društvo „ECOLOGICA“ redovno održava tokom 20 godina.
Teme Međunarodnih Konferencija bile su aktualna svetska zbivanja u oblasti nauka o životnoj sredini: Održivi razvoj, Milenijumski ciljevi razvoja, Klimatske promene, Globalno otopljavanje, Zeleni rast i Zelena ekonomija, Cirkularna ekonomija, Zakonska regulativa u oblasti zaštite životne sredine, Nove tehnologije za zaštitu životne sredine, Finansiranje novih projekata zaštite životne sredine, Zelena energetika, Ekoturizm, Organska proizvodnja, Značaj 4. industrijske revolucije za zaštitu životne sredine, Uticaj pandemije COVID-19 na ekonomiju i životnu sredinu, Monitoring i digitalizacija parametara životne sredine i mnoge druge.
Multidisciplinarnost i aktuelnost tematskih oblasti obuhvaćenih našim konferencijama privlače mnoge naučnike iz različitih zemalja i naučno-obrazovnih institucija (državnih i privatnih univerziteta, naučnih instituta, visokih škola i akademija).

Uređivačka politika časopisa ECOLOGICA

Uređivačka politika časopisa ECOLOGICA usklađena je s Pravilnikom o kategorizaciji i rangiranju naučnih časopisa (Službeni glasnik RS, broj 159 od 30. decembra 2020.).
Tematske, teorijske i metodološke smernice zbog multidisciplinarnosti tematike časopisa ECOLOGICA povezane su s različitim oblastima nauke. Metodološke smernice opisane su u Uputstvu, koje se obično nalazi na kraju svakog broja časopisa ECOLOGICA. Najnovije Uputstvo priloženo prvom broju časopisa iz 2022. godine sadrži sve neophodne informacije za autore u vezi pripreme radova za objavljivanje u časopisu, u skladu s Pravilnikom o kategorizaciji i rangiranju naučnih časopisa.
Časopis objavljuje originalne naučne i pregledne radove, koji su prošli proveru na plagijarizam i dobili pozitivna mišljenja recenzenata. Spisak recenzenata se daje u prvom broju časopisa iz svake kalendarske godine. Radovi moraju biti napisani na srpskom ili engleskom jeziku i uljućuju apstrakte na engleskom i srpskom jeziku.
Recenzenti su dužni da kvalifikovano i u zadatim rokovima dostave glavnom uredniku ocenu naučne vrednosti rukopisa. Recenzenti vode posebnu brigu o stvarnom naučnom doprinosu i originalnosti rukopisa.
Recenzija mora sadržati objektivan i precizan pregled rukopisa. Sud recenzenata mora biti jasan i potkrepljen argumentima. Od recenzenata se očekuje da svojim sugestijama unaprede kvalitet rukopisa. Ako procene da rad zaslužuje objavljivanje uz korekcije, dužni su da predlože načine pomoću kojih korekcija može da se ostvari.
Rukopis poslat recenzentu smatra se poverljivim dokumentom.
Svaki autor snosi moralnu i etičku odgovornost za podatke objavljene u radu.
Uredništvo časopisa proverava prihvatljivost naučnog rada za objavljivanje pomoću međunarodnih proverivača na plagijarizam.
Konačnu odluku o prihvatanju rukopisa za objavljivanje donosi isključivo glavni urednik časopisa.
Glavni urednik i članovi uredništva dužni su da preduzmu sve razumne mere da recenzenti ostanu anonimni tokom i nakon procesa evaluacije u skladu s procedurom. Recenzije se arhiviraju zbog spornih slučajeva, kad se autori ne slažu s mišljenjem recenzenata.

ECOLOGICA, Vol. 31, No 116 (2024), 345-352
https://doi.org/10.18485/ecologica.2024.31.116.3
Originalni naučni rad
UDC: 504.5:621.039

Nuclear accidents: past, present and maybe the future

Nuklearni akcidenti: prošlost, sadašnjost, a možda i budućnost

Ana A. Čučulović[1], Jelena N. Stanojković[2], Rodoljub D. Čučulović[3]*

[1,2]University of Belgrade, Institute for the Application of Nuclear Energy, Banatska 31b, 11080 Zemun, Serbia / Univerzitet u Beogradu, Institut za primenu nuklearne energije – INEP, Banatska 31b, 11080 Zemun, Srbija

[3]University MB, Faculty of Business and Law, Teodora Drajzera 27, 11000 Belgrade, Serbia / Univerzitet MB, Poslovni i pravni fakultet, Teodora Drajzera 27, 11000 Beograd, Srbija

* Corresponding author / Autor za prepisku

Received / Rad primljen: 29.09.2024, Accepted / Rad prihvaćen: 21.11.2024.

Abstract: Radioactive contamination is the unintentional and undesirable presence of radioactive elements on surface or within organism. Such contamination can be result of technological developments, peaceful nuclear energy use, experimental nuclear activities, and the use of nuclear weapons in warfare. To mitigate the risk of radioactive contamination, protective measures are being implemented. During the period from 1945 to 1987, 28 accidents occurred due to human actions. Before the Chernobyl accident (26.04.1986, Ukraine), there were three notable cases of unintentional radioactive leakage from nuclear power plants: Kyshtym (1957), Windscale (1957), and Three Mile Island (1979). The incident at the Lenin nuclear power plant in Chernobyl resulted in global environmental contamination, with cesium residues are still present in Serbia to this day. At 1999 southern Serbia experienced contamination with long-lived radionuclides from depleted uranium used in the bombings. The Fukushima nuclear incident in Japan (2011) did not result in significant contamination in Serbia due to the considerable distance. Regardless of their development level, all states face common threats and risks in economic, informational, technological, biological, and nuclear security, which could potentially lead to new nuclear accidents.

Key words: radioactivity, nuclear accidents, radioaktive contamination, Chernobyl.

Sažetak: Radioaktivna kontaminacija je neplanirano i nepoželjno prisustvo radioaktivnih elemenata na površini ili unutar organizma. Može da nastane usled tehnološkog razvoja, mirnodopskog korišćenja nuklearne energije, eksperimentalnih nuklearnih proba, kao i usled primene nuklearnog oružja u ratnim sukobima. U cilju sprečavanja radioaktivne kontaminacije stanovništva sprovode se mere zaštite. Čovekovim delovanjem u periodu od 1945. do 1987. godine desilo se 28 akcidenata. Do akcidenta u Černobilju (26.04.1986, Ukrajina) zabeležena su tri slučaja ispuštanja značajne radioaktivnosti iz nuklearnih elektrana u okolinu: Kištim (1957), Vindskejl (1957), Ostrvo Tri Milje (1979). U nuklearnoj elektrani Lenjin u Černobilju, desio se akcident koji je doveo do globalne kontaminacije životne sredine, pa i Srbije. Na teritoriji Republike Srbije i danas su prisutne rezidue ^{137}Cs. Teritorija juga Srbije je 1999. godine dodatno kontaminirana dugoživećim radionuklidima u napadima agresora koji je koristio municiju sa osiromašenim uranijumom. Nuklearni akcident u Fukušimi (Japan) desio se 2011. godine, ali na sreću zbog velike udaljenosti nije doveo do kontaminacije životne sredine u Srbiji. Sve države se, bez obzira na stepen razvijenosti, suočavaju sa zajedničkim pretnjama i rizicima u oblasti ekonomske, informacione, tehnološke, biološke i nuklearne bezbednosti, koji mogu da dovedu do novih nuklearnih akcidenata.

Ključne reči: radioaktivnost, nuklearni akcidenti, radioaktivna kontaminacija, Černobilj.

[1]orcid.org/0000-0001-9315-4559, e-mail: anas@inep.co.rs
[2]orcid.org/0000-0003-3784-842X, e-mail: jelenas@inep.co.rs
[3]orcid.org/0000-0003-4472-0424, e-mail: rodoljub_cuculovic@yahoo.com

THE RADIOACTIVITY CONCEPT AND RADIONUCLIDE TYPES

Radioactivity and ionizing radiation were present even before the formation of planets and life on Earth. All organisms on planet Earth are exposed to radiation, which according to their place of origin, can be divided into: radiation of terrestrial and cosmic origin. Sources of ionizing radiation according to their genesis and occurrence in the environment can be divided into: natural (primordial or terrestrial, cosmogenic and cosmic radiation); anthropogenic (radioactive fallout and medical technology) and radioactive waste (Dangić, 1995).

Primordial radionuclides (^{235}U, ^{238}U, ^{232}Th, ^{226}Ra, ^{222}Rn, ^{40}K and others) are the most important sources of ionizing radiation in the environment. They have a long physical half-life (10^5-10^{16} years) and differ significantly in their physical and geochemical properties, types of radioactive decay (alpha, beta and gamma), radiation intensity, isotopic abundance, mode of occurrence, migration and geochemical cycles (Dangić, 1995).

Factors that affect the intensity of natural radiation are: the type of cosmic radiation, altitude, latitude and longitude, the content of natural radioactive elements in the biosphere and the geological characteristics of the soil. Natural radionuclides in the soil (formed in the process of nucleo synthesis, billions of years ago) make the largest contribution to gamma radiation (96%) in the environment. Natural radioactivity is part of the environment. It changes from place to place and affects the population over a very long period of time. According to the UNSCEAR report, the average mass concentrations (concentration range) of uranium, radium, thorium and potassium in the world's soil are: 2.82 (1.29-8.87) mg/kg; 3.18 (1.53-5.45) mg/kg; 7.32 (2.68-15.61) mg/kg and 1.54 (0.54-3.28) (%), respectively (UNCSEAR, 2000). Araxá in Brazil, Kerala and Madras in India, and Ramsar in Iran are examples of geographical areas on Earth where radiation doses up to 800 times higher than average have been measured (UNCSEAR, 2000).

Cosmogenic radionuclides (^{3}H, ^{7}Be, ^{10}Be, ^{14}C, ^{26}Al, ^{32}Si, ^{36}Cl and others) due to their low concentrations, relatively short half-lives and low radiation intensities, have little significance in the total irradiation of the population.

Generated or anthropogenic radionuclides (^{3}H, ^{131}I, ^{129}I, ^{137}Cs, ^{90}Sr, ^{99}Tc, ^{239}Pu, and others) have been amplified or created by human activity. They have different half-lives and emergencies. Contamination with these radionuclides is mainly regional in nature, but it can also be on a wider scale in the case of powerful nuclear explosions (Aakrog, 1988). Radioactive contamination of the environment with artificial radioactive elements occurs by: accidental release of radioactive effluents from nuclear power plants, accidents at nuclear facilities, discharge of waste from research laboratories and hospitals, inadequate disposal of nuclear waste or testing of nuclear weapons.

RADIOACTIVE CONTAMINATION

Radioactive contamination represents the unplanned and undesirable presence of radioactive elements on a surface or inside an organism. Radioactive contamination of certain parts of the environment can occur in several ways: due to technological development, peaceful use of nuclear energy, experimental nuclear tests, as well as due to the use of nuclear weapons in war conflicts. Regardless of the origin and manner in which radioactive substances are released into the environment, radionuclides pose a threat to the radiation safety of the population.

CONTAMINATION WITH ANTHROPOGENIC RADIONUCLIDES

Nuclear weapons testing and accidents at nuclear installations represent the main sources of contamination of the atmosphere by artificial radionuclides. There are two types of nuclear weapons: fissional or atomic bombs, in which nuclear energy is released by fission of uranium or plutonium nuclei, and fusion bombs (also called thermonuclear or hydrogen bombs), in which the atomic bomb is the trigger that causes the fusion of tritium and deuterium nuclides. Atmospheric testing of fission bombs leads to contamination of the atmosphere with fission products. Fusion bombs contaminate the atmosphere with ^{3}H, ^{14}C and other radioactive elements. They also release fission products, due to the use of fission material as a trigger for the explosion.

Radioactive elements that enter the environment, whether air, water or soil, begin their migration through the ecosystem and food chain and contribute to the overall irradiation of living beings occupying a certain territory. The behavior of radionuclides in the environment, their migration degree and inclusion in the food chain depends on: the manner of introduction into the environment, climatic factors, geographical characteristics of regions, physico-chemical characteristics of the soil and physiological-morphological characteristics of plants animals and mineral fertilizer (Čučulović et al., 2024). The migration of radionuclides through different ecosystems and links in the food chain is called the biological cycle of radionuclides. Radioactive elements of fission origin, which are easily incorporated and migrate through the food chain and pose a danger to all living things, are called biologically significant radionuclides. In order for a radioactive element to belong to this group, it is necessary: that it is formed in large quantities during nuclear fission, that it has a sufficiently long half-life, that it is present in large quantities in food and water, that it is easily absorbed in the body, that it has its own chemical analogue or stable isotope in the body and that it is excreted from the body in a short period of time and in large quantities. The most important biologically significant radionuclides are ^{134}Cs, ^{137}Cs, ^{89}Sr, ^{90}Sr and ^{131} (Mitrović, 2021).

The radioisotopes ^{134}Cs (physical half-life ($T_{1/2}$) = 2.06 years) and ^{137}Cs ($T_{1/2}$ = 30.17 years) are fission elements, beta and gamma emitters, whose radioactive decay produces stable isotopes ^{134}Ba and ^{137}Ba. Both radionuclides are present in the fuel elements of a nuclear reactor, from which they are released into the environment. An example of this is the behavior of ^{137}Cs. In the case of a nuclear bomb explosion, ^{137}Cs is initially present in the atmosphere in negligible quantities, after 2 months it is represented by 0.1%; after 9 months with 1%; after 2 years at 4%; and 20 years later, by 22 %. Due to its long half-life, it stays in the stratosphere for a long time and then gradually reaches the troposphere (Simon, 1971). The cesium ion is a chemical and biochemical homologue of potassium and follows its metabolism in the body. It is completely soluble in body fluids and is evenly distributed throughout the body. Because of this property, there is no critical organ for cesium and it is an organotropic radionuclide. Radiocesium is an extremely toxic element, and its physicochemical characteristics are such that it actively participates in the human and animal food chain through plants, because it metabolically replaces potassium. A biokinetic model of cesium in the human body shows that 10% of total cesium has a half-life of 2 days, and 90% has a half-life of up to 110 days. It is estimated that 80% of cesium is eliminated from the body in the urine (ICPR Publication, 1979). Cesium uptake processes from the external environment include: physical and chemical sorption and ion exchange. Radiocesium most often reaches plants through dry or wet rainfall. Sorption of radiocesium by vascular plants can be through the crown, stem or root system (Melnikov, Zanoni, 2010).

^{131}I is a biologically important radionuclide for the population. It is produced in significant quantities during nuclear fission or accidents at nuclear reactors and appears in elemental form or in the form of iodide, to a lesser extent directly from the air (as a radioactive aerosol), and mostly indirectly through green food and vegetables that are radioactively contaminated with atmospheric precipitation. The physical half-life of ^{131}I is 8 days. The biological half-life of ^{131}I varies in mammals, differing between species, but also within species. Absorbed from food, about 90% of ^{131}I reaches the bloodstream, from where 30-50% of it is taken up by the thyroid gland and fixed to its saturation, and the remaining amounts are excreted from the body through urine and feces (Drozdovitch, 2021).

NUCLEAR TESTS AS A SOURCE OF CONTAMINATION BY ANTHROPOGENIC RADIONUCLIDES

The Trinity test, the first nuclear test, was conducted in 1945 by the United States in New Mexico. The era of the use of nuclear weapons began in the same year, when the first atomic bombs were dropped on the cities of Hiroshima and Nagasaki (Japan), when more than 200,000 people died (were killed) almost instantly.

In the periods from 1954 to 1958, from 1961 to 1962, and from 1972 to 1982, the United States, the Soviet Union, and the United Kingdom conducted intensive tests (air, ground, underground, and underwater) of nuclear weapons. During the tests, hundreds of thousands of tons of earth was torn out, scorched, sucked into a fireball, quickly spreading into mushrooms and clouds, from which large pieces of various materials (soil, construction of buildings) fell to the ground, covering a surface similar to a circle (direct radioactive fallout). Local radioactive fallout occurs between 10 and 20 hours after the explosion and consists of large particles, larger than 5 μm in diameter, that fall from the atomic cloud into a confined space of ellipsoidal shape, forming "islands" of greater contamination. Smaller particles that entered the troposphere in the next 2 to 3 weeks after the explosion gradually fall to the earth's surface. This precipitation is called tropospheric radioactive fallout (semi-global or continental). Depending on the direction of the winds, it spreads around the Earth, making a full circle in 4 to 7 weeks. Stratospheric or global radioactive fallout is made up of very tiny particles that enter the stratosphere. Annually, about 10% of these particles are deposited on the ground. Radioactive elements that are deposited on the ground by radioactive fallout begin their migration process through the food chain and lead to irradiation and contamination of all living beings in the area (Simon, 1971). When nuclear bombs explode, the total precipitation is spread over large areas and significant amounts of radioactive particles fall into the world's seas. In 1963, the United States, the USSR and Great Britain signed an agreement in Moscow to partially ban nuclear tests in the atmosphere, oceans and space. Between 1972 and 1982, 20 above-ground tests were carried out (6 in the Northern Hemisphere and 14 in the Southern Hemisphere) (Jovanović, 1983). The consequences of these experimental nuclear explosions are manifold, the dangers are diverse and in many cases unpredictable. Between 1945 and 1990, about 540 atmospheric and 1,900 underground nuclear tests were conducted, while between 1945 and 1975, about 800 nuclear tests were carried out, with a cumulative strength of 325045 kT trinitrotoluene (TNT) (Mitrović, 2021).

NUCLEAR ACCIDENTS AS A SOURCE OF CONTAMINATION BY ANTHROPOGENIC RADIONUCLIDES

To meet the energy demands of humanity, nuclear power plants have been built, which, in normal operation, would contribute very little to the exposure of the population to radiation. Thus, in 1956, the first nuclear power plant, Colder Hall, with a capacity of 50 megawatts, was put into operation in Great Britain. Until then, both the United States and the USSR had their own reactors, but their power was negligible (only 2.4 MW and 5.0 MW respectively). By 1997, 442 power generation reactors had been built in 34 countries, with an installed capacity of 350825 MW. The construction of another 36 reactors with a capacity of 27678 MW was planned (IAEA Bulletin, 1997). By 2021, there were more than 400 nuclear power plants in the world distributed in thirty-one countries (Mitrović, 2021).

A nuclear accident is an unexpected event, human error, equipment failure and other irregularities whose consequences or possible consequences are not negligible from the point of view of protection against ionizing radiation, nuclear or radiation safety or security. Accidents at nuclear facilities can lead to regional, semi-global or global environmental contamination. Between 1945 and 1987, there were 28 accidents involving 272 exposures to excessive radiation and 35 deaths. Of the 27 accidents prior to the Chernobyl accident, only three cases resulted in significant releases of radioactivity into the environment: Kishtim - USSR (September 29, 1957), Vindscale - Great Britain (October 8, 1957), Three Mile Island - USA (March 28, 1979). The accident in Kishtim (southern Urals) discharged 49×10^{15} Bq ^{144}Ce; 19×10^{15} Bq ^{95}Zr and ^{95}Nb; 4.0×10^{15} Bq ^{90}Sr and 2.7×10^{15} Bq ^{106}Ru. Only 0.027×10^{15} Bq of radiocesium-137 was released. About 740 PBq radionuclides are thought to have been released into the atmosphere. The Vindscale accident contaminated the territory of Great Britain and Europe. On that occasion the following was released: 0.74×10^{15} Bq ^{131}I; 0.022×10^{15} Bq ^{137}Cs; 0.003×10^{15} Bq ^{106}Ru; 1.2×10^{15} Bq ^{133}Xe and 0.0088×10^{15} Bq ^{210}Pb. The accident at the Three Mile Island nuclear power plant (USA) emitted the most noble gases: about 370×10^{15} Bq (mostly ^{133}Xe) and 0.55×10^{15} Bq ^{131}I (Bennett, 1995; Kirchmann, 1997; Wirght et al. 1999).

In order to assess the accident extent and its consequences for human health and the environment, the International Radiation Protection Agency (IAEA) has adopted criteria for classifying them into seven safety categories or levels, known as the International Nuclear and Radiological Event Scale (INES scale). Events are classified into seven levels, of which levels 0 to 3 are considered incidents and levels 4 to 7 are considered accidents.

The accident that marked the 20th century was an accident at the Lenin nuclear power plant in Chernobyl, then the Soviet Union, now Ukraine, on the border with Belarus and Russia. The accident that occurred on April 26, 1986 at 01:23 a.m. once again pointed to the human factor as an always possible source of errors with catastrophic consequences. With their unfortunate manipulations, the operators of the power plant caused insufficient heat dissipation from the reactor core. Overheating of fuel elements, sudden production of steam and a chemical explosion produced a shock wave whose power was equal to several hundred kilograms of TNT explosives. As a result of the accident, a high-energy boiling reactor, with a power of 1 million watts and the production of 7.4×10^{19} Bq of various radionuclides, was destroyed, and the consequences of this accident were felt throughout the Northern Hemisphere and affected millions of people. The composition of the released material depended on the stage at which it was released. There were four characteristic periods of radionuclide emission from the damaged reactor: 1. explosion on April 26, 1986 (mechanical ejection of materials with iodine, tellurium, cesium and inert gases); 2. From 26 April to 2 May 1986, due to the covering of the reactor with about 5000 tons of boron, lead, dolomite and sand, the release of radioactivity decreased; 3. From May 2 to May 5, 1986, there was again an increase in the release of radioactivity, because there was an accumulation of heat in the reactor and thus an increase in the emission of volatile fission products, primarily iodine; and 4. After May 6, 1986. due to the measures taken, a decrease and termination of radionuclide discharge from the damaged reactor was observed.

The most significant and dangerous radionuclides released into the atmosphere were ^{131}I, ^{134}Cs and ^{137}Cs. About 12x10^{18} Bq of radioactive materials was released into the environment. About 85% of the released material originated from radionuclides with a half-life of less than one month (^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{133}Xe, ^{135}Xe, ^{132}Te, ^{131}I, ^{132}I, ^{135}I, ^{140}Ba, ^{239}Np); 13% of radionuclides with a half-life of several months (^{95}Zr, ^{95}Nb, ^{103}Ru); 1% of radionuclides with a half-life of about 30 years (^{137}Cs, ^{90}Sr) and about 0.0001% with a half-life of over 50 years (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Am, ^{242}Cm) (Xavkes et al., 1987). The data show that in the period from 1945 to 1980, nuclear tests released about 6500 TBq of ^{239}Pu and 4300 TBq of ^{240}Pu into the atmosphere, and the Chernobyl accident released only 70 TBq of these radionuclides.

The dispersal of the ejected material, and therefore territorial pollution was largely due to meteorological conditions. At the time of the first explosion, in which the column of ejected material reached its highest height, local winds of variable direction were blowing over Chernobyl. They propelled the radioactive material to the north and east, rotating in the direction south of Chernobyl. Thus, the material first reached Scandinavia and Finland. During all this time, the radioactive cloud was mainly circling over the USSR and on April 28 its trajectory was diverted to the west and south, and a day later in the direction of Germany and France. On April 30, a southern direction developed: through Hungary, Austria and Yugoslavia, towards Greece and even western Turkey, where increased activity was observed from May 1 to May 5, 1986. Eventually, this material again reached Poland and Scandinavia.

As a result of the accident, countries outside the Soviet Union received more radiocesium than the Soviet Union itself. Of the 1.5x10^{17} Bq emitted in total ^{134}Cs and ^{137}Cs, 45x10^{15} Bq was deposited in the Soviet Union, while most of the activity of ^{90}Sr and transuranic elements was kept within the borders of the USSR (Battiston et al., 1987).

Most deposits of the activities were mainly in the central, northern and southeastern parts of Europe, at a distance of 2000 km from Chernobyl. Comparing the precipitation from nuclear weapons testing, the total ^{137}Cs released by the Chernobyl accident was an order of magnitude smaller, while its radioecological impact was 30% greater than that of radiocesium-137 resulting from nuclear tests. This is explained by the fact that Chernobyl activity was deposited in densely populated areas with relatively high agricultural production (Aakrog, 1988). In the accident, 237 people were highly irradiated, and 32 died during the first weeks of the accident as a result of radiation. All of the highly irradiated were members of the intervention teams that were engaged in cooling the crashed reactor and extinguishing the fire in the initial phase of the accident. The intervention teams were made up of operating and firefighting personnel.

According to UNSCEAR, the radioactive cloud affected the territory of Yugoslavia in two waves. It is estimated that during 1986, about 2.4% of the total radionuclides (excluding inert gases) were deposited on the territory of Yugoslavia, i.e. about 5% of ^{131}I and about 10% of ^{137}Cs (Savezni komitet za rad, zdravstvo i socijalnu zaštitu, 1987). In 1996, an estimated 80x10^{15} Bq of long-lived radionuclides, mainly ^{137}Cs and ^{90}Sr, were present in Europe.

In the laboratory of Institute for the Application of Nuclear Energy, INEP, immediately after the accident in May 1986, high levels of total gamma activity were measured in grass (30.6 kBq/kg) and soil of Belgrade (6.8 kBq/kg), while the activity levels of ^{137}Cs were 5.3 kBq/kg and 1.6 kBq/kg, respectively. (Stanković, Stanković, 1999). In the immediate aftermath of the accident, animal fodder was heavily contaminated with ^{134,137}Cs. Compared to other bulky, grainy and concentrated foods, alfalfa was the most contaminated (up to 6,234 Bq/kg was found in in alfalfa flour in 1986) (Stanković, Stanković, 1999). As a result of the contamination of animal feed, in 1986, high levels of ^{137}Cs activity were measured in meat (537 Bq/kg in sheep meat) (Mitrović, 1995). INEP measured high levels of ^{137}Cs activity in milk in the first half of 1986 that amounted to 292 Bq/kg. (Stanković, Stanković, 1996). In the INEP laboratory, high levels of ^{137}Cs activity were measured in the period from 1986 to 1991, in the meat of snails (521 Bq/kg, 1987) and game, deer (up to 60 Bq/kg, in 1986). These levels of activity are much lower than the ones determined in the meat of roe deer from Northern European countries, which suggests that the territory of Yugoslavia suffered less from the Chernobyl accident than the countries of Northern Europe (Stanković, Stanković, 1998; Stanković, Stanković, 1996). Medicinal plants were also heavily contaminated with ^{137}Cs. In 1986, Asperula (*Herba asperulae*) was the most contaminated with measured 4190 Bq/kg, while in 1987 hawthorn (*Sumitates crataegi*) exhibited 5579 Bq/kg. (Stanković et al., 1993). Immediately, after the accident the activity levels of ^{137}Cs in bioindicators were high: in mushrooms - morels it was up to 2389 Bq/kg, in lichen *Cladonia fimbriata* from the mountain Sinjajevina (Montenegro) it was 13610 Bq/kg. Moss was also contaminated immediately after the Chernobyl accident (Stanković, Stanković, 1996; Čučulović et al., 2014).

Today, in Serbia, the activity levels of ^{137}Cs in meat samples of domestic and wild animals, milk, dairy products, are less than 1.0 Bq/kg. Radioactive residues of ^{137}Cs can still be found on the territory of Serbia in bioindicators: fungi (< 20 Bq/kg), lichens and mosses, but these are values that would correspond to the values before the Chernobyl accident (Čučulović et al., 2020).

At the beginning of 1999, depleted uranium ammunition was used on the territory of Serbia and Montenegro, which caused contamination of the attacked territory: Pljačkovica, Borovac, Bratoselce, Bukurevac, Reljan (Serbia) and Cape Arza (Montenegro). After the launch of depleted uranium missiles, environmental pollution with depleted uranium can be: 1) carried by the wind; 2) transport by insects, war and human activities; (3) biological and chemical corrosion processes, and (4) rain, surface water and groundwater, which become secondary sources of uranium pollution. Studies have shown that in air samples (filters) taken in the given areas, the activity level of ^{238}U ranged from 1.99 to 42.1 μBqm^{-3}; ^{234}U from 0.96 to 38.0 μBqm^{-3} and ^{235}U from 0.05 to 1.83 μBqm^{-3} (Jia et al., 2005).

Prior to the Fukushima disaster, one of the world's 25 largest nuclear power plants, Japan had 55 nuclear reactors. The Fukushima nuclear accident (Okuma, Futaba Area, Japan, March 11, 2011) was one of the largest since the Chernobyl accident, but less dangerous for the local population, as much smaller amounts of radioactive materials were released. It included a series of nuclear accidents and device failures that occurred as a result of a large and strong earthquake (9 on the Richter scale). The plant consisted of six 4.7 GW BWR nuclear reactors. At the time of the earthquake, reactors 1, 2 and 3 were automatically shut down, while reactors 4, 5 and 6 were not operational. After the earthquake, a large tsunami struck reactors 1, 2 and 3 and flooded the entire area. As a result, the diesel generators that powered the reactor cooling pumps were left without electricity. Over the next few days, there was a partial meltdown of the core of reactors 1, 2 and 3 and a hydrogen explosion that destroyed the roofs of the building where reactors 1, 3 and 4 are located. The explosion damaged the container of reactor 2, and several fires also damaged reactor 4. Due to fears of the spread of radiation, the population was evacuated from an area of 30 km around the nuclear power plant. No one was killed in the disaster. Radioactive particles were released from the reactor into the external environment, the most important of which was ^{131}I, and prophylactic iodine tablets were distributed to the population. In addition to ^{131}I, ^{134}Cs and ^{137}Cs, highly radioactive plutonium, were released from the reactor. The accident was at level 7 on the INES scale out of a possible 7, the same as the Chernobyl accident, except that the radiation released was less than 10% of the radiation from Chernobyl.

The Chernobyl accident led to global environmental contamination. On the territory of the Republic of Serbia, ^{137}Cs originating from Chernobyl is still present in the environment, especially in hilly and mountainous regions. The accident in Fukushima, due to its long distance, did not lead to significant contamination of the environment of the Republic of Serbia.

In the Republic of Serbia, the construction of nuclear power plants, nuclear fuel production plants and spent nuclear fuel processing plants is prohibited by law, so these activities, as well as the mining and processing of uranium ore, do not contribute to additional irradiation of the population on our territory.

LEGISLATIVE BODIES AND LEGAL REGULATIONS AT THE GLOBAL AND NATIONAL LEVEL

In 1925, the first international congress of radiologists was held in London, where the need for the formation of a radiation protection committee was discussed. In 1928, the International Commission on Radiological Protection (ICRP) was founded in Stockholm and today it is an international organization whose recommendations are adopted by: the International Atomic Energy Agency (IAEA), the UN FAO (Food and Agriculture Organization of the United Nations) and the World Health Organization (WHO).

The first rulebook on protection measures when working with X-ray devices and radioactive substances in the Federal People's Republic of Yugoslavia was adopted in 1947, and in 1959 the Law on Protection against Ionizing Radiation was passed. In 1965, the Basic Law on Protection against Ionizing Radiation was adopted in the Socialist Federal Republic of Yugoslavia. Protection against ionizing radiation was the responsibility of the Federal Commission for Nuclear Power, the Federal Institute for Health Protection and the Federal Committee for Health and Social Protection. In the period from 1970 to 1987, the Federal Committee for Health and Social Protection published the results of measurements of radioactivity in the environment once a year in the publication "Radioactivity of the Environment in Yugoslavia". In 2009, the Agency for Radiation Protection and Nuclear Safety was established in the Republic of Serbia in order to provide conditions for the quality and efficient implementation of measures of protection against ionizing radiation and nuclear safety measures in the performance of radiation activities and nuclear activities. In 2018, the Agency changed its name to the Directorate for Radiation and Nuclear Safety and Security of Serbia.

The Yugoslav Radiation Protection Society was founded on October 11, 1963 in Portorož during the Yugoslav Symposium on Radiological Protection. In 1969, the Society became a full member of the International Commission on Radiation Protection (ICRP). In the period from 1972 to 2003, the Society changed its name to the Yugoslav Radiation Protection Society, and in 2005 it was renamed the Radiation Protection Society of Serbia and Montenegro.

FUTURE

We live in a world where the actions of some states are directly aimed at undermining legitimate authorities, social stability and traditional values, and eroding trade and cultural ties. Developed and underdeveloped countries face common threats such as terrorism, organized crime, drug trafficking, illegal migration, radicalism and extremism, as well as economic, informational, technological and biological security risks. We live in a world full of strained relations and the opening of new conflicts in a number of regions, new confrontations in which civilians are primarily killed. Are we on the brink of World War III? Are we so negligent of ourselves, our descendants, the environment in which we live in to use nuclear warheads? Can there be new nuclear accidents? The answer is yes if we don't come to our senses.

Acknowledgments

Authors acknowledge the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia for financial support (Grant No. 451-03-66/2024-03/200019).

REFERENCES

[1] Aakrog, A. (1988). The radiological impact of Chernobyl debris compared with from nuclear weapons fallout. *J. Environ. Radioact*. 6, 151-162.

[2] Battiston, G.A., Degetto, S., Gerbasi, R., Sbrignadello, G., Tositti, L., Croatto, U. (1987). The deposition of Chernobyl fallout in north-east Italy. *Inorg. Chim. Acta*, 140, 327-329.

[3] Bennett, B.G. (1995). Exposures from worldwide releases of radionuclides. Environmental Impact of Radioactive Releases, *IAEA, Proceedings of a symposium*, Vienna, 3-12.

[4] Čučulović, A., Sabovljević, M., Veselinović, D. (2014). The activity concentrations of ^{40}K, ^{226}Ra, ^{232}Th, ^{238}U and ^{7}Be in moss from spas in eastern Serbia in the period 2000-2012. *Arch. Biol. Sci., Belgrade*, 66 (2), 691-700.

[5] Čučulović, A., Stanojković, J., Čučulović, R. (2024). Radioaktivnost u uzorcima mineralnog đubriva iz uvoza analiziranim tokom 2023. godine, Ecologica, 31(114), 173-178

[6] Čučulović, A., Stanojković, J., Veselinović, D. (2020). A twenty-year radiocontamination study of edible fungi of Serbia Activity Levels of ^{137}Cs and Estimated dose to the Population, *Nucl.Technol. Radiat. Protect*. 35(2), 165-171.

[7] Dangić, A. (1995). Geohemijski procesi u prirodi i radionuklidi. U: *Jonizujuća zračenje iz prirode*, Jugoslovensko društvo za zaštitu od zračenja. Institut za nuklearne nauke Vinča, Beograd, 41-56.

[8] Drozdovitch, V. (2021). Radiation exposure to the thyroid after the Chernobyl accident. *Frontiers in endocrinology*, 11, 569041

[9] IAEA Bulletin, (1997). 39 (1).

[10] ICPR Publication, (1979). 30, 91.

[11] ICPR Publication, (1988). 54, 155

[12] Jia, G., Belli, M., Sansone, U., Rosamilia, S., Gaudino, S. (2005). Concentration and characteristics of depleted uranium in water, air and biological samples collected in Serbia and Montenegro. *Appl. Radiat. Isot*., 63, 381-399.

[13] Jovanović, M. (1983). *Jonizujuća zračenja i životna sredina*. Vojnoizdavački zavod, Beograd, 107-190.

[14] Kirchmann, R. (1997). Historical overview of radioecology in the world. In: Proceedings of International Meeting on Influence of Climatic Characteristics upon Behavior of Radioactive Elements, Rokkasho, Aomori, Japan, Editors Ohmomo Y., Sakurai N., Institute for Environmental Sciences, Japan, 3-10.

[15] Mitrović, B. (2021). *Radiobiologija sa radijacionom higijenom*, Beograd, 1-4.

[16] Mitrović, R. (1995). *Radijaciona higijena i zaštita u mlekarskoj industriji*, Veterinarska komora Srbije, Beograd.

[17] Melnikov, P., Zanoni, L.Z. (2010). Clinical Effects of Cesium Intake, *Biol. Trace Elem. Res*. 135, 1-9, doi:10.1007/s12011-009-8486-7.

[18] Savezni komitet za rad, zdravstvo i socijalnu zaštitu, (1987). *Nivo radioaktivne kontaminacije čovekove sredine i ozračenost stanovništva Jugoslavije 1986. godine usled havarije nuklearne elektrane u Černobilju*, Beograd.

[19] Simon, S., (1971). *Atlas Medical des radionucleides utilise en medicine, biologie, industrie et agriculture*, Euroatom, Bruxeles,

[20] Stanković, A., Stanković, S., (1999). Černobilj – elementarna nepogoda svetskih razmera, *Savetovanje Meteorološki podaci – nacionalno blago*, Republika Srbija, Republički hidrometeorološki zavod, Vrnjačka banja, 21-23. april 1999. godine, 54-59.

[21] Stanković, S., Stanković, A., (1996). Biodiverzitet i radioekologija u uslovima akcidenta, Zbornik radova, savetovanje, *Černobilj, 10 godina posle*, Budva, 4-7. jun 1996. god. Jugoslovensko društvo za zaštitu od zračenja (JDZZ), INN Vinča, 111-117.

[22] Stanković, S., Stanković, A., (1998). Bioindikatori radioaktivne kontaminacije, referat po pozivu, Zbornik radova I, VII Kongres veterinara Jugoslavije sa međunarodnim učešćem, Beograd, Sava centar, 27-29. Oktobar 1998.

[23] Stanković, S., Krainčanić, M., Stanković, A. (1993). Kontaminacija bilja biološki aktivnim radionuklidima, *II Simpozijum hemija i zaštita životne sredine*, Vrnjačka banja, 9-13. juni 1993. 585-586.

[24] UNCSEAR, (2000). United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and Effects of Ionizing Radiation. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes, New York.

[25] Wirght, S.M., Howard, B.J., Strand, P., Nylén, T., Sickel, M.A.K. (1999). Prediction of ^{137}Cs deposition from atmospheric nuclear werapons tests within the Arctic, *Environ. Pollut*., 104, 131-143.

[26] Xavkes, N., Lean, G., Leigh, D., McKie, R. (1987). Pringle P., Wilson A., *Najgora nesreća na svijetu*, *Černobil: kraj nuklearnog sna*, Globus, Zagreb.