Strategic Research Agenda for Radiological Protection in Poland

Strategiczna Agenda Badawcza dla Ochrony Radiologicznej w Polsce

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Summary: The Strategic Research Agenda (SRA) for Radiological Protection (RP) in Poland was created as a comprehensive plan for the development of basic research aimed at indicating radiological protection research priorities for the next decade, in the context of the growing importance of nuclear energy, medical applications of radiation, and civil and military threats.

Establishing long-term priorities for research activities will enable the coordination of efforts among various research centres to accomplish the long-term objectives of Poland's science policy. This approach aims to enhance Poland's role in international research projects and develop necessary competencies ahead of the commissioning of the first Polish nuclear power plant, scheduled for 2035. The Agenda aims to outline key research priorities for Poland, aligning with similar European initiatives such as the PIANOFORTE White Paper published in 2025 and the Strategic Research Agenda (SRA) of the European Ionising Radiation Dosimetry Group (EURADOS).

The SRA is divided into four main research areas. The „Human" area mainly concerns the biological effects of radiation, radiotherapy and exposure to cosmic radiation. The area of „Safety" includes the issues of accidents and contamination, radio protectors, as well as psychology and communication of threats. In the „Energy" area, research is postulated that will result in increased work safety in the nuclear industry, better dosimetry and radioactive waste management. In the area of „Environment", research directions are postulated that will help improve the principles of monitoring, understand the migration of contamination or model the long-term impact of waste. In each of the areas, prospective research directions (perspectives) and corresponding challenges are defined.

RP does not yet have a permanent place in the structure of research funding in Poland. We call for the creation of an interdisciplinary thematic panel at the NCN[b], which would create a permanent institutional framework for the planned and sustainable development of research in the field of RP, meeting both the needs of science and the requirements of public safety.

Streszczenie: *Strategiczna Agenda Badawcza (SAB) dla Ochrony Radiologicznej (OR) w Polsce powstała jako kompleksowy plan rozwoju badań podstawowych mający na celu wskazanie priorytetowych kierunków badań dla ochrony radiologicznej na najbliższą dekadę, w kontekście rosnącego znaczenia energetyki jądrowej, medycznych zastosowań promieniowania oraz zagrożeń cywilnych i militarnych.*

Wytyczenie długoterminowych priorytetów prac badawczych pozwoli na koordynację wysiłków różnych ośrodków naukowych dla realizacji długofalowych celów polityki naukowej państwa polskiego, wzmocnienie roli Polski w międzynarodowych projektach badawczych oraz rozwój kompetencji w obliczu planowanego na 2035 rok uruchomienia pierwszej polskiej elektrowni jądrowej. Agenda jest próbą sformułowania głównych dla Polski priorytetów badawczych w odniesieniu do podobnych inicjatyw europejskich, takich jak opublikowana w 2025 roku biała księga projektu PIANOFORTE czy SAB Europejskiej Grupy Dozymetrii Promieniowania Jonizującego EURADOS.

SAB podzielona jest na cztery główne obszary badawcze. Obszar „Człowiek" dotyczy głównie skutków biologicznych działania promieniowania, radioterapii i ekspozycji na promieniowanie kosmiczne. Obszar „Bezpieczeństwo" obejmuje zagadnienia awarii i skażeń, radioprotektorów oraz psychologii i komunikacji zagrożeń. W obszarze „Energia" postulowane są badania, których efektem będzie zwiększone bezpieczeństwo pracy w energetyce jądrowej, lepsza dozymetria i gospodarka odpadami promieniotwórczymi. W obszarze „Środowisko" postulowane są kierunki badań, które pomogą w ulepszeniu zasad monitoringu, zrozumieniu migracji skażeń czy modelowaniu długoterminowego wpływu odpadów na środowisko. W każdym z obszarów określone są perspektywiczne kierunki badawcze (perspektywy) i odpowiadające im wyzwania.

OR nie ma jeszcze trwałego miejsca w strukturze finansowania badań w Polsce. Postulujemy utworzenie interdyscyplinarnego panelu tematycznego w Narodowym Centrum Nauki (NCN), w którego obszarze zostaną stworzone trwałe ramy instytucjonalne dla planowego i zrównoważonego rozwoju badań z zakresu OR, odpowiadające zarówno potrzebom nauki, jak i wymogom bezpieczeństwa publicznego.

1. Admission

1.1. Introduction

Radiological protection (RP) is an interdisciplinary field of science that deals with the study and implementation of methods for determining and reducing the exposure of humans and the environment to ionizing radiation. Progress in the field of RP concerns not only the practical implementation of methods to reduce exposure to radiation of humans and the environment, but above all the expansion of knowledge about the mechanisms and effects of radiation. A key role in the development of RP is played by basic research, providing fundamental knowledge on the interaction of ionizing radiation with matter, in particular with living organisms. They consist of the successes of natural sciences, in particular physics, chemistry, biology or geology, medical sciences (medicine, medical biology, genetics, epidemiology, bioengineering) and environmental sciences (ecology, sozology, earth science). Mathematical sciences, in the field of statistics

[b] NCN (Narodowe Centrum Nauki) – *National Science Center*.

and modelling of the mechanisms of hazard formation, and social sciences, especially in the field of communication of hazards and risks associated with exposure to ionising radiation, play an increasingly important role.

The Strategic Research Agenda (SRA) defines the most important research goals for a long-time horizon, usually covering at least the next decade. The point is to indicate priorities and avoid dispersion of efforts of various research centres to achieve the long-term goals of the state or a given organization. Between 2010 and 2020, multiannual research plans were prepared by the so-called research platforms, which group European institutions conducting research in various areas of radiological protection. *The European Radiation Dosimetry Group* (EURADOS), associating over 80 European institutions (including 4 Polish ones), published its SRA in the field of dosimetry in 2010 and updated it in 2020 [1]. Similar agendas have been published by *the Multidisciplinary European Low Dose Initiative* (MELODI) [2], the *European Platform on preparedness for nuclear and radiological emergency response and recovery* (NERIS) [3], the *European Alliance for Medical Radiation Protection Research* (EURAMED) [4], the *European Alliance for Radioecology* [5], and *the Sciences and humanities in ionizing radiation* (SHARE) [6]. The European Commission's Directorate-General for Research has agreed to establish research priorities in the area of RP on the basis of these updated research agendas. These programmes provide the basis for the formulation of European scientific policy in the field of RP, and in detail, are used to propose research priorities in current projects related to RP. Many Polish research teams actively participate in international research projects in these areas, although they very rarely have a leading role in them.

In March 2025, the European Partnership for Radiation Protection Research (PIANOFORTE) published a document addressed to the European Commission, „*The Vital Role of Radiation Protection Research in Europe's Future*" [7], defining the basic objectives of RP in terms of improving public health and environmental protection, supporting research on RP to develop industrial innovations, and preparing for emergencies. The document also highlights the importance of RP research for the European Research Programme 2024–2029, and in particular for actions on human health and the environment, competitiveness, a risk-aware society and the choice of energy sources to mitigate climate change.

In July 2023, a symposium entitled „Radiological Protection in Poland in the Face of the Challenges of the Polish Nuclear Energy Program (PPEJ)" was organized at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Krakow. At that time, the report of the Polish Consortium for Radiological Protection (PKOR) [8] on the role of radiological protection in Poland in relation to the PPEJ program was presented. One of the postulates formulated during the symposium was the need to prepare the SRA for Radiological Protection. The Agenda would provide substantive assistance to the Ministry of Science and Higher Education, the Ministry of Climate and Environment, the Ministry of Industry and to research funding agencies in Poland to conduct scientific policy in the area of RP and in related fields such as physics, chemistry, biology, medicine, geology and others. This is particularly important in light of the prospective Polish Nuclear Energy Programme, the development of radiotherapy and nuclear medicine, or the growing involvement of the Polish Space Agency in activities related to space exploration. In addition, the research agenda could provide significant support in articulating Polish research needs within the framework of European projects.

The changing socio-political environment, the growing number of states possessing nuclear weapons and the repeated threats of their use by the Russian Federation have resulted in a growing interest in the issues of civil defence, both from the perspective of monitoring potential radioactive contamination and the ways of informing about threats. On 5 December 2024, the Act on Civil Protection and Civil Defence in Poland came into force, which defines, among others, the rules of operation and organisation of civil defence in the context of possible threats, also as a result of the use of weapons of mass destruction.

In the current model of funding science, research projects in the field of RP, due to their interdisciplinary nature, often encounter difficulties related to their proper substantive evaluation compared to projects in traditional scientific disciplines. Therefore, one of the key postulates of the PKOR report was the creation of a thematic panel on Nuclear Safety and Radiation Protection (BJiOR) at the National Science Centre. The creation of such a panel would enable the creation of a permanent institutional framework for the planned and sustainable development of research in the field of RP, corresponding to both the needs of science and the requirements of public security, and, as a natural consequence, a more adequate assessment of research projects in this area.

1.2. Objectives

The development of nuclear energy (based on both large power reactors and geographically dispersed small modular reactors), the improvement of new technologies for generating radiation (such as accelerators and high-power lasers), the search for new energy sources (e.g. fusion energy), as well as the rapid progress of applications of ionizing radiation in radiotherapy and medical diagnostics generate several new challenges in the field of RP. At the same time, issues related to the safe storage and treatment of radioactive waste and the growing interest in space exploration require the development of an integrated, new approach to the fundamental issues of RP, in particular in the context of the assessment of the risks caused by radiation exposure and the differences in biological efficacy of different types of radiation. This is also important in connection with the introduction of new radioactive nuclides into nuclear medicine or the occurrence of materials containing increased concentrations of natural radionuclides in the immediate human environment and in the work environment.

It is the issue of the biological effects of human exposure to ionizing radiation that is the most controversial field of basic research in RP. The views of the supporters of the linear no-threshold model (LNT), which assumes that even the smallest dose of ionizing radiation carries the risk of causing cancer, compete with concepts suggesting the existence of adaptive response mechanisms, according to which low doses of radiation can activate the body's immune system and increase its resistance to subsequent exposures, and with the radiation hormesis hypothesis, which postulates potentially beneficial effects of very low doses of radiation. The results of these studies may have a direct impact on the association between levels and types of exposure and their possible adverse consequences.

This Strategic Research Agenda aims to set out promising directions of scientific activity, the development of which in the coming decade will enable the strengthening of national competences in the area of RP including the impact of nuclear energy on humans and the environment. A key element is to identify existing gaps and needs for further scientific work and to solve new and emerging challenges in the field of RP. The implementation of the SRA will contribute to enhancing the substantive and operational potential of research teams in Poland prior to the launch of the first nuclear power plant in 2035.

The Agenda will have a positive impact on the participation of Polish scientific units in the process of shaping new research programmes at the European level. Currently, Poland receives draft documents for consultations from the European Commission defining research priorities in subsequent framework programs and under the Euratom Treaty. These documents are often drawn up taking into account the interest and research potential of selected Member States, research centres or research teams. Having its own SRA enables Polish organizations to proactively participate in the process of defining European Union research programs, increasing the chances of implementing projects that meet the real needs and research priorities of Poland and the region of Central and Eastern Europe.

1.3. Research directions: areas, perspectives and challenges

Research in the field of radiological protection is inherently interdisciplinary, integrating knowledge and methodology from many areas of science. They include issues in the field of natural sciences, medicine, environmental sciences, mathematical and social sciences.

This document divides the research topic into four key areas: Human, Energy, Safety, and Environment (Fig. 1). Although this division is somewhat arbitrary, it reflects the primary research directions related to RP and provides a structured arrangement of research priorities. The **Human** area concentrates on the biological and medical aspects of ionising radiation. The **Energy** area examines nuclear energy and its effects on humans, flora, fauna, and the management of radioactive waste. The **Security** area encompasses all aspects of radiological protection con-

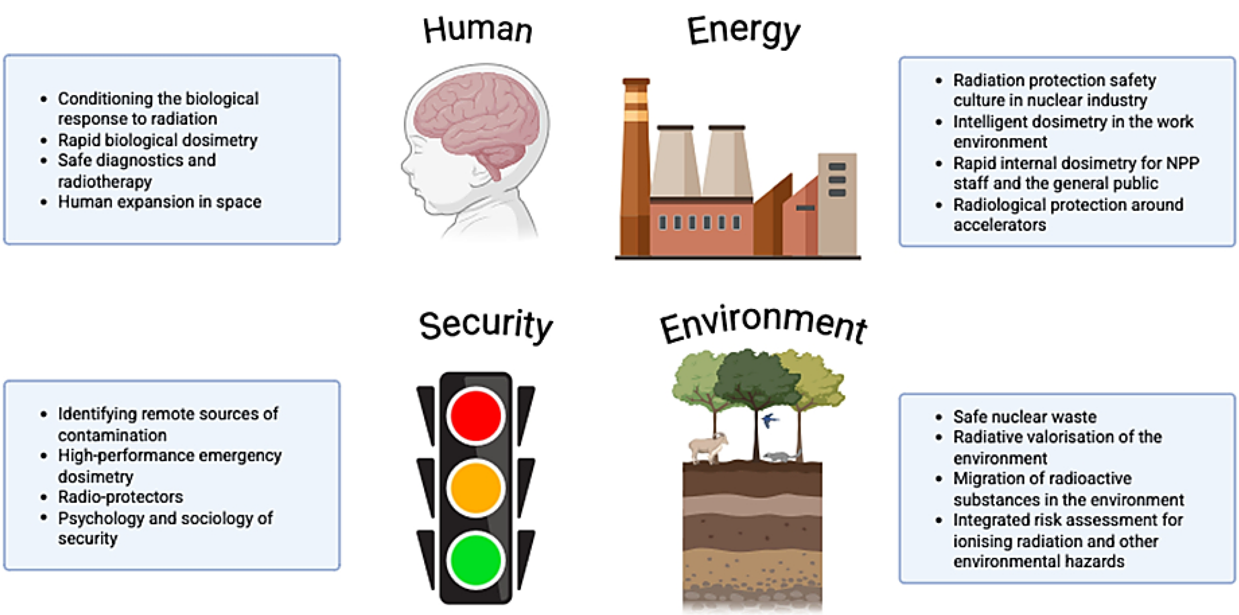


Fig. 1. Prospective research directions ("perspectives") for radiological protection in the areas of HUMAN, ENERGY, SAFETY and ENVIRONMENT.
Rys. 1. *Perspektywiczne kierunki badawcze dla ochrony radiologicznej w obszarach CZŁOWIEK, ENERGIA, BEZPIECZEŃSTWO i ŚRODOWISKO.*

cerning nuclear accidents, terrorist acts, and the use of nuclear weapons. The **Environment** area primarily involves specialised methods for monitoring radioactivity levels, nuclide transfer, and indicators of environmental change. These areas frequently intersect, sharing the common goal of ensuring safety in exposure to ionising radiation.

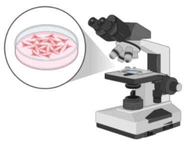
In each of these areas, perspectives are formulated to indicate the main research priorities in which, due to their scientific importance and public interest, it is worth investing in the next decade. Within each perspective, examples of needs and challenges are also identified, which may serve as a focus of individual projects.

2. Strategic Research Agenda

2.1. The „Human" area

The study of the impact of ionizing radiation on the human body is one of the most difficult and one of the most controversial issues of modern science. Research in this area is carried out at the intersection of radiobiology, micro-dosimetry and medical physics. Studies on the biological effects of low doses of radiation do not yield conclusive results, and this issue is of key importance for the foundations of RP. At the same time, in the context of the use of high doses of radiation in medical procedures, the need for their individualization, taking into account both the biological characteristics of the patient and the characteristics of a specific therapy, is increasingly noticed. There is also a growing interest in research into human presence in space, where high-energy cosmic rays may be one of the main risk factors in interplanetary flights.

Perspective 2.1-1: Conditioning the biological response to radiation
Perspektywa 2.1-1: Warunkowanie odpowiedzi biologicznej na działanie promieniowania



This perspective includes advancing our understanding of the molecular, cellular and genetic mechanisms of the human body's response to ionizing radiation. Understanding these mechanisms will lead to the development of new strategies to protect against the harmful effects of radiation, as well as to improve the precision and effectiveness of radiotherapy techniques, both in the context of cancer treatment and the protection of healthy tissues. This research could also lead to the development of new biomarkers and biophysical/numerical models that will be used in medicine to monitor and predict the body's response to radiation.

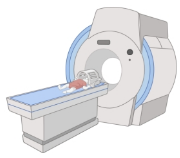
- *Challenge 1: Identification of detailed mechanisms that determine the response of cells to ionizing radiation, including at the level of nucleic acids, proteins, lipids of intra- and extracellular structures (exosomes).*
- *Challenge 2: Study of individual radiosensitivity and factors modulating the individual response to ionizing radiation (radioprotectors and radiosensitizers, adaptation to low doses).*
- *Challenge 3: Research on the molecular mechanisms of action of nanostructures and nanosystems in the context of protecting healthy cells from damage or promoting DNA repair in cells that have been damaged by radiation.*
- *Challenge 4: Understanding the mechanisms of the body's individual response to different ways of delivering the dose of ionizing radiation (FLASH technique, mixed radiation, fractionation).*

Perspective 2.1-2 Rapid biological dosimetry to assess human exposure to emergency situations
Perspektywa 2.1-2: Szybka dozymetria biologiczna do oceny ekspozycji człowieka w sytuacji awaryjnej

This perspective focuses on the use of radiobiological research to develop methods for assessing the dose of radiation after exposure. The retrospective dosimetry is crucial in case of radiation accidents or nuclear accidents. The main problem of the currently used methods of retrospective dosimetry is the long-time of measurements, relatively low sensitivity, high level of complication, limiting their mass application.

- *Challenge 1: Automation and application of artificial intelligence and machine learning to analyse DNA damage and other biomarkers.*
- *Challenge 2: Cytogenetics of FISH, m-FISH, m-BAND, PCC for biological dosimetry.*
- *Challenge 3: Determination of the baseline level of bio-dosimetry markers and the ranges and reasons for their fluctuation in the Central European population.*

Perspektive 2.1-3: Safe diagnostics and radiotherapy
Perspektywa 2.1-3: Bezpieczna diagnostyka i radioterapia



Ionizing radiation used in the diagnosis and treatment of cancer patients is not selective – it can also affect healthy cells and tissues, leading to genetic damage, organ dysfunction, and even the development of secondary cancers. The development of modern diagnostics and radiotherapy is associated with a constant need to improve the accuracy, safety and effectiveness of procedures, while minimizing the risks associated with exposure to ionizing radiation. Despite advanced technologies such as thomo therapy or proton therapy, there is still a risk of unintentional damage to healthy tissues, especially near the tumors.

- *Challenge 1: To develop accurate bio-dosimetry models for real-time monitoring of radiation dose.*
- *Challenge 2: Research on the possibility of reducing the dose of scattered radiation in modern methods of radiation oncology.*

- *Challenge 3: Development of new tissue-like materials, including 3D printing technology, for verification and personalization of radiotherapy.*
- *Challenge 4: Innovative radio-pharmaceuticals for personalized medicine in diagnostics and radioisotope targeted therapy.*
- *Challenge 5: Modelling of radiobiological processes taking into account the biological efficacy of different types of radiation and physicochemical interactions at the nanometre scale, as a basis for further development of biologically targeted radiotherapy planning.*

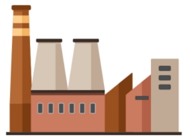
Perspective 2.1-4: Human expansion in space
Perspektywa 2.1-4: Ekspansja człowieka w kosmosie

Cosmic rays are one of the main environmental factors limiting the possibility of long-term human stay in space, especially beyond the Earth's orbit. There is no consensus in the scientific community on the principles of radiological protection in space, and individual space agencies have their own policies in this area. Research directions should concern both methods of reducing exposure, methods of reducing the effects of radiation (radioprotectors, radio-modulators) and post-exposure management. To develop a risk assessment under conditions of exposure to cosmic radiation, both mathematical models that enable the simulation of occurring phenomena and radiobiological experiments are necessary. A separate issue is the problem of the resistance of electronics to cosmic radiation, especially to secondary radiation, generated as a result of the interaction of high-energy particles with the material of the spacecraft.

- *Challenge 1: Development of radiobiological models for the assessment of the effects of acute and chronic exposure to cosmic radiation.*
- *Challenge 2: Study of the effects of solar and galactic radiation of different spectral composition on humans and electronics.*
- *Challenge 3: Testing the reliability of electronic systems under conditions of chronic and acute exposure to cosmic radiation.*
- *Challenge 4: Study of electrical and optical phenomena caused by ionizing radiation in semiconductor materials, scintillators, luminescent crystals for innovative methods of detection, spectrometry, dosimetry of cosmic rays.*
- *Challenge 5: Research on plant growth under exposure to high-energy cosmic rays.*
- *Challenge 6: Investigation of the composition and radioactivity of rocks and regoliths of extraterrestrial origin.*
- *Challenge 7: Simulation of cosmic rays using accelerators.*

2.2. The „Security" area

The increasing risk of nuclear conflict, attack on nuclear installations or contamination with a dirty bomb gives high priority to radiation safety research. One of the priorities is to study the mechanisms of radioactive contamination transport in the environment, which, combined with the development of atmospheric physics and ultra-sensitive methods of radionuclide detection, will enable early detection of contamination and will allow for the identification of the site of contamination emission and the original emission value. It is extremely important to look for more efficient indicators that allow you to assess a large number of people in a short period of time.



Perspective 2.2-1: Identifying remote sources of contamination
Perspektywa 2.2-1: Identyfikacja odległych źródeł skażeń

Modern air monitoring methods enable the detection of trace concentrations of radioactive elements. Conducting research and testing with radioactive substances leads to releases that can be detected from long distances. Such events occurred, for example, in 2017 during the uncontrolled release of the Ru-106 in the southern Urals and during the failed test of the Burevestnik nuclear-powered missile at the Nyonoksa test site in 2019. Individual types of nuclear reactors can also have their own unique release signature, which was shown, for example, during the Fukushima disaster. Determination of the scale of radioactive emissions and their composition based on measurements taken at a great distance from the source allows for early detection and monitoring of accidents or activities involving the use of nuclear technologies or radioactive sources carried out outside the arrangements resulting from international treaties.

- *Challenge 1: Methods of multipoint contamination detection data analysis to identify the place of emission, source and scale of radioactive element emissions.*
- *Challenge 2: Determination of the stoichiometry of anthropogenic and natural nuclides in order to determine the origin of sources of radioactive contamination.*
- *Challenge 3: Selective methods of detection and spectrometry of radionuclides using air, land and sea drones.*

Perspective 2.2-2: Identifying remote sources of contamination
Perspektywa 2.2-2: Wysokowydajna dozymetria awaryjna

In the case of exposure of the population to high doses of radiation, a rapid assessment of individual doses is necessary for a decision on possible treatment. Currently used methods of emergency dosimetry do not allow for such an assessment in cases of exposure to hundreds or thousands of people. The search for physical and chemical phenomena, finding materials and developing rapid measurement methods should significantly increase the possibilities of rapid triage of victims exposed to unknown doses of ionizing radiation. Such a rapid assessment of absorbed doses in irradiated people can also prevent panic outbreaks.

- *Challenge 1: Searching for a signature of phenomena that will enable the assessment of the absorbed dose based on rapid physical screening of items of clothing or everyday equipment.*
- *Challenge 2: Physical emergency dosimetry for neutron radiation exposure.*
- *Challenge 3: Concepts of algorithms and mathematical models for the analysis of environmental data and exposure times supporting automatic radiation triage.*

Perspective 2.2-3: Radio-protectors
Perspektywa 2.2-3: Radioprotektory

Radioprotectors are substances that limit exposure to radiation associated with the intake of radionuclides or reduce the adverse effects of exposure to high doses of ionizing radiation. One example of a well-known radioprotector is potassium iodide, used to protect the thyroid gland from the uptake of radioactive iodine. Radioprotectors are also used to reduce the number of free radicals that damage DNA, proteins and cell membranes; to support cell repair mechanisms; reduce apoptosis of healthy cells and alleviate inflammation after irradiation. In addition to amifostine, used in radiotherapy, gold nanoparticles, vitamin E, selenium and other substances have some radiation-protective properties.

- *Challenge 1: Understand the mechanisms and development of targeted radioprotectors that act mainly in healthy tissues rather than cancers.*
- *Challenge 2: Development of radio-protectors for mass applications, in particular for the military, rescuers in radiation events, astronauts, etc.*

Perspective 2.2-4: Psychology and sociology of security
Perspektywa 2.2-4: Psychologia i socjologia bezpieczeństwa

In the case of radiation accidents, it is easy for panic attacks, and false information or conspiracy theories spread by social media can easily undermine the effectiveness of protective measures. To prevent panic outbreaks, trust in authorities, healthcare services, scientists, and experts is crucial in emergency situations. Communication errors after the Chernobyl reactor disaster, involving the concealment of true data, result in long-term distrust of official sources of information. In the case of accidents with a large number of victims, stigmatization and exclusion of people from contaminated areas may also occur. After such events, symptoms of post-traumatic stress, anxiety, and depression may also appear even in people who are not physically irradiated, which can worsen health more than the radiation itself. The aim of the research will be to understand the mechanisms and develop principles and methods of communication under normal conditions of radiation sources use and after the occurrence of a radiation event, disaster, or outbreak of conflict involving weapons of mass destruction.

- *Challenge 1: To develop educational methods, adapted to the level of knowledge of the society, to build trust in institutions and experts.*
- *Challenge 2: Study of the perception of risk associated with radiation exposure for different social groups (age, education, occupation).*
- *Challenge 3: Developing methods to determine the readiness of state services and medical personnel to work in radiation hazard conditions.*

2.3. The „Energy“ area

Broadly understood radiological protection in nuclear power is aimed at ensuring the safety of employees, society and the environment under normal operating conditions and in an emergency situation at a nuclear power plant (NPP) and in the long-term management of radioactive waste. One of the elements of ensuring radiological safety for employees, the public and the environment is the preparation of a multi-level radiation protection system, covering biological, medical, organizational and social aspects. The construction of nuclear power plants is one of the greatest civilizational challenges of Poland nowadays. A project is underway to build the first Polish nuclear power plant in Lubiatowo-Kopalino with AP1000 nuclear reactors from *Westinghouse Electric Company*, and the construction of a number of small modular reactors BWRX-300 is being considered. Social acceptance of this project is inextricably linked to the safety of using this energy source. Scientific research conducted in order to increase radiological safety in connection with nuclear energy activities should combine basic sciences (materials science, biology, physics), social sciences (psychology, sociology) and modern technologies (AI, sensors, robotics).

Perspective 2.3-1: Radiation protection safety culture in the nuclear industry
Perspektywa 2.3-1: Kultura bezpieczeństwa ochrony radiologicznej w energetyce jądrowej

One of the causes of accidents, including radiation accidents, is human error and failure to respect the rules and follow work instructions. This is how the Chernobyl reactor disaster occurred, in which the reactor staff conducted reactor tests without proper preparation, ignoring operational rules and disabling safety systems. Research into the adherence to procedures by personnel and the causes of operational errors is an indispensable part of the mosaic that guarantees the safe operation of nuclear power plants. This also applies to those responsible for monitoring radiation safety at the NPP. This research aims to learn about the causes and then to develop methods to eliminate human error as the causes of incidents.

- *Challenge 1: Development of indicators and tools for an objective assessment of the principles of safety culture in nuclear energy.*
- *Challenge 2: To investigate the phenomenon of anaesthesia to risk in a long-term without incidents and to develop methods to eliminate it.*

Perspective 2.3-2: Intelligent Dosimetry in the Work Environment
Perspektywa 2.3-2: Inteligentna dozymetria w środowisku pracy

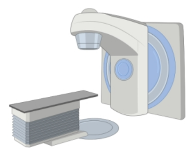
Nuclear power plant personnel are subject to routine monitoring of external and internal exposure to ionizing radiation, conducted by accredited dosimetric laboratories. Dose measurements from external sources are generally carried out using passive luminescent dosimeters (TL, OSL), personal electronic dosimeters (EPDs) and environmental monitors. A significant difficulty in dosimetric measurements is also the need to provide measurements for the dose-rates changing from the natural background to extremely high levels. The integration of results from different measurement systems is generally not straightforward and does not allow for retrospective analysis of the causes, locations and scale of exposure. An intelligent, integrated NPP dosimetry system would enable better dose reconstruction for individual personnel members, especially in the event of a radiation emergency. In the case of emergency situations, it is advisable to use mathematical models that enable real-time simulation of the effective dose based on human numerical phantoms.

- *Challenge 1: Rapid machine learning and artificial intelligence systems for analysis and synthesis of exposures from multiple measurement systems.*
- *Challenge 2: Intelligent sensors and dosimeters with data transmission for monitoring doses in the mixed radiation field.*
- *Challenge 3: Development of algorithms and mathematical models for real-time simulation of radiation transport in the environment, integrated with advanced numerical phantoms for effective dose assessment.*
- *Challenge 4: Identification of dynamic changes in exposure to ionizing radiation in the work environment at the NPP.*

Perspective 2.3-3: Rapid internal dosimetry for NPP staff and the general public
Perspektywa 2.3-3: Metody szybkiej oceny ekspozycji wewnętrznej dla personelu EJ i ogółu ludności

Nuclear power plants, even during normal operation, are a source of radionuclide emissions into the environment. The rate of this emission is continuously monitored and compared with the release limits set for the NPP. The development of methods for measuring the concentration of radioactive substances in the environment enables more accurate prediction of the value of their ingestion or inhalation. Current methods for measuring the presence of radioactive substances in the body, such as a whole-body counter or testing the concentration of radionuclides in physiological fluids, are time consuming and cannot be performed quickly for a large population.

- *Challenge 1: Algorithms for the evaluation of intake and committed effective dose based on the results of environmental measurements and individual and emergency dosimetry.*
- *Challenge 2: Adaptation of radiochemical methods used for the determination of selected radionuclides for on-line measurements during normal operation of a nuclear facility.*
- *Challenge 3: Biokinetic models of radionuclide transport in the human body to increase the precision of the assessment of the effective loading dose.*
- *Challenge 4: Epidemiological, economic and sociological studies of the impact of a nuclear facility on its environment.*



Perspective 2.3-4: Radiological protection around accelerators
Perspektywa 2.3-4: Ochrona radiologiczna wokół akceleratorów

Acceleration of charged particles in medical, industrial and scientific applications leads to the formation of a strong primary and secondary radiation field, often with a pulsed structure. Particular attention is paid to high-intensity beams of the FLASH type and innovative methods of accelerating particles using high-power lasers. Scattered radiation consists of gamma radiation, neutrons and charged particles with a wide energy spectrum. High-energy particles can activate structural elements, and the resulting radionuclides provide exposure even after the accelerator is switched off. Therefore, the issue of exposure to secondary radiation around accelerators is a growing concern for researchers.

- *Challenge 1. Development of methods for detection and dosimetry of radiation around accelerators operating in pulsed mode, including FLASH technology and laser-generated beams.*

- *Challenge 2. Development of methods for neutron radiation detection and spectrometry, enabling the recording of the neutron radiation spectrum in situ.*
- *Challenge 3: Activation processes and forecasting secondary radiation doses for employees and bystanders.*

2.4. The „Environment" area

The environment is a separate object of radiological protection. Individual components of the environment, and in a special case biotope and biocenosis, are protected regardless of existing relationships with humans (ICRP 103) [9]. The type and scope of data necessary to carry out an analysis of the current state of the environment and the possible impact of ionizing radiation includes data characterizing the subject of protection, processes responsible for the migration of radionuclides and effects that should be expected at the level of the abiotic environment, individual organisms, populations or even ecosystems. Basic research is usually limited to the study of the interaction of individual elements of the environment with selected radionuclides within the framework of the so-called radioecology. On the basis of the results obtained, mathematical models are usually created that allow for a certain generalization of the observed phenomena. The results obtained by such simulations are subject to very high uncertainty, usually resulting from the variability of the simulated situation, a simplified description of the subject of research or the phenomenon and the use of averaged (generalized) parameters and coefficients usually obtained as part of the study of another object. In addition to facilities strictly related to the nuclear industry, phenomena related to the occurrence of natural radionuclides are important in the context of the environment, in particular in a situation where exposure to radiation emitted by natural radionuclides is increased as a result of accidental or intentional human activity.

Perspective 2.4-1: Safe nuclear waste
Perspektywa 2.4-1: Bezpieczne odpady jądrowe

Long-term storage of spent fuel and radioactive waste is one of the most complex challenges in nuclear science and technology. The geological materials and structures used should last tens of thousands of years without corrosion, cracking and loss of tightness under conditions of exposure to radiation, high pressure, temperature and the presence of water. Spent fuel generates significant amounts of heat and can destroy protective barriers or alter water flows in rocks. In the presence of water, chemical reactions can take place: dissolution of fuel, release of gases. It is also important to realistically define the purposes of waste storage, as current regulations sometimes result from arbitrary political decisions, in the absence of a reliable scientific basis.

- *Challenge 1: Analysis of the properties of spent nuclear fuel in the context of possible interactions with the environment at the intended final/intermediate storage site and the materials used for the construction/construction of the repository.*
- *Challenge 2: Investigation of the impact of biochemical and microbiological processes on isotope migration in radioactive waste repositories.*
- *Challenge 3: Developing reliable, probabilistic models to simulate and predict changes in the functionality of radioactive waste repositories.*

Perspective 2.4-2: Radiative valorisation of the environment
Perspektywa 2.4-2: Waloryzacja radiacyjna środowiska

From the perspective of radiological protection, natural, and to some extent also artificial radionuclides present in the environment are treated in general as part of the natural background of radiation. However, exposure to environmental conditions, interactions with the biosphere and the impact of intentional or accidental human activity causes these radionuclides activity concentration to change in a way characteristic of a given environment (natural, human environment or work environment), creating typical signatures determined primarily by the way the land, or natural resources in general, are used. Having detailed data in this area allows for the interpretation of the results (or constitutes boundary conditions), basically for all types of environmental monitoring, regardless of the assumed monitoring goal.

- *Challenge 1: Creation of a database of radiative valorisation of the environment, taking into account the impact of land use/natural resources in relation to artificial and natural radionuclides (radon).*
- *Challenge 2: Research creating a scientific basis for the organization of environmental monitoring, in particular areas with significant area and variability.*
- *Challenge 3: Study of processes and methods towards strengthening the resilience of the environment to radiation hazards.*

Perspective 2.4-3: Migration of radioactive substances in the environment
Perspektywa 2.4-3: Migracja substancji promieniotwórczych w środowisku

The complexity of radionuclide transport processes in the environment remains a major source of uncertainty in predicting their impact on the biosphere. The emission of radionuclides into the environment occurs both as a result of short-term releases and as a result of their long-term migration from the site of primary deposition. With the diversity of ecosystems, the rapid spread of contamination in the atmosphere, migration in surface and groundwater, and bioaccumulation at different levels of ecosystem organization, the uncertainty of radiological risk assessment based on simulations is very high. The experience of the Chernobyl disaster has shown that radioactive fallout contamination was a complex function of atmospheric conditions, and in particular of local fallout.

- *Challenge 1: Improvement of models with high temporal and spatial resolution to simulate the proliferation of radionuclides in the atmosphere and aquatic environment to predict the extent and scale of contamination, taking into account a new type of data, including satellite data.*
- *Challenge 2: Development of new methods for modelling processes occurring in the environment based on experimental reductionism – databases of basic parameters for the migration of radionuclides.*
- *Challenge 3: Studies of long-term processes, on a scale of decades and centuries, changes in the behaviour of radionuclides in the environment.*

Perspective 2.4-4: Integrated risk assessment for ionising radiation and other environmental hazards
Perspektywa 2.4-4: Zintegrowana ocena ryzyka dla promieniowania jonizującego i innych zagrożeń środowiskowych

Integrated risk assessment for ionizing radiation in the context of the coexistence of toxic agents and other physical hazards is one of the most challenging topics in environmental toxicology and radiobiology. Chemical contaminants can be toxic, but the integration of risk assessment for different toxicity mechanisms, including ionizing radiation, is difficult both at the cellular level and for higher organisms. The results of tests carried out without considering possible synergies/antagonisms may lead to incorrect conclusions based on requirements usually expressed as a limit on the radioactive concentration in a given environmental component. It is important to distinguish between contamination and pollution, the lack of which may result in misinterpretation of the monitoring results. An additional problem to be addressed is the general tendency to take a different approach to anthropogenic and natural radionuclides in the environment, when exposures from natural sources are more easily accepted.

- *Challenge 1: Integration of radiological protection of humans, flora and fauna and ecosystems based on the „one health" assumption.*
- *Challenge 2: Interdisciplinary models of biological response combining the effects of ionizing radiation with chemical toxicology.*
- *Challenge 3: Research/analysis of synergy/antagonism of radioactive and chemical pollutants from the perspective of waste management, classification and reclamation of post-industrial sites.*

3. Summary

Many organizations around the world, including those operating in the field of radiation protection, are making efforts to prepare research programs that become a guideline for activities for the coming years and decades. These agendas cover the entire spectrum of topics, from basic research, through its applications and implementation, to the implementation of educational and training objectives. Research programs of European platforms in radiation protection such as EURADOS, MELODI, Radioecology ALLIANCE have become guidelines for formulating research topics at the European level, e.g. in the PIANOFORTE project, preparing calls for projects implemented under EURATOM funding.

In Poland, the most important entities funding science are the National Centre for Research and Development (NCBR), which supports scientific research, development work, commercialisation of research results and implementation of innovative solutions, and the National Science Centre (NCN), responsible for financing basic research without direct commercial applications. The NCBR manages strategic research and development programmes, usually carried out within a strictly defined time horizon. NCN projects are awarded as part of 26 panels that are relatively stable in time, thematically covering the entire area of scientific research in three main sections: Arts and Humanities; Physical and Technical Sciences and Life Sciences. Due to the interdisciplinary nature of research, encompassing the social sciences, natural sciences, and life sciences, the establishment of a panel dedicated to radiological protection within the NCN will create significant opportunities for the development of this scientific field, the strengthening of human resource potential, and the enhancement of scientific competencies. The Strategic Research Agenda presented in this document can be used as a guide for both scientists and panel members in selecting projects of key importance for the future of radiation protection.

The Strategic Research Agenda should create the foundations for innovative research, as well as become an inspiration for researchers to undertake new projects in the field of radiation protection in Poland. The scientific foundation of radiological protection is basic research in physics, chemistry, biology, and related fields. Without them, it would not be possible to effectively reduce exposure or develop modern methods of monitoring, diagnostics and prevention of the effects of radiation. This research should provide knowledge about the mechanisms of radiation action, help to understand how ionizing radiation affects the cellular and molecular level, enable understanding of the risk of cancer induction and provide the foundation for models and standards used in radiation protection.

Biography

1. W. Ruhm et al., *Visions for Radiation Dosimetry over the Next Two Decades - Strategic Research Agenda of the European Radiation Dosimetry* EURADOS report [2014-01], Braunschweig May 2014, ISBN 978-3-943701-06-7.
2. S. Bouffier, A. Auvinen, G. Baiocco, S. Candelas, E. Cardis, U., Galdieris, L. Lundholm, B. Maadas, S. Morel, S. Pazzaglia, R., Quinten's, M. Blattner, J.-M. Dolo, S. Haughtiest, *Strategic Research Agenda of the Multidisciplinary European Low Dose Initiative* (2022) https://melodi-online.eu/wp-content/uploads/2023/03/MELODI-SRA-2022-FINAL-post-consultation1.pdf
3. A. Beson, S. Andrianopoulos, P. Corail, M. Montero Prieto, D. Oughton, W. Raskob, C. Turcanu and on behalf of the NERIS platform R&D committee *The NERIS roadmap: research challenges in emergency preparedness, response and recovery Radioprotection* 2023, 58(3), 169–180.
4. Common *strategic research agenda for radiation protection in medicine* Insights Imaging (2017) 8:183–197.
5. The ALLIANCE Strategic Research Agenda (SRA) https://www.ceh.ac.uk/our-science/projects/radioecology-strategic-research-agenda
6. *Strategic Research Agenda for the SHARE platform for social sciences and humanities research relating to ionizing radiation* (2020), https://www.ssh-share.eu/wp-content/uploads/2020/10/Revision-SSH-SRA-After-consultationAugust2020-October-2020-FINAL.pdf
7. J. Garnier-Laplace, G. Jean-Christophe, F. Mahaveer, F. Rauser, A. Wójcik, E. Sainsbury, S. Bouffier, M. Davydova, T. Kalita, and Ch. Hoeschen. *The vital role of radiation protection research in Europe's future: a PIANOFORTE white paper*. Journal of Radiological Protection 45, no. 2 (2025): 023001.
8. *Rola ochrony radiologicznej w Polsce wobec programu PPEJ*. Prezentacja raportu Polskiego Konsorcjum Ochrony Radiologicznej (PKOR) na sympozjum IFJ PAN „Ochrona Radiologiczna w Polsce wobec wyzwań Polskiego Programu Energetyki Jądrowej (PPEJ)", Kraków, lipiec 2023. https://drive.google.com/file/d/15W9xRidMDavGnNbB4Bbe2q-9iJ7M5bHs/view?usp=sharing
9. ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4).