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Forty Years After the Chornobyl Accident: A Historical Overview of Post-Accident Response Measures

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Issues of nuclear safety gained particular prominence worldwide following the accident at the Chornobyl Nuclear Power Plant (ChNPP). The 1986 disaster raised profound doubts about the future development of nuclear energy. Addressing these concerns requires communicating to the broader public the views of specialists in nuclear energy — scientists, engineers, ecologists, and medical professionals — who possess essential knowledge about the technological, scientific, environmental, medical, and social challenges surrounding the nuclear industry, as well as possible ways to resolve them. A comprehensive understanding of nuclear energy must encompass not only its advantages — such as its contribution to global electricity production and its environmental benefits — but also its limitations, associated risks, and the challenges of managing radioactive waste and spent nuclear fuel. Particularly valuable in this context is information on the measures undertaken to mitigate the consequences of the Chornobyl accident. Forty years have passed since the ChNPP disaster — an interval sufficient for a realistic assessment of the measures implemented and for summarizing decades of post-accident activities. This article reviews key historical facts related to the accident and presents the results of monitoring efforts aimed at transforming the Chornobyl “Shelter” into an environmentally safe system. The article also pays particular attention to the assessment of radiation doses received by liquidators and the affected population, as well as to the associated social aspects. In addition, it discusses prospects for the future development of the Exclusion Zone and draws attention to existing challenges that require further solutions.

Introduction

Drawing on national experience in nuclear industry development, the Soviet Union adopted the uranium-graphite reactor as its basic model for high-power reactors, while most other countries focused on pressurized water reactors. A characteristic design feature of channel-type reactors is not only the absence of a pressure vessel, but also the lack of a dedicated containment structure. Consequently, the RBMK-1000 reactor — a heterogeneous, channel-type thermal neutron reactor using graphite as a moderator and water as a coolant — was selected as the principal design for the Chornobyl Nuclear Power Plant. Chornobyl became the third NPP equipped with RBMK-1000 units after the Leningrad and Kursk plants, commissioned in 1973 and 1976, respectively.

On 26 April 1986, during tests of one of the design safety systems of Unit 4 at the Chornobyl NPP, an accident occurred that was classified on the International Nuclear Event Scale (INES) as a level-7 severe accident — the highest category. The reactor core and all physical barriers intended to contain radioactive materials were destroyed, resulting in the release of a massive quantity of radioactive substances into the environment (Fig. 1).

Among the many urgent problems arising from the accident, the most critical was the construction of a protective enclosure over the destroyed reactor unit. The Shelter facility was completed and placed under maintenance on 30 November 1986 (Fig. 2).

Erected under extremely challenging radiological conditions, the Shelter Object was, from the outset, a structure requiring continuous monitoring and control, as well as corrective measures whenever safety parameters deviated from established limits. Because direct human involvement in installation works was impossible, extensive use of remotely operated equipment introduced

Fig. 1. 1986, the accident at the Chornobyl NPP

Fig. 2. The Shelter Object

numerous shortcomings. Significant concrete intrusions occurred inside the premises, complicating access and increasing the volume of radioactive waste, while load redistribution affected the supporting structures. In addition, uncertainties remained regarding the strength of certain supports, which incorporated pre-existing elements that had been impacted by the accident.

Under these conditions, the long-term safe operation of the Shelter Object was unattainable. Therefore, by 1991 the fundamental approaches for transforming the structure into a long-term, environmentally safe system were formulated (Decision of the Scientific and Technical Council of the Ministry of Atomic Energy and Industry of the USSR, 1991) [1]. In 1992, the Government of Ukraine announced an International Competition for projects and technical solutions for the transformation of the Shelter Object into an ecologically safe system (Description of the Shelter Object, 1992) [2]. In 1993, based on the decision of the competition jury, the terms of reference for developing a feasibility study were issued (Fig. 3).

Fig. 3. The author of the article near the Shelter Object

The accident at the Chornobyl NPP affected virtually all sectors — from nuclear technology safety to the socio-economic consequences of the disaster (Nosovskyi, Vasylchenko, Kliuchnikov, & Prister, 2006; Nosovskyi, 2017; International Chornobyl Project, 1992; Nosovskyi, Mitichkina, & Khomaziuk, 1996; Moroz & Deshevoi, 2002; Romanenko, Niagu, & Kalinauskas, 1991; Tukov, Kleieva, & Shafranskyi, 2000; Riabukhin, 2000; Avetisov, Buldakov, Gordieiev, & Ilyin, 1989) [3–11]. The purpose of this article is to analyse the measures implemented to manage the consequences of the accident over the past 40 years and to develop recommendations for future activities.

Research Methods

The study is based on an analysis of domestic and international scientific publications related to the mitigation of the Chornobyl accident consequences and the experience gained in addressing its technical and social dimensions. The research employed the historical method and a systems approach, which made it possible to reconstruct the actual sequence of measures implemented to address the consequences of the accident. Methods of observation and comparison were used to identify the reasons behind the adoption of ineffective measures, while induction and deduction helped reveal the underlying patterns of this process. Logical analysis and synthesis were applied in formulating the conclusions and positions presented in the article.

Results and Discussion

The accident at the Chornobyl NPP revealed numerous systemic problems that have required continuous attention from the scientific, engineering, and regulatory communities over the past four decades. These challenges include enhancing the operational safety of nuclear power plants, constructing a protective enclosure over the destroyed reactor unit, implementing large-scale decontamination measures, ensuring public protection, and addressing many other technical and social issues.

Given the breadth and complexity of these topics, it is not possible to examine all of them within a single publication. Therefore, this article focuses on the key aspects that, in the author's view, remain particularly relevant: the transformation of the Shelter Object into an environmentally safe system, the assessment of radiation doses received by liquidators and the affected population, the associated social issues, and the prospective rehabilitation and development of the Exclusion Zone.

Technical Aspects. Throughout the entire period of the Shelter Object existence, Ukrainian specialists conducted extensive scientific and practical work, including radiation surveys of the damaged unit to determine the locations of nuclear fuel residues, the development of safety, diagnostic and operational systems, the assessment of the amount of nuclear fuel, studies of the damaged structural elements of the unit, and the development of a strategy for transforming the Shelter Object into an environmentally safe system, among other activities (Krasnov, Nosovskyi, Rudko, & Shcherbin, 2016) [12].

In 1997, Ukrainian, American, and European experts elaborated a comprehensive action plan for the Shelter — known as the Shelter Implementation Plan (SIP) — which defined the measures and scope of work required to transform the facility into an environmentally safe system. The principal objectives of the SIP included the construction of a new protective enclosure capable of ensuring safety for at least 100 years and the development of a strategy for retrieving fuel-containing and other radioactive materials from inside the Shelter.

At the end of 2016, the New Safe Confinement (NSC) was moved into its design position at the Chornobyl NPP, becoming the main safety barrier for the Shelter and isolating it from the environment. Commissioning activities for the NSC were completed in 2019. The construction of the NSC significantly reduced the risk of radioactive contamination that could result from a collapse of unstable Shelter structures. It also enabled progress toward the long-term transformation of the Shelter into an environmentally safe system due to its durability and the capability it provides for dismantling unstable structures and retrieving nuclear materials (Fig. 4).

After the NSC was commissioned, planning began for dismantling the Shelter's structural elements whose service life expired in 2023, as well as for determining options for managing the nuclear materials remaining inside the facility.

One of the most technically challenging issues throughout the post-accident response has been bringing the nuclear fuel remaining inside the Shelter into a controlled and nuclearly safe state. This required identifying the main locations of fuel-containing material (FCM) accumulations, determining their physical-chemical properties, assessing nuclear and radiation safety, establishing monitoring systems, and preparing countermeasures for potential emergency scenarios. In the long term, FCM must be retrieved from the Shelter and transferred for safe management and disposal. Work in this direction began immediately after the accident and has continued for 40 years (Nosovskyi, 2017) [4]. Although many individual tasks have been successfully completed, the problem remains unresolved. A considerable portion of FCM inside the Shelter is not yet fully characterized or controlled, which necessitates the application of conservative safety approaches (Fig. 5).

The issue of nuclear safety regarding certain FCM accumulations also remains open. Due to insufficient knowledge, numerous uncertainties, divergent expert opinions, and debates persist. To fully close the nuclear safety issue, additional research is required. The results must support a rigorous justification of nuclear safety and provide confidence that a nuclear accident is impossible

Fig. 4. New Safe Confinement

Fig. 5. Fuel-containing materials accumulations

under current and future conditions. Continuous monitoring of major FCM accumulations is essential.

According to Ukrainian legislation, FCM must be brought into a controlled state and transferred to temporary controlled storage with subsequent disposal. There is positive international experience: at the Three Mile Island NPP (USA) nuclear material was successfully retrieved, and in Japan a retrieval strategy is being implemented at the Fukushima NPP.

Transition to decommissioning will only become possible once FCM is brought into a nuclearly safe state and placed into controlled storage or prepared for disposal. A range of complex scientific, technical, and organizational activities must be undertaken, including staged retrieval of nuclear materials within the NSC's operational lifetime, packaging into certified containers, and placing these containers at a designated site or in a specially constructed storage facility.

Before beginning retrieval works, technological solutions and detailed engineering designs must be developed. This includes the containerization of waste, the use of remotely operated robotic equipment, and the creation of infrastructure for FCM management, such as systems for sorting, monitoring, characterization, decontamination, construction of a temporary storage site, and development of a container fleet.

The FCM retrieved from the Shelter are long-lived radioactive waste and require disposal in repositories located in stable geological formations. Since such facilities do not yet exist in Ukraine and cannot be created in the near future, a decision must be made regarding temporary long-term storage, i. e., establishing an interim FCM storage facility. International and Ukrainian experience shows that open storage platforms equipped with physical protection systems and safe container-handling infrastructure can be used for long-term storage of spent fuel.

Fig. 6. A site in front of the NSC

This approach is also suitable for FCM retrieved from the Shelter Object.

It is proposed to use the existing concrete platform, used for NSC structures erection, located about 300 meters from the Shelter, as such a storage site. The platform has usable lighting, storm-water drainage with sedimentation basins, fencing, and a functional physical protection and access-control system (Fig. 6).

However, these plans were disrupted by Russian military aggression. The outbreak of full-scale war, the occupation of the Chornobyl NPP and the Exclusion Zone by Russian forces, and subsequent damage to the NSC caused by a combat drone strike have indefinitely postponed the implementation of all planned measures (Fig. 7).

Fig. 7. Impact site of a Russian combat drone on the NSC

Radiation Doses. The combination of proper work organization, the use of remote construction technologies, strict radiation monitoring and protection of personnel and equipment, as well as the involvement of qualified specialists, made it possible in 1986 to complete, in full and on schedule, all planned construction activities of the Shelter Object facility over the destroyed reactor unit without cases of personnel overexposure. Analysis of the radiation doses received by personnel during the construction of the Shelter Object allows the following conclusions:

more than 50 % of personnel received doses between 1 and 5 cSv;

0.6 % (155 persons) received doses exceeding 25 cSv;

the maximum recorded individual dose was 49.2 cSv.

All construction work was carried out by a workforce of 21,545 people, including all military personnel assigned to Shelter construction. These were exclusively construction-specialty reservists aged 35–45 called up for duty (Fig. 8).

The average individual external dose was 8.7 cSv, while the permissible limit at that time was 25 cSv. Thus, in 1986, all work was completed within the established deadlines, and the radiation doses of personnel remained within the safety norms and regulations in force at that time (Nosovskyi, 2006) [13].

Overexposure above 25 cSv was recorded in 155 individuals — highly qualified specialists who often had no replacements available, forcing them to work several consecutive shifts. Many supervisors, unwilling to send

Fig. 8. Military personnel removing radioactive materials

Fig. 9. Group of radiation safety specialists

subordinates into the most hazardous areas, personally conducted preliminary engineering and radiological inspections. In 1987, during restoration and preparation for the restart of Unit 3, the doses received by personnel were significantly lower than in 1986 (Fig. 9).

A total of approximately 600,000 people took part in the accident-mitigation activities, including 240,000 military personnel. For most individuals in this category, the main tasks involved decontamination. The average effective external dose for these workers was 17 cSv in 1986 and 13 cSv in 1987. Thus, the average radiation doses received by the majority of liquidators in 1986–1987 — those who were not part of the units involved in constructing the Shelter facility or in the restoration of Unit 3 of the Chornobyl NPP — turned out to be two or more times higher than the doses received by the specialists directly involved in those operations. This occurred despite the fact that they performed virtually all of the most radiation-hazardous and dose-intensive work in the period 1986–1987.

Nevertheless, without diminishing the importance of the work performed by organizations that were not involved in the construction of the Shelter facility, it can be stated that a number of hazardous operations were not dictated by urgent necessity. The majority of radiation-hazardous activities carried out within the 30-km zone were not directly related to the stabilization of Unit 4 and were neither urgent nor essential; these tasks could have been performed after normalization of the radiation situation, without subjecting personnel to unjustified radiation exposure.

Approximately 90% of the collective radiation dose received by all liquidators did not correspond to the nature, scope, or actual significance of the work they performed in eliminating the consequences of the Chornobyl NPP accident. The primary reasons for this were insufficient competence in planning radiation-hazardous activities and disregard for established radiation safety requirements.

Immediately after the accident, a significant number of managerial positions responsible for coordinating accident mitigation activities within the 30-km zone were occupied by individuals who lacked the necessary professional qualifications. Many of them demonstrated dedication and personal courage during the first days and weeks, attempting to mitigate the consequences of the accident while receiving high radiation doses. However, it soon became clear that their activities were ineffective. This was not their personal fault; nevertheless, at that stage it would have been appropriate — while acknowledging their contributions during the initial emergency period — to limit their responsibilities to reactor operation and to remove excess personnel from the accident zone. Accident mitigation activities should have been led by specialists competent in radiation emergency management. At the plant site, emergency response management was primarily entrusted to NPP operating personnel. Although most of them were highly qualified reactor operators, they lacked expertise in radiation accident mitigation. This lack of competence resulted in attempts to accomplish tasks by any means, often in violation of radiation safety rules. In many cases, such disregard for radiation safety requirements during the liquidation of the Chornobyl accident was perceived by managers as an act of heroism and was not dictated by any real necessity.

A serious negative factor in ensuring radiation safety was the presence of a large number of liquidators within the 30-km zone who were not engaged in any meaningful work. This was not their fault, but rather a consequence of management decisions during the initial phase, when large numbers of people were mobilized without being provided with adequate workloads, thereby exposing them to unjustified radiation doses.

Certificates identifying individuals as participants in the liquidation of the Chornobyl accident were issued to more than 600,000 people; however, their actual involvement varied greatly. After the completion of the main emergency works on the Shelter Object — when radiation conditions across most facilities within the zone had decreased to safe levels and public fear had largely subsided — there was no shortage of volunteers seeking employment in the zone. This was driven by significantly increased financial compensation and a range of substantial benefits, which formally and in practice served as compensation for the additional radiation risk that individuals accepted knowingly and voluntarily.

Consequently, the vast majority of the hundreds of thousands of so-called "honorary liquidators" who arrived in the Exclusion Zone after completion of the primary emergency works, under normalized radiation conditions, and who today demand increasing social benefits and compensation, in fact deserve no greater privileges than employees of any nuclear power plant or other enterprise of the nuclear industry. During the period 1988–1990, most liquidators present in the Exclusion Zone were exposed to risks only marginally higher than the everyday non-radiation risks faced by the general population. Moreover, the overwhelming majority of these individuals entered employment within the Exclusion Zone voluntarily, with the exception of military personnel.

Thus, the roots of the excessive socio-economic burden borne by society in compensating individuals involved in accident liquidation were laid by violations of established radiation safety requirements during work organization and execution, as well as by the incompetence of certain managers, which resulted in unjustifiably high collective radiation doses. In addition, a significant contributing factor in this case was the adoption of scientifically unsubstantiated legislation establishing extensive benefits and compensation for a very large number of population categories whose health risks during work in the Exclusion Zone were minimal.

Social Aspects. Forty years have passed since the accident at the Chornobyl NPP, and this period is sufficient to carry out a realistic assessment of the social and medical consequences of the accident. A considerable number of scientific organisations have studied the consequences of the Chornobyl disaster, and numerous international programmes have been implemented. The results of these studies have been presented in scientific publications, monographs, and reports at conferences and seminars. However, some public figures and politicians, using mass media, disregard these objective data and disseminate deliberately unfounded information based on pseudoscientific claims, including narratives about large numbers of victims, "radioactive monsters," and mutants. It has been asserted that millions of people could be regarded as victims of the Chornobyl accident. The main driver behind the emergence of such "Chornobyl myths" is the assumption of a harmful effect of any radiation dose, no matter how small.

Any large-scale disaster entails socioeconomic problems that require solutions. In global practice, such problems have been addressed through one-time compensation for the damage inflicted. In the case of the Chornobyl accident, a different decision was adopted – to monitor changes in health status and, on that basis, assign corresponding material compensation, moreover for life. And there it began…

Specialised expert councils were established to determine the causal link between diseases/disability and the Chornobyl accident. It was envisaged that these councils would consider individual cases of illness among accident recovery workers. However, the flow of applications proved so large that the councils could hardly cope with their functions. The most rapid increase in disability among liquidators began in 1991.

With such growth in disability, mortality would inevitably have to increase as well. Nevertheless, as an analysis of data from the National Register of Ukraine shows, mortality among liquidators is even lower than in the control group. This provides grounds to assert that there have been exaggerations in the granting of social benefits and erroneous decisions regarding the attribution of diseases and disability to the accident. In this context, one cannot but recall the recent high-profile case involving an exceptionally large number of disability status certifications among employees of the prosecutorial bodies and other law-enforcement agencies…

Links between diseases/disability and the accident were often established solely on the basis of the fact of participation in recovery work. Materials of the expert councils indicate that in many cases a person's presence in the Exclusion Zone was limited to only a few hours, at a sufficient distance from the epicentre of radiation exposure, and not in the first days and months after the accident; meanwhile, deterioration of health due to pre-existing illnesses or age-related changes was attributed to the Chornobyl accident.

The core difficulty lies in the desire of many liquidators to obtain and retain lifelong "affected person" status. This situation is inevitable as long as such a strong motivation exists – namely, solving social and economic security problems through illness. In no country in the world do illness and disability ensure a higher standard of living than work. In Ukraine, by contrast, it has become more advantageous to be ill and to have a disability than to be healthy. Resolving issues of social and economic security through illness is unjustified and inevitably generates questionable diagnoses.

A way out of this situation is possible. First and foremost, it is necessary to develop adequate legislative acts that would guarantee affected persons a one-time compensation for damages in line with global practice in the event of such accidents. Specialised expert evaluation should be conducted only for those affected who have radiation sickness, local radiation injuries, radiation cataract, neoplasms, and who received, over a short period (2–3 months), radiation doses exceeding the permissible level by five times or more. In all other cases, assessment of work capacity does not require specialised councils.

Endless visits to hospitals, not always appropriately selected sanatoria, and a focus on society's demands — combined with real socioeconomic problems of the state and exaggerations of the actual consequences — form a vicious circle. They lock people into the status of "lifelong victims of Chornobyl". It is precisely these factors, rather than radiation exposure, that underlie many mental disorders, deform an individual's personality, and isolate the person from family and society.

A major negative role in the early period after the accident in Chornobyl was played by medical personnel whose knowledge in radiation medicine was either entirely absent or largely based on media reports. Many medical workers interpreted symptoms of ordinary diseases as having a radiation nature. Throughout the entire post-Chornobyl period, political leaders and medical workers, using the mass media, convinced residents of territories affected by radioactive contamination that the accident had caused enormous damage to their health. As a result of such an information attack, more than half of Ukraine's population suffered psychological stress, which led to an increase in mental disorders, sleep disturbances, endocrine diseases, and many other conditions unrelated to irradiation (Moroz & Deshevoi, 2002) [7].

It was declared that millions of people could be considered victims of the accident and, according to current legislation, were entitled to material benefits and compensation. As a result, in Ukraine alone more than three million people were registered as affected by the Chornobyl accident, several tens of thousands of whom were recognised as persons with disabilities; to provide their social support, Ukraine is forced to spend a substantial part of its state budget (Bahniuk, 2002) [14].

The resettlement of the population from radioactively contaminated territories to new places of residence caused enormous damage — both to the state budget and to the health of the people themselves. The dose limits applied during resettlement were much lower than the real radiation doses from the natural background in many regions of the world (Ryabukhin, 2000; Avetisov, Buldakov, Gordeev & Ilyin, 1989) [10, 11]. These limits, which lacked scientific justification and were based exclusively on emotional schemes proposed by certain "humanists", only created discomfort in people's lives and pushed them toward rash actions. People abandoned what they had built, severed ties with the land and their homes, and became displaced persons. All this was done to reduce a risk comparable to the risk of disease from smoking one pack of cigarettes per day. Thus, reliance on recommendations lacking scientific justification led to mass resettlement and contributed to the development of radiophobia with psychosomatic consequences among the population.

A dose of 1 mSv is received by an individual during a single chest X-ray examination. During a full radiological examination of the gastrointestinal tract, the dose received ranges from 350 to 450 mSv. This dose is comparable to the lifetime dose level proposed by domestic scientists as early as 1986, exceeding which served as a criterion for resettlement from territories affected by radioactive contamination. However, when this lifetime level of 350 mSv was communicated to the public without any professional explanation, a wave of public outrage forced this scientifically substantiated radiation protection concept out of further consideration.

It is therefore evident that the population must first be provided with basic radiological knowledge before being engaged in public discussion.

People require simple and comprehensible comparative examples drawn from everyday life. In the case of the proposed lifetime level of 350 mSv, it should have been explained that the dose accumulated by an individual over 70 years is comparable to that received during a single radiographic examination. Even then, fundamentally different biological mechanisms are involved: one may take 350 aspirin tablets at once or spread them over 70 years — in the first case the outcome would be fatal, whereas in the second case no harm would occur.

Over its existence, the International Commission on Radiological Protection (ICRP) has continuously worked to summarise and formalise decision-making methods in radiation protection related to ionising radiation and its effects on the human body.

Radiation safety standards include a system of principles, criteria, and rules for ensuring radiation protection of the population. The term “standard” denotes a criterion that makes it possible to distinguish acceptable (normal) conditions from unacceptable ones. Thus, a standard is a threshold below which explicit and potential danger is absent and radiation safety is fully ensured.

Under the influence of the Chornobyl syndrome and radiophobia, certain members of the scientific community exerted pressure on the ICRP, resulting in a new publication (Keirim-Markus, 1990) [15], which used risk coefficients derived for doses exceeding 1 Sv and extrapolated them to the low-dose range. Therefore, risk estimates for low doses produced using these coefficients are maximal and lead to an overestimation of the real hazard. As a result, without any scientific justification, dose limits for personnel and the population were substantially reduced. Under these recommendations, the ICRP considers any arbitrarily small dose to be adverse to health, and counts all individual doses — down to zero — toward collective dose. Consequently, the consequences of the Chornobyl accident under such a methodology were assessed as millions of victims worldwide.

High-dose exposure may lead to loss of work capacity, radiation sickness, and even death; however, this does not apply to the low-dose region. After the accident in Chornobyl, society began discussing the hazard of low radiation doses, usually understood as doses up to 0.1 Sv. A statistically significant increase in cancer incidence was identified in most studies only at dose levels exceeding 1 Sv. No increase in leukaemia incidence was found among persons who received doses below 1 Sv after the atomic bombings of Hiroshima and Nagasaki. Studies among residents of the East-Ural trace area, as well as results of 40-year observations of populations living in radioactively contaminated territories due to the Chornobyl accident, did not reveal an increase in morbidity or mortality from malignant neoplasms that could be associated with the radiation factor. This conclusion also applies to overall mortality among the population and among participants in accident recovery work at the Chornobyl NPP.

Sooner or later, we all die; moreover, 38 % of women and 45 % of men will leave this world due to cancer. And if the linear no-threshold hypothesis (LNT model) is correct, and any irradiation increases cancer risk by 0.5 %, then an increase in mortality in this case is simply impossible to register. Today, it can be concluded with full confidence that prolonged exposure of an adult, practically healthy person to a dose up to 0.1 Sv, in general, does not cause any adverse effects that can be reliably detected using modern research methods. As for genetic effects of low doses, their existence has not been proven to date.

The ICRP states that, due to the lack of convincing evidence for a threshold at present, it is necessary to assume that any ionising radiation exposure may entail some risk of harmful effects; therefore, a linear no-threshold relationship between dose and probability of harm is recommended. Yet it is understood that applying the LNT model substantially overestimates real hazard. Despite the lack of substantiation and proof of the LNT hypothesis, it continues to play a central role in radiation protection standards, while critical statements by many scientists (The world’s nuclear news agency, 1999; HPS Newsletter, 1996) [16–17] remain unheard. The LNT model further amplifies the already high public fear of nuclear power, while the industry incurs extraordinary expenses to comply with radiation protection standards based on LNT.

When scientists speak of a no-threshold concept of ionising radiation effects, this is merely a working hypothesis used by specialists in radiobiology for humane considerations. It is a formal principle — unconfirmed by science — that transfers harmful effects from the domain of high doses to the domain of low doses. But this does not mean that, in nature, ionising radiation is truly harmful to living organisms, including humans, at any arbitrarily small dose. If any increase in background radiation truly increased negative effects, then human health would vary across the globe depending on the level of natural radioactivity: the higher the natural background, the shorter the life expectancy and the higher the incidence of hereditary disease. Yet this is not observed.

Thus, the no-threshold claim for low-dose effects finds confirmation neither in nature nor in experiment. It may be discussed as a hypothesis, but humanity has no factual grounds to conclude that any low dose is hazardous. Moreover, direct studies have shown that if living organisms are placed in an environment completely shielded from background radiation, plants and organisms cannot develop normally; many do not flower or bear fruit, and suppression of organisms occurs up to death (Keirim-Markus, 2000; Guskova, 1999; Keirim-Markus, 2002; Yarmonenko, 2000) [18–21]. This suggests that radioactivity is not as dangerous as assumed, and it is reasonable to consider that, in moderate amounts, it may be necessary.

Already in the late 1950s, researchers noted that hypotheses of exclusively harmful effects of ionising radiation had lost their significance, and that radiation, like light and thermal energy, has both physiological and pathological levels (Bak & Aleksander, 1963) [22]. Changes in the body as a result of exposure do not necessarily cause harm. Beneficial effects of low-dose radiation have been observed, for example, in stimulation of seed germination and growth of many plant species; increased physiological activity of bacteria and mammalian cells; increased lifespan of insects, mice, and rats under chronic exposure; reduced cancer mortality in humans as shown in recent epidemiological studies; and absence of any health deterioration, including increased cancer incidence, among populations living under elevated natural background radiation.

It is known that natural background radiation existed before humans appeared on Earth. Humans as a biological species formed under natural background radiation and have always been exposed to ionising radiation from natural sources. Even today there are many regions (in Brazil, India, Iran, China, and other countries) where natural background radiation is tens or hundreds of times higher than the global average. The best-known example is the province of Ramsar in Iran. Compared to the global average annual dose of 3.5 mSv, the annual dose in Ramsar is about 260 mSv. Yet in Ramsar there is no observed increase in mortality or in births of children with congenital malformations.

In India, over many generations, the population receives doses from natural background radiation that are more than 20 times higher than the doses received by populations in contaminated territories of Ukraine from which people were resettled after the Chornobyl accident. No harmful consequences of this exposure have been identified in India, nor in other areas with elevated natural background radiation. Moreover, residents of such areas exhibit longer life expectancy and lower cancer incidence than the general population (Jaworowski, 1997) [23]. These compelling observations suggest that a safe exposure level does in fact exist.

Life emerged and evolved under background radiation. Background radiation is necessary for all living things just as air, sunlight, and water are. All living organisms, including humans, have adapted to this background and developed biological defence mechanisms against harmful effects of ionising radiation. These mechanisms repair radiation-induced disturbances in cells and organs. At dose rates below 0.001 Sv/year, suppression of vital activity is observed; at dose rates above 1.0 Sv/year, substantial harmful biological effects appear.

Therefore, natural background radiation is an integral component of the ecological system and of the human environment. Consequently, the struggle that has been waged in recent years against natural background radiation — particularly against radon — contradicts common sense and is a typical manifestation of radiophobia. Apart from harm and enormous material and financial costs, this struggle will bring no benefit.

Crossing a street outside a pedestrian crossing, or driving from Kyiv to Lviv, entails greater risk than an NPP accident. It is important that society understands that the risks of diseases associated with an NPP accident are extremely small, and therefore there is no reason for special concern. However, the public and the media most often discuss not tsunamis, floods, earthquakes, and other natural disasters that claim thousands of lives, but rather the NPP accidents at Three Mile Island, Chornobyl, and Fukushima, where the number of victims was minimal. This indicates that nuclear energy specialists devote insufficient attention to public outreach aimed at education and demonstrating the safety of nuclear technologies. Therefore, special attention should be paid to specialists and organisations that shape public opinion through the media, as well as to doctors, teachers, lecturers, and other sources of public knowledge. By showing society how NPP safety is being enhanced, comparing this safety level with alternative electricity sources, and demonstrating improvements in reactor operation worldwide, it is possible to significantly strengthen the foundations for further development of nuclear power in Ukraine.

There is a rather large group of people worldwide who have received substantial doses over their lifetime.

Radiation risk coefficients used worldwide were derived from analyses of the consequences of exposure among survivors of Hiroshima and Nagasaki. When analysing mortality among those who survived the atomic bombings, a characteristic feature emerges: first, people died from very high doses incompatible with life, yet no general reduction in life expectancy is observed among those exposed to low doses. On the contrary, people who received moderate doses have, on average, a life expectancy about two years longer than the rest of the population (Kondo, 1993) [24]. The reason is that this group receives far greater social and medical attention. Why, then, is an apparent increase in morbidity reported in territories contaminated after the Chornobyl accident? Morbidity did not increase; rather, medical attention increased, the level of diagnostics rose sharply, and this in turn increased detection of previously undiagnosed diseases.

For a long time, the media published information that, in one way or another, distorted scientific facts (Burlakova et al., 1996) [25]. Claims were circulated about medical consequences of the Chornobyl accident suggesting increases in oncological, genetic, and other diseases, leading to "national degradation" and other social catastrophes. Such information, when it appears, is evidently of interest to certain parties. Indeed, by means of such claims, virtually any national problem can be attributed to the Chornobyl disaster.

As far as the medical consequences attributable to Chornobyl exposure are concerned, according to (International Conference on Chornobyl [ICC], 2008) [26], they include the following: acute radiation sickness in 134 persons who participated in emergency works during the first day after the accident; and 1,800 detected cases of thyroid cancer in children and adolescents. Fewer than 50 deaths have been directly attributed to accident-related radiation exposure, and in nearly all cases the affected individuals were liquidators who received high doses. Of these, 28 died within a few months after the accident; the rest died in subsequent years. A causal association has been confirmed for a sharp increase in thyroid cancer incidence among individuals exposed to significant doses in childhood and adolescence. Detected thyroid cancer cases in the adult population are not associated with exposure.

With regard to other types of cancer, no elevated levels of corresponding morbidity have been recorded in contaminated territories. The highest-risk group in this regard comprises liquidators with high doses. For the general population, any increase in cancer incidence does not exceed statistical uncertainty.

An analysis of mortality among Chornobyl accident-response participants showed that their mortality rate was lower than that of men across all age groups and of men of working age. Forty-two percent of liquidators died from injuries and poisoning, and 33 % from circulatory system diseases (Riabukhin, 2000) [10]. The mortality structure corresponds to that observed in men of working age. No correlation was found between the duration of participation in Chornobyl emergency work, radiation dose, and causes of death. Thus, analysis of medico-demographic health indicators in the affected population and among liquidators did not reveal deviations from spontaneous mortality levels that would indicate a negative impact of radiation. The main reason is relatively low absorbed doses.

The principal conclusion of the international scientific community (ICC, 2008) [26] is that Chornobyl exposure does not threaten public health at the population level; observed and expected effects are not priorities for practical health care, but belong to the domain of radiation epidemiology. By contrast, promotion of healthy lifestyles and adequate nutrition, prevention of cardiovascular diseases, and improvement of mental health are priorities.

The vast majority of residents of contaminated territories currently receive a lifetime dose from fallout below 70 mSv, i. e., below the average lifetime dose from global natural background radiation of 170 mSv, and many times lower than doses in many regions worldwide. Therefore, most exposure-related restrictions and benefits should be cancelled. The absence of increased incidence of solid cancers refutes misinformation about catastrophic medical consequences.

When comparing lifetime doses in several European countries with those in Chornobyl regions with low, medium, and high contamination levels, it is clearly seen that evacuation decisions were entirely mistaken. Had Ukrainian standards been applied in European countries, the entire population of Finland would have been evacuated, along with vast territories of Sweden and France.

The population of Ukraine should not fear radiation more than residents of Finland, Sweden, and France — countries where radiation background levels are also high, yet whose populations have among the highest life expectancies in the world.

At present, several million people have been included in the group of “radiation victims” of Chornobyl, confirming the erroneous nature of the post-accident radiation assessment. It is time to change this: to allow people to return to their customary places of residence and to establish realistic contamination thresholds that ensure genuine safety, thereby breaking the vicious circle of fear. Policy must be changed and exposure limits brought into line with modern knowledge.

The population still lacks information and remains influenced by misunderstanding and myths regarding radiation hazards and unresolved contradictions in assessing health effects of low doses. The time has come to abandon the LNT concept as the basis for assessing the Chornobyl situation, and to explain to people that the hypothesis used to define administrative measures does not entail practical danger, pointing to examples of other population groups and their health data. Now, with new experimental and theoretical evidence available, this issue should be reconsidered. A model for such reassessment can be found in the French Academy of Sciences and the French Academy of Medicine, which officially stated that low levels of exposure do not pose a health risk.

Therefore, the ongoing review of the classification of territories as affected is timely and should reduce the burden on the state budget, allowing resources to be redirected to more urgent priorities. Improving the social conditions of life in affected areas is the main direction in which tangible progress can be achieved in improving public health.

Vision for the Future of the Chornobyl NPP Region. If one abstracts from the global challenges associated with mitigating the consequences of the Chornobyl NPP accident, one of the key unresolved issues remains the future use of the Exclusion Zone. The current condition of the Chornobyl Exclusion Zone and the prospects related to transforming the Shelter Object into an environmentally safe system make it unlikely that the plant site can be brought to a "greenfield" state in the foreseeable future. Consequently, the Chornobyl NPP site will continue for a considerable period to be used to meet the needs of Ukraine's nuclear sector. Activities at the site will include decommissioning operations, retrieval of nuclear materials from the Shelter Object, their processing, and storage in specially constructed facilities (Fig. 10).

Based on the studies conducted during the first phase of the project to transform the Shelter Object into an environmentally safe system, a programmatic decision was adopted defining a preliminary strategy for the retrieval of fuel-containing materials and the management of radioactive waste (RW). This decision envisages that large-scale retrieval of nuclear materials from the Shelter Object will become feasible only after 30–50 years, provided that a dedicated repository for the final disposal of long-lived high-level radioactive waste is established. On this basis, one of the key design criteria for the New Safe Confinement (NSC) was set as an operational lifetime of no less than 100 years. At present, facilities for the management of liquid and solid radioactive waste and spent nuclear fuel have been constructed at the Chornobyl NPP site. These facilities are intended for the processing and subsequent storage of RW generated during the operation of the Chornobyl NPP and the liquidation of the consequences of the 1986 accident, as well as waste that will arise in the course of decommissioning activities and the transformation of the Shelter Object into an environmentally safe system. At present, issues related to the processing of radioactive waste from other nuclear power plants in Ukraine are also under consideration.

Technologies for RW management and methods of decommissioning will be in demand in the future both in Ukraine and internationally. Therefore, the use of the Chornobyl NPP site as a test ground for the development and implementation of new decommissioning technologies, as well as for refining methods for the mitigation of large-scale technological accidents, is a highly relevant task.

The Chornobyl NPP site and the territory of the Exclusion Zone host a network of research and technological laboratories that can be used for student education, advanced training of specialists, research and development

Fig. 10. Chornobyl NPP site

Fig. 11. Chornobyl Exclusion Zone

activities, testing, and the development of new technologies. The plant site itself can serve as a laboratory base for practical training in decommissioning, accident response, decontamination, radiation protection, NPP equipment maintenance, environmental studies, and the management of spent nuclear fuel and radioactive waste.

In addition, the Chornobyl NPP site should, of course, be considered for the deployment of new nuclear energy facilities. These may include a new multipurpose research reactor needed for a country developing its nuclear power and industrial sectors, as well as new nuclear installations based on small modular reactor (SMR) technologies.

Thirty years after the Chornobyl nuclear power plant accident — on 26 April 2016 — by Decree of the President of Ukraine No. 174, the Chornobyl Radiation and Ecological Biosphere Reserve was established. The reserve is territorially located within the Ivankiv and Poliske districts of Kyiv Region and covers approximately two-thirds of the Chornobyl Exclusion Zone (Fig. 11).

The current area of the Chornobyl Radiation and Ecological Biosphere Reserve is slightly more than 226,000 hectares. Within the reserve, nature conservation, scientific research, environmental education, and activities aimed at the rehabilitation of radioactively contaminated lands are carried out.

The 10-km zone of the Chornobyl NPP is not part of the biosphere reserve. It is designated for industrial purposes related to the decommissioning of the NPP power units, the transformation of the Shelter Object into an environmentally safe system, and the management of spent nuclear fuel and radioactive waste.

In the 1990s, scientific programmes were conducted in the Exclusion Zone aimed at returning parts of the territory to economic use. These programmes addressed, inter alia, the development of decontamination methods, the cultivation of clean agricultural products on radioactively contaminated land, and related issues. Based on monitoring results and practical experience gained during decontamination activities in the city of Slavutych (Nosovskyi, Oskolkov, Ivanov & Udovichenko, 2001) [27], the author of this article submitted an analytical memorandum in 1995 to the leadership of the Ministry of Chornobyl Affairs of Ukraine, substantiating the feasibility of returning certain areas of the Exclusion Zone to economic use.

And this was already in 1995. Therefore, today — taking into account the accumulation of new scientific knowledge — researchers understand that the boundaries of the Chornobyl Exclusion Zone can be refined and significantly reduced. However, even those parts of the territory that could already be returned to economic use are, in practice, of limited interest to the state. At least, this is how most officials respond, arguing that the lands of the Ukrainian–Belarusian Polissia region do not possess high agricultural fertility and that the creation of viable infrastructure on returned lands would require substantial capital investment, which Ukraine currently lacks. Moreover, the former infrastructure has been almost completely destroyed and is not subject to restoration.

Unfortunately, in recent years scientific and practical interest in rehabilitation measures for the affected territories has become minimal, giving way to empty declarations by officials regarding the economic use of the Chornobyl Exclusion Zone. And yet it is being "used." Immediately after the accident, the activities of local councils in the affected areas were terminated, and special state bodies were established to perform administrative management functions in the Exclusion Zone. The officials working in these bodies were not interested in the revival of the affected territories or in the return of the population. Instead, the Exclusion Zone was perceived as an industrial platform for generating profit. Large-scale logging, metal sales, the introduction of tourism, and other activities were carried out.

By contrast, in the areas affected by the Fukushima NPP accident, no special administrative structures were created. Territorial management remained with local authorities, who were directly interested in restoring the affected areas. As a result, in recent years the Exclusion Zone around Fukushima has been substantially reduced, most territories have been returned to economic use, and residents have been allowed to return to their homes — indeed, the majority of the population has already returned.

It is clear that mass voluntary return of residents to those parts of the Chornobyl Exclusion Zone that still remain radioactively contaminated is unlikely. Nevertheless, work in this direction is necessary, and the first step should be the restoration of local self-government. The communities of Ivankiv, Slavutych, and the Poliske region could form a local self-governing body located in the city of Chornobyl (Fig. 12).

In recent years — prior to the announcement of quarantine measures related to the global COVID-19 pandemic and the subsequent outbreak of war — a steady increase was observed in the number of people wishing to visit the territory excluded as a result of the Chornobyl catastrophe. In 2019 alone, the Exclusion Zone was visited by 124,000 people. The phenomenal success of the television series Chernobyl, produced by the American network HBO and released in May of the same year, significantly contributed to the growing interest in visiting the Zone. Chornobyl tourism has thus become a sector that generates immediate financial profit for its organisers (Fig. 13).

However, since its establishment, the Chornobyl Exclusion Zone has never been intended to accommodate unrestricted public access. Its primary purpose is to serve as a barrier preventing the spread of radionuclides beyond the boundaries of radioactively contaminated territory. The Zone does not attract visitors by architectural masterpieces; on the contrary, people are drawn to it in order to see an almost uninhabited area and the abandoned,

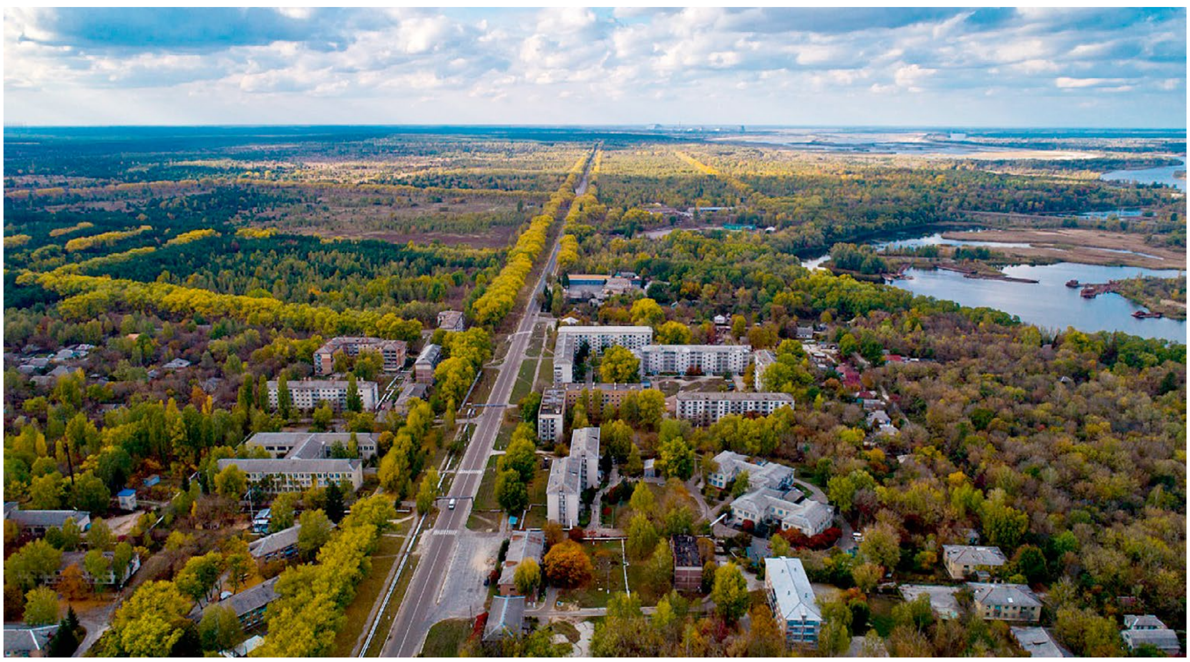

Fig. 12. The city of Chornobyl

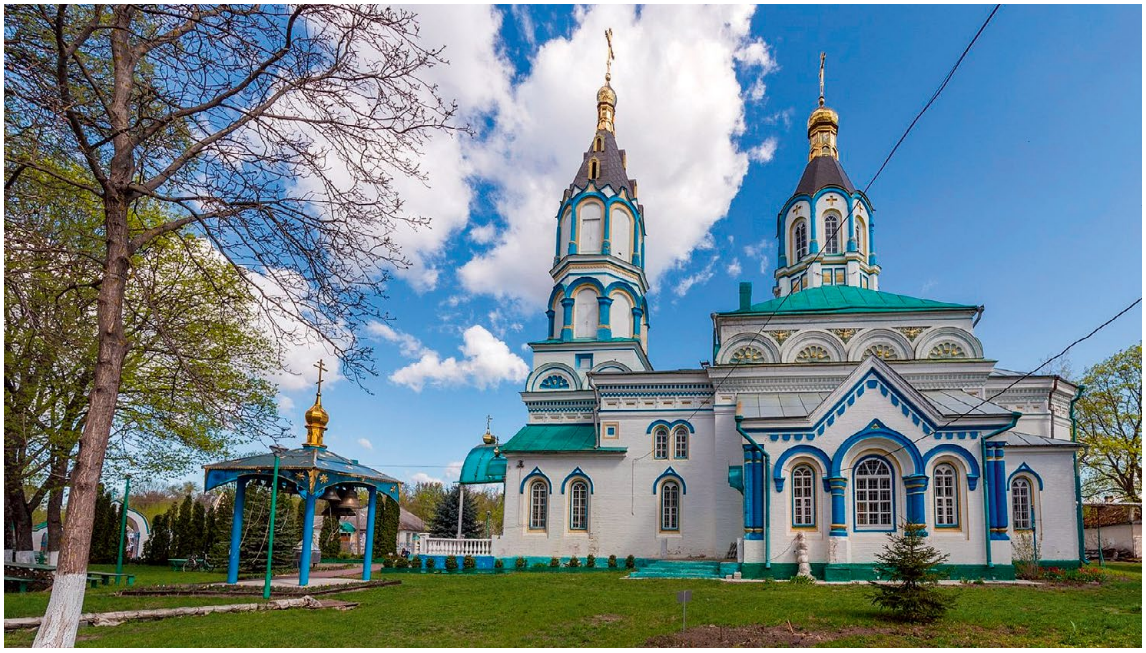

Fig. 13. Church in the city of Chornobyl

Fig. 14. The central square of the city of Pripyat

partially ruined city of Pripyat, which bears the imprint of the nuclear catastrophe.

Accordingly, the load on the infrastructure of the Exclusion Zone is increasing, while this infrastructure is unable to keep pace with the growing volume of tourist flows (Fig. 14). Activities aimed at increasing the number of visitors to the Exclusion Zone for tourism purposes are inconsistent with the fundamental principles of radiation protection.

Ukrainian legislation provides for mandatory measures aimed at preventing the removal of radionuclides from radioactively contaminated areas, ensuring environmental monitoring, maintaining territories in proper sanitary and fire-safe conditions, and applying methods for immobilising radionuclides in situ. All types of activities must be carried out with limitations on the total collective radiation dose, as well as with restrictions on the number of personnel involved. Therefore, under

Fig. 15. The school building in the city of Pripyat

conditions of radioactive contamination, only tourism with scientific or professional purposes can be considered justified. Thus, at the Fukushima Daiichi NPP in Japan, access to the controlled zone remains restricted to the general public to this day, with the exception of professional activities.

Travel to the 10-km zone of the Chornobyl NPP is always associated with certain risks. Transuranium elements may be present in soils, air, water, and on virtually any surface within the Exclusion Zone. However, radiation hazards are not the only concern; there are also general safety risks. Almost all buildings in the city of Pripyat are in a structurally unsafe condition (Fig. 15). Presence in the Exclusion Zone not only affects visitors and poses specific risks to their health, but also, conversely, visitors themselves may pose a threat to the Zone — especially during fire-hazard periods. In addition, the underdeveloped infrastructure of the Exclusion Zone remains a significant constraint for massive tourism activities.

Unlike mass tourism, professional and scientific–educational tourism in the Chornobyl Exclusion Zone may serve as an important channel for fostering evidence-based knowledge about the Chornobyl disaster, measures undertaken to mitigate its consequences, and practices related to spent nuclear fuel and radioactive waste management as essential conditions for the safe functioning of Ukraine's nuclear sector as a whole. However, such activities are acceptable only under strict compliance with physical and radiation safety requirements for visitors and with the development of appropriate infrastructure capable of meeting visitors' needs.

Conclusions and Recommendations

When analysing the measures undertaken to mitigate the consequences of the Chornobyl NPP accident, from today's perspective, forty years later, it appears reasonable to conclude that at least some of the environmental, social, and medical consequences that formed under the influence of the so-called "Chornobyl syndrome" were perceived by the population as more negative than the actual effects of ionising radiation that did in fact occur.

From a technical perspective, the most important future tasks related to mitigation of the Chornobyl accident consequences include the following:

restoration of the operational capabilities of the New Safe Confinement following damage caused by a Russian combat drone strike;

development of design documentation and dismantling of unstable Shelter structures whose service life has expired;

monitoring, research, and substantiation of nuclear safety for major accumulations of nuclear materials within the Shelter facility;

development of technologies, design documentation, and implementation of staged retrieval of nuclear materials from the Shelter facility;

preparation of a site for temporary containerised storage of high-level radioactive waste.

With regard to medical and other social consequences, analysis of medico-demographic health indicators of the population affected by the accident and of liquidators did not reveal any deviations in morbidity or mortality rates that would indicate a negative impact of the radiation exposure factor.

Therefore, the revision of the classification of territories as affected by the accident is timely and should lead to a reduction in state budget expenditures. Improving living conditions, everyday life, medical care, and overall living standards represents the primary avenue for improving public health in regions affected by the Chornobyl accident.

The 10-km industrial zone of the Chornobyl NPP should be used to meet the needs of nuclear sector development, including activities related to the decommissioning of the plant's power units, transformation of the Shelter Object into an environmentally safe system, and management of spent nuclear fuel and radioactive waste.

The NPP site may also serve as a laboratory base for hands-on training of specialists and may also be considered as a potential location for the deployment of new nuclear energy installations.

The first step toward restoration of the Exclusion Zone and potential return of population should be the establishment of a local self-government body in the city of Chornobyl.

Professional and scientific-educational tourism in the Chornobyl Exclusion Zone may be allowed only in a limited format, involving small visiting groups, and strictly subject to compliance with physical and radiation safety requirements and the development of infrastructure capable of supporting such activities.

In conclusion, the author expresses deep gratitude and appreciation to all builders, scientists, firefighters, operators, medical personnel, representatives of various professions, nationalities, and faiths — women and men, civilians and military personnel, workers and managers — who, without loud declarations of heroism or demands for social privileges, demonstrated high professionalism, discipline, and organisational capacity, and had fulfilled their civic and professional duty in mitigating the consequences of the catastrophe under extremely difficult radiation conditions.

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Історичний огляд заходів з ліквідації наслідків Чорнобильської катастрофи: до 40-ї річниці аварії

Проблеми безпеки ядерної енергетики набули особливої актуальності в суспільній свідомості в усьому світі після аварії на Чорнобильській АЕС. Саме тоді, в 1986 р., перспективи розвитку атомної енергетики були поставлені під сумнів. Щоб розвіяти його, потрібно довести до відома широкої громадськості думки фахівців, котрі працюють у сфері використання ядерної енергії, учених, інженерів, екологів, медичних фахівців, які володіють інформацією про наявні технологічні, наукові, екологічні, медичні й соціальні проблеми, які оточують ядерну енергетику, та про шляхи їх вирішення. Необхідно знати й розуміти не тільки позитивні аспекти використання ядерної енергії, її внесок у загальне виробництво електричної енергії, екологічні переваги, але й усі її недоліки, ступінь ризику, проблеми захоронення радіоактивних відходів та відпрацьованого ядерного палива. Особливу цінність у галузі таких знань становить інформація щодо заходів із подолання наслідків аварії на Чорнобильській АЕС. Минуло 40 років після аварії на Чорнобильській АЕС. Цей строк є достатнім для проведення реалістичної оцінки заходів щодо подолання наслідків аварії та підбиття підсумків цієї багаторічної діяльності. Наведено історичні факти, що стосуються аварії на Чорнобильській АЕС, результати моніторингу стану робіт з перетворення об’єкта «Укриття» на екологічно безпечну систему. Особисту увагу приділено проблемам оцінки доз опромінення, отриманих ліквідаторами та населенням, а також соціальним аспектам. Зроблено спробу обговорення перспектив відродження зони відчуження та привернути увагу громадськості до наявних проблем й необхідності їх вирішення.

Ключові слова: Чорнобильська АЕС, об’єкт «Укриття», новий безпечний конфайнмент, доза опромінення, зона відчуження.

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