Chornobyl Center for Nuclear Safety, Radioactive Waste and Radioecology

The report prepared in a framework of GEF UNEP Project "Project entitled "Conserving, Enhancing and Managing Carbon Stocks and Biodiversity in the Chornobyl Exclusion Zone" (Project ID: 4634; IMIS: GFL/5060-2711-4C40)

Revision and optimization of the systems of routine and scientific radiological monitoring of terrestrial and aquatic ecosystems in the ChEZ
Analysis by

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Summary

The report is devoted to the revision of the existing systems of routine and scientific radiological monitoring of terrestrial and aquatic ecosystems in the ChEZ (forests, former farmland and meadows, water objects, atmosphere, settlements, objects of infrastructure, places of localization of radioactive materials).

The SE “Ecocenter” conducts the routine monitoring of terrestrial and aquatic ecosystems in the ChEZ according to the Regulations. But these regulations should be optimized. Too much attention is paid to aquatic ecosystems, wherein terrestrial ecosystems are poor investigated.

Currently, there is no consensus about degree of ionizing radiation influence on the accumulation of carbon (biomass growth, decomposition of organic matter, etc.), as well as on the biodiversity changes in aquatic and terrestrial ecosystems of the ChEZ. This problem may be solved in the frame of the scientific ecological monitoring only. Scientific monitoring in the ChEZ is conducted by scientific organizations and institutes of different departmental subordination and should be coordinated, harmonized and optimized. For this purpose, a survey of all organizations engaged in the monitoring in the ChEZ, will be performed. By the results of this survey and taking into account statistical analysis of landscape, the criteria and recommendations for optimization and development of the scientific monitoring system in the ChEZ and data collection and storage system will be developed.

Harmonization of existing and additional monitoring polygons with needs of all groups of the project (location, landscape type, biodiversity, density of radioactive contamination etc.) must be performed.

For development, support and operation of the system of the complex monitoring in the ChEZ, working plan for 2016–2019 was created.

1. INTRODUCTION

1.1 System of the radioecological monitoring in the territory of Ukraine alienated after the Chernobyl accident

Exclusion Zone and Zone of Unconditional (Obligatory) Resettlement (hereinafter referred to as “Chernobyl Exclusion Zone”) is the part of Ukrainian territory, most contaminated with radioactive material in the result of the Chernobyl accident, separated from the adjacent territories, provided by the special legal regime, where any economic activity is prohibited. (Fig. 1) [1].

There are several subjects: Exclusion Zone and a part of the Zone of Unconditional (Obligatory) Resettlement legally assigned to the Exclusion Zone, where population was resettled. This part of the Zone of Unconditional (Obligatory) Resettlement is situated in Zhytomir oblast and Chernihiv, and it is managed by the State Agency of Ukraine on Exclusion Zone Management (SAEZ).
Radioecological monitoring is an integral part of the radiation safety system. It is provided by a number of legal acts of Ukraine, in particular, by the Resolution of the Cabinet of Ministers of Ukraine of 30.03.1998 № 391 “On Approval of the Regulation on the State Environment Monitoring System”. According to this Resolution, State Environment Monitoring System is a system of observation, collection, processing, transmission, storage and analysis of information about state of the environment, which is necessary for the prediction of changes in the environment and development of the scientific-based recommendations for administrative decisions aimed at the prevention of adverse changes in the environment and promoting compliance with environmental safety standards.

Monitoring system in Ukraine is aimed at the improvement of the research level and information pool about the ecological state of the environment, speed and quality of information service for users at all levels, justification of environmental protection measures and effectiveness of their implementation, development of international cooperation in the field of the environmental protection, rational use of natural resources and environmental safety.

The main tasks of subjects of the monitoring system are:
- long-term systematic observations of the state of the environment;
- assessment of the ecological state of the environment and forecasting its changes;
- analytical and information support of informed decision-making in the field of the environmental protection, rational use of natural resources and ecological safety;
- information service of the state and local government agencies, and informing population and international organizations about ecological situation.

In Ukraine radioecological monitoring of the environment (radionuclides content in the objects of the monitoring and dose characteristics) in the Chernobyl Exclusion Zone is performed by:

**Ministry of Ecology and Natural Resources** carries out the monitoring of atmospheric air and fallouts; sources of industrial emissions into the atmosphere; surface and marine waters; sources of waste water discharge; water bodies within protected areas (background quantity of radionuclides); soils for various purposes, including soils in protected areas; radiation situation (on the points of the fixed network); terrestrial and marine ecosystems (background quantity of radionuclides); landfills of industrial and household wastes.
State Agency of Ukraine on the Exclusion Zone Management (SAEZ) - is central executive authority that implements the state policy in the management of the Exclusion Zone and Zone of an Unconditional (Obligatory) Resettlement – carries out the radioecological monitoring in the territories subordinated by the Administration of the Exclusion Zone and Zone of an Unconditional (Obligatory) Resettlement, as well as another territories radioactively contaminated in the result of the Chernobyl accident. This monitoring implies control of the atmospheric air; surface water and groundwater; terrestrial and aquatic ecosystems (bioindicator assays); soils and landscapes; sources of emissions into the atmosphere (content and size of emissions); sources of wastewater discharge (content and size of discharges); radioactive waste disposal sites (content and radiation characteristics).

Ministry of Ecology and Natural Resources, as well as National Academy of Sciences (NAS) and National Academy of Agrarian Sciences (NAAS) are responsible for the methodological support of the individual components of the monitoring system. The following principles are used in the methodology of the radioecological monitoring:

- unified research methodology framework for the assessment of the state of the environment, including biota, and for the investigation of the anthropogenic influence on the environment;
- application of the standardized methods for the assessing and forecasting properties of the environment, computerization of the research activity and information communication;
- common rules for creating and maintaining distributed databases and data banks and knowledge system, mapping the environmental information, application of standard techniques using geographic information systems

The primary objectives of the radioecological monitoring are:

- estimation of power of ionizing radiation;
- measurement of radionuclides content and doses for living organisms;
- estimation of level of radioactive contamination of the surface air layer and underlying surfaces (soil, etc.), surface water and groundwater;
- monitoring of the terrestrial and aquatic ecosystems.

In order to obtain sufficient, reliable, relevant and useful information, and to spend financial, material and human resources rationally, following components of the monitoring system must be optimized:

- objects – it is possible to observe equivalent dose rate, specific activity of radionuclides in the air, water, soil, fauna and flora objects;
- network – spatial frequency of control or sampling points (distance between them);
- regularity – temporal frequency (time interval) of measurements of controlled parameters or sampling;
- sampling methods and analytical assays, statistical processing, transmission, storage and interpretation of obtained data.

In general, the monitoring is divided into three functional types, as well as, in particular, in the ChEZ:

- basic/routine (standard) monitoring is conducted by the State Enterprise “Ecocentr” and units of the ChNPP;
- emergency (operative) monitoring is conducted by the State Enterprise “Ecocentr”, units of the ChNPP and other temporary engaged organizations in the case of the extreme situations, such as fires, floods, works on radiation dangerous objects, etc.;
- scientific and specific (precision) monitoring is conducted by the scientific organizations and institutes of different departmental subordination.

Systems of routine and scientific radiological monitoring in the ChEZ, supported by various organizations (State Enterprise "Ecocenter", UIAR of NUBIP of Ukraine, IRL of Chornobyl Center, Institute of Hydrobiology and Institute of Geological Sciences, Ukrainian Hydrometeorological Institute et al.), has been carried out for a long time. Data, which have been obtained in the frame of these monitoring programs, enable us to estimate dynamic of external radiation dose, radionuclide concentration (¹⁰⁹Sr, ¹³⁷Cs, ²³⁸-²⁴⁰Pu и ²⁴¹Am) in the air, ground and surface water, soil and sediments, in some of reference organisms. Just a few studies on behavior of ¹⁴C, ³⁵Cl, ⁹⁰Tc, ¹²⁵I in the ecosystems of the ChEZ have been performed for 30 years.

Reduced research funding in Ukraine has resulted in degradation of the system of scientific radiological monitoring. Now, the monitoring program requires optimization of networks, schedule and objects. Monitoring of radiation doses and radiobiological effects in referent plants has carried out in recent years occasionally, in frames of international projects only. Many crucial regular series of radioecological observations/experimental data could have collected for 30 years but this information has been lost for science forever.

The project is planned to optimize and expand the systems of routine and scientific radioecological monitoring of the most common terrestrial and aquatic ecosystems within the ChEZ (objects, network,
timetable). The monitoring programs will be done to detect changes in long term trends in activity concentrations (including the long-lived radionuclides $^{14}$C ($T_{1/2} = 5730$ years), $^{36}$Cl ($T_{1/2} = 310,000$ years), $^{99m}$Tc ($T_{1/2} = 212,000$ years), $^{137}$I ($T_{1/2} = 17$ million years)) in different environmental monitoring objects. The monitoring will involve the estimation of absorbed dose for reference plants and animals at the population and ecosystem levels and the observation of radiobiological effects in reference organisms exposed to ionizing irradiation in the ChEZ. The collected environmental monitoring data will be employed as input data for development of methods and radiation protection criteria for non-human biota. The monitoring data will enable to understand current and future status of biodiversity in the ChEZ.

Organizations involved in the project will be participate in establishment of the Virtual Centre for Environmental Research and Conservation in the ChEZ. The Center will be used for training purpose and for international joint scientific investigation at the experimental monitoring sites.

2. Exclusion Zone

Total area of the ChEZ, which is administered by the State Agency of Ukraine on the Exclusion Zone Management (SAEZ), is 259 799.8 ha (259403.7 ha in Kiev oblast and 396.1 ha in Zhytomyr oblast). 204436.9 ha of the total area are considered to be Exclusion Zone, and 55363.0 ha –Zone of Unconditional (Obligatory) Resettlement. The length of the border perimeter of the ChEZ is 441. 237 km, where 154.5 km is a border with Republic of Belarus. Total length of the served roads is 536 km; total number of bridges is12; total length of the river network is 260 km, including 60 km of the Pripyat River.

The ChEZ is situated in the northern part of Kyiv Oblast and partly in Zhytomyr Oblast, between the rivers Pripyat and Uzh, primarily, but 18 % of the territory is situated between the rivers Pripyat and Dnieper in the east and Uzh and Teteriv in the south. According to the landscape zoning, this area is a part of the Kyiv district of the Ukrainian Polesia.

There are seven landscape types in the ChEZ territory, which are classified by the soil forming rocks, hydrological characteristics, soil type and type of vegetation. The major type of the soil found in this area is sod-podzolic sandy soil, and significantly smaller part of the territory is covered with gley, marshy and peaty soils.

The rest territory with area of 144 037 ha, where economic activity is inhibited, is considered to be Zone of Unconditional (Obligatory) Resettlement, situated in Zhytomyr, Kyiv and Chernihiv oblasts and managed by the local authorities. The Drevlyansky Nature Reserve was created in Zhytomyr oblast in the area of 33 000 ha in 2009.

Radioactive contamination of the territory ChEZ is represented by a fuel component, i.e. particles of fine-dispersed nuclear fuel (similar to the Windscale accident, UK, 1957), and a condensed component, formed as a result of condensation of volatile fission products on surface of different carriers (similar to the Kyshtym accident, Russia, 1957 and the Fukushima-1 accident, Japan, 2011). Nowadays, at the long-term phase of the Chernobyl accident, the levels of radionuclide contamination of the most contaminated areas in the exclusion zone are as follows: $^{137}$Cs - above 100 MBq/m$^2$; $^{90}$Sr - 50 MBq/m$^2$; $^{239-240}$Pu - 1 MBq/m$^2$. Such important radionuclides as $^1$H, $^{14}$C, $^{36}$Cl, $^{90}$Sr, $^{99}$Tc, $^{137}$I, $^{137}$Cs, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu and $^{241}$Am are still presented in the environment. External equivalent gamma dose rate at the air near ground surface reaches the level of 0.0 mSv h$^{-1}$. Today yearly absorbed dose in non-human biota can reach of tens Gy.

These features make the Chernobyl exclusion zone a unique polygon for radioecological and radiobiological research for training of specialists in practice.

2.1 Natural facilities

The Exclusion Zone covers an area of approximately 2,600 km$^2$, including terrestrial (forest ~ 60%, meadow and fallow land ~28%), aquatic ecosystems (lakes and rivers ~6%, swamps ~3%), and disturbed ecosystems (Pripyat town and other evacuated settlements, radioactive waste storages, cooling pond ~3%). Landscapes of the ChEZ are inhabited by 182 vascular plants species and 48 mosses, 66 mammalian, 249 avian, 62 fishes, 11 amphibian and 7 reptilian (Ivanov, 2010). Industrial facilities are located in the central part of the ChEZ in the relatively small area (about 20–25 thsd ha), and it has no significant anthropogenic effect. The results of numerous studies indicate the stimulating effect on the flora and fauna objects in the most part of the ChEZ territory due to the elimination of the anthropogenic pressure on the ecosystems. There are unique conditions for the restore of the natural geographical complex of forest, meadow and marsh biogecenoses of Polesia (that were destroyed by humans) in the large area (more than 470000 ha) of the ChEZ and Belarusian Polesie State Radioecological Reserve.

2.2 Industrial (technical) facilities
For today, there are the following industrial facilities in the ChEZ territory:

- Chornobyl NPP units 1, 2 and 3;
- Shelter Object (ShO) and New Safe Confinement “Arka”;
- Cooling pond of the ChNPP (CP ChNPP) with the complex of hydraulic structures;
- Liquid Radioactive Waste Treatment Plant;
- Industrial Complex for Solid Radioactive Waste Management;
- Wet Spent Nuclear Fuel Storage Facility (ISF-1);
- Dry Spent Nuclear Fuel Storage Facility (ISF-2);
- facilities designed for radioactive wastes management in the Exclusion Zone
  - Vector Complex (Stage I and II);
  - Sites for Temporary Localization of Radioactive Waste (STLRW);
- Facilities to be constructed:
  - Centralized Spent Fuel Storage Facility (Centralized ISF).

The radioecological monitoring at the industrial site of the ChNPP – that includes the estimation of the EDR, radionuclides concentration in the air, groundwater, waste water and water used in the reactor, etc. – is conducted by the units of the ChNPP and temporary engaged organizations.

### 2.2.1 Facilities at the ChNPP industrial site

At present, all four units of Chernobyl NPP are shut down: unit 4 – in 1986; unit 2 – in 1991, unit 1 – in 1996, and unit 3 – in 2000. ChNPP units 1, 2 and 3 currently are under decommissioning stage and the Shelter is being transformed into environmentally safe system.

The water elevation of the Cooling pond of ChNPP (CP ChNPP) is about 5-7 m over the Prypiat river due to the artificial dam with length of about 22 km. The CP ChNPP area is approximately 22 km², volume – 151.2 million m³, length – 11.5 km, and mean width is 2.2 km. Average and maximum depths are 6.6 m and about 18 m, respectively. In 2015, the work of the coastal pumping station was stopped and then the water level decreased by approximately 4 m due to infiltration through the dam in the Pripyat River during the years 2015-2016. According to the results of the studies about \(288\) \(137\)Cs, \(42.5\) TBq \(90\)Sr and \(0.74\) TBq \(239+240\)Pu are accumulated in the CP ChNPP. About 30-50% of the total content of radionuclides is concentrated at a depth less than 7 m. In the result of the water level decrease in the CP ChNPP for the next 3–5 year 13–18 km² of radioactive sediments will be left bare. It will cause changes in the radioecological situation at the adjacent to the CP ChNPP territories, as well as in the CP ChNPP due to changes in the groundwater level and radionuclides redistribution.

Significant amount of liquid and solid radioactive waste with different level of radionuclides activity was accumulated at the ChNPP during its exploitation and the liquidation of the consequences of the Chernobyl accident. In order to localize radioactive waste Liquid Radioactive Waste Treatment Plant and Industrial Complex for Solid Radioactive Waste Management were built within the territory of the SSE ChNPP site. Spent nuclear fuel is stored in the Wet Spent Nuclear Fuel Storage Facility (ISF-1). And now for further safe storage of the spent nuclear fuel it is planned to replace it to new Dry Spent Nuclear Fuel Storage Facility (ISF-2).

### 2.2.2 Facilities in the Exclusion Zone

The Vector Complex is located in the Exclusion Zone in the south-west direction in a distance of 11 km from Chernobyl. The Vector Complex is a complex of facilities on decontamination, transport and disposal of radioactive waste.

During the implementation of urgent measures on liquidation of the consequences of the Chernobyl accident the sites for disposal and localization of radioactive waste were created in 1986-1987. These are Sites for Disposal of Radioactive Waste (SDRW “Buriakivka”, SDRW “Pidlisnyi”, SDRW “The 3rd stage of the ChNPP” and Sites for Temporary Localization of Radioactive Waste (STLRW).

SDRW “Buriakivka” has been under operation since 1987. The disposal site consists of thirty near-surface trenches for radioactive waste disposal. Approximately 687000 m³ of Chernobyl origin radioactive waste have been stored in SDRW Buriakivka since the beginning of its operation. At present, possible reconstruction of the facility is considered due to exhaustion of SDRW design life.
SDRW “Pidlisnyi” and “The 3rd stage of the ChNPP” were constructed in the first years of ChNPP accident elimination. These facilities included the most hazardous high-level and long-lived radioactive waste. In future, this radioactive waste shall be retrieved from these facilities and redispersed in the geological repository.

Nine Sites for Temporary Localization of Radioactive Waste (STLRW) are located in the Exclusion Zone: “Stantsiia Yaniv” (1280 thsd m²), “Naftobaza” (420 thsd m²), “Pishchane Plato” (880 thsd m²), “Rudyi Lis”, “Stara Budbaza” (1220 thsd m²), “Nova Budbaza” (1250 thsd m²), “Prypiat” (700 thsd m²), “Kopachi” (1250 thsd m²), “Chystohalivka” (60 thsd m²), with a general area of about ten hectares. Trenches and pits with radioactive waste are located at RICP territories. Efforts are ongoing on survey of STLRW territories, service and keeping trenches and pits safe (Fig. 2, Fig. 3).

Fig. 2. Localization of the radioactive waste confinement points in the Exclusion Zone (gray shading)
2.2.3 Facilities to be constructed:

Centralized Storage Facility for Nuclear Fuel of National WWER NPPs and deep geological depository are planned to build in the ChEZ [3]. These facilities should be located in the ChEZ because the main part of radioactive waste arte Chernobyl origin. For this reason it is irrational to create depository for radioactive waste in the inhabited areas of Ukraine.

2.3 Settlements

There are 76 settlements in the ChEZ territory, including such towns as Pripyat, Chernobyl and Chernobyl-2, where population was evacuated in 1986, as well as part of 86 settlements, which were considered to be Zone of Unconditional (Obligatory) Resettlement in 1991. Small amount (less than 100 people) of illegal residents – so-called “self-settlers” or “samosely” – lives in these settlements. Most people, who stay in the ChEZ (about 5000) are employees of companies, such as industrial site of the ChNPP and other industrial facilities, concentrated in the Chernobyl town with a total area of less than 2% of the ChEZ territory. The State Enterprise “Ecocenter” conducts the routine radioecological monitoring in these settlements of the ChEZ, including the estimation of level of radioactive contamination of the staple foods. The radioecological monitoring in settlements of the Zone of Unconditional (Obligatory) Resettlement is carried out within the framework of the National Dosimetry Certification (it includes estimation of the terrestrial density of radionuclides contamination, content of $^{90}\text{Sr}$ and $^{137}\text{Cs}$ in milk and potatoes, as well as the measurement of the $^{137}\text{Cs}$ specific activity in the organisms of residents using the WBC). Last time it was conducted in 2013.

2.4 Periodic monitoring

2.4.1 Goals and objectives

The main goal of the radiological monitoring of the territory and objects of the ChEZ is inventory of the radioecological state of these objects. It is necessary for the management decision-making such as energy resources supply, development of the alternative energy sources, etc., as well as expert reports. In these reports – which should be prepared according to the Law [4] – the necessity to change boundaries of the radioactively contaminated zones is analyzed, as well as necessity to change status of the territory.
according to the intended use, for example, creation of the special industrial zones for radioactive waste management, or creation of the radiecological natural reserve, etc. Such studies are conducted periodically – for example, every 10–15 years for forests –or in the case, when it is necessary, for example, in the case of the planned change of the status (intended use) of the territory and facilities. Periodic radiological investigation of the territory of settlements, forests, meadows, water bodies, etc., is carried out using the relevant regulatory and procedural documents [10]. When it is necessary to analyze the possibility and justify the resumption of the economic activity in the territory without any restrictions, special investigation of this territory is conducted according to the protocol of field research “Radioecological inspection and assessment of lands, which should be excluded from the Exclusion Zone and Zone of Unconditional (Obligatory) Resettlement in order to be used in the economic activity without any restrictions” [5], when this territory is inside the ChEZ. And when the territory is outside the ChEZ, such special investigation is performed according to the “Method of the complex radiation investigation of the territories radioactively contaminated in the result of the Chernobyl accident, excluding the territory of the Exclusion Zone [9].

2.4.2 Regulatory and procedural documents

According to the Law of Ukraine [7] the management of the Exclusion Zone and Zone of Unconditional (Obligatory) Resettlement after the complete evacuation of residents is conducted by the State Agency of Ukraine on Exclusion Zone Management (SAEZ) that is central executive authority, which implements the state policy in the management of these areas. The Agency is responsible for the prompt, complete and objective informing population about the ecological situation in these areas (Paragraph 8).

Until complete resettlement of residents of settlements in the Zone of Unconditional (Obligatory) Resettlement has been performed, the management of this zone and Zone of a Guaranteed Voluntary Resettlement is conducted by the local Region Councils (Paragraph 9).

The Cabinet of Ministers of Ukraine informs the population about the radiation situation (Paragraph 10). Monitoring of the state of the environment and medical and biological monitoring are obligatory measures for the Exclusion Zone and Zone of Unconditional (Obligatory) Resettlement (Paragraph 13).

The assessment of radiation situation, radioecological monitoring and coordination of the relevant research activity in the radioactively contaminated areas is conducted by the SAEZ.

According to the concept of implementation of the state policy in the field of the development of the areas radioactively contaminated in the result of the Chernobyl accident [9], scientific studies in the ChEZ should be conducted, in particular:

- radiation monitoring of the environment, long-term forecasting and assessment of risk of the radionuclides migration in natural and technogenic ecosystems of the Exclusion Zone;
- radioecology, radiobiology and radiogenetic researches of fauna and flora objects, development of methodological approaches of radiation protection of biota
- investigation of the transformations of the urbanized ecosystems under the influence of the emergency factors (on the example of Pripyat town), which also provides with information about the consequences of radioactive contamination of urbanized landscapes in the result of accidents or acts of terrorism
- study and evaluation of the barrier properties of the basic elements of the natural and technogenic barrier system of the Exclusion Zone with the purpose of optimization of these properties;
- researches, which are necessary in order to justify the intended functional zoning of the Exclusion Zone, in particular, the use of the territory for building of the radiation-nuclear facilities, research and economic activities.

Radioecological monitoring in the ChEZ territory is carried out according to the Regulations approved for a definite period [9].

2.4.3 Forests

Periodic inspection of the forest fund of the Exclusion Zone and the Zone of Unconditional (Obligatory) Resettlement is carried out according to the Instructions for Ordering Forest Fund of Ukraine (Part I: Field work. 2006) [5], keeping all the points related to forests of Ukrainian plains. Forest inventory should be carried out every 10 years. The following information is noted for each forest area (forest block): forestry, quarter number, number of the forest block and category of forest. The following forest inventory parameters are determined by the results of the forest blocks study: species composition of stand; layering; average age; mean height of stand; site index; diameter at breast height (DBH); basal area; general and merchantable volume of wood stock by species; site class; availability and species composition of understorey and undergrowth.
In the radioactively contaminated zones additional studies and measures are carried out, as well as soil sampling, which is performed each three months according to the Standard requirements (SOU 74.14-37-425.2006 [10]). They are:

- measurement of the equivalent dose rate around the perimeter of the forest blocks (the distance is 100 meters)
- dividing the blocks into homogeneous contaminated sampling sites, if the EDR values differ by more than 30 % (with GPS reference rotation angles)
- collection of litter and soil samples (depth – 20 cm, diameter – 40 mm) at 5 points on the sampling sites— where the EDR values don’t differ by more than 30 % (with GPS reference rotation angles) – for preparation of the combined sample, which is used for measurement of the $^{90}$Sr, $^{137}$Cs content and $^{241}$Am/$^{238-240}$Pu ratio;
- collection of the wood samples, using special tool (age borer), at a height of 1.3 m, in at least 10 trees (with similar diameter and height) of major and minor species (more than 10 % of total content of the sample) at each sampling site. The weight of the combined sample should be not less than 20 g (dry weight) in order to conduct measurement of the specific activity of $^{90}$Sr and $^{137}$Cs in the wood samples with values of about 50 Bq·kg$^{-1}$ (at the minimal detected value of 1 Bq).

### 2.4.4 Former agricultural lands and fields

The last investigation of the Exclusion Zone territory was carried out in 1997. It was done as part of the work on mapping contamination of the territory with radionuclides of fuel components and detailed study of the radiation situation of the territory, where the rehabilitation is planned [11]. The kind and size of the study are determined by the problems, which should be solved in order to change the status of the territory. If the territory is planned to be excluded from the Exclusion Zone and Zone of Unconditional (Obligatory) Resettlement, inspection works are carried out according to the protocol [12].

In order to clarify the terrestrial contamination density of $^{90}$Sr, $^{137}$Cs and $^{241}$Am/$^{238-240}$Pu the studies are carried out according to the current standards [13, 14]:

- the EDR measurement is conducted on a regular network in the tacks way within the test site of 5-100 ha with a GPS reference rotation angle (the distance between routing lines is 100 m). The size of the test site is determined on the base of gradient of the radioactive contamination density, and technical and financial capabilities.
- soil sampling is performed with help of the borer (depth is 20 cm, diameter is 40 mm) at 5 points in the sampling sites, where the EDR values don’t differ by more than 30 % (with reference GPS). Specific activities of $^{90}$Sr, $^{137}$Cs и $^{241}$Am/$^{238-240}$Pu are measured in the combined soil sample.

### 2.4.5 Water bodies

In order to reveal trends and regularities of changes in parameters of quality of surface water and groundwater, to develop the complex of measures aimed at the improvement of the monitoring and assessment of the ecological state of water bodies in the ChEZ the periodic studies of different parameters are performed. The comparison of the obtained results with retrospective data makes it possible to reveal trends and factors of anthropogenic pressure on aquatic ecosystems in the ChEZ, where radioactive contamination is still the main anthropogenic factor. The works on the assessment of the state of the hydraulic structures of special purposes such as seepage barriers, bridges, dams, melioration canals, etc., are also performed. Often such works are carried out as part of scientific research programs, involving specialized contractors.

### 2.4.6 Settlements

The inspection of all the settlements, from which the population was evacuated after the accident, has not been carried out (Zone 1). The detailed investigation of the radiation situation was performed by the Center of Dosimetric Control in the Exclusion Zone in the 90’s only for those settlements, where “samosely” (illegal residents) live. The inspection of settlements of the Zone of Unconditional (Obligatory) Resettlement (Zone 2) was conducted at the beginning of the 90’s. Usually, the radiation inspection of settlements is conducted, when the status of the territory is planned to be changed. And in this case it is performed in order to clarify the terrestrial contamination density of $^{90}$Sr, $^{137}$Cs and $^{241}$Am/$^{238-240}$Pu according to the Standard [3].
In the case of homogeneous contamination of the settlement (if the EDR values don’t differ by more than 30 %) 5 sampling sites are selected. As usual, one sampling site is located in the center of the settlement, and another 4 sites are on the periphery.

In the case of inhomogeneous contamination the territory is divided into homogeneously contaminated sampling sites (not more than 5), where the EDR values don’t differ by more than 30 %.

- soil sampling is performed with help of the borer (depth is 20 cm, diameter is 40 mm) at 5 points in the sampling sites, where the EDR values don’t differ by more than 30 % (with reference GPS). Specific activities of $^{89}$Sr, $^{137}$Cs, $^{241}$Am/$^{238,239}$Pu are measured in the combined soil sample.

2.4.7 Infrastructure facilities

During the radiation inspection in the ChEZ high attention was not paid at the infrastructure facilities, and they were not investigated as individual objects of the study. Just the gamma dose rate survey should be used for the estimation of the radiation level of these facilities.

2.4.8 Radioactive waste confinements sites

Works on the exploitation of the valid SDRW “Buryakivka”, Vector Complex; monitoring and survey of the SDRW “Pridlisny”, “the 3rd stage of the ChNPP” and 9 STLRW are conducted by the State Specialized Enterprise “Central Enterprise for the Management of Radioactive Waste” (SSE “CEMRW”) under the licenses issued by the State Nuclear Regulatory Committee of Ukraine. In the ChEZ 5 STLRW were fully investigated, and 2 STLRW were partly investigated by 2014. There are 467 repositories, which contain radioactive wastes, among 680 repositories found in the investigated territory. The last investigation was performed in 2009–2012. The data, obtained as a result of the STLRW investigations, are recorded to the State Radioactive Waste Register and State Cadastre of Radioactive Waste Storage Facilities. Radioactive wastes of unstudied repositories are also registered, but information about them is not full and based on the approximate estimates, obtained during the inventory in 1989.

The investigation is carried out by the protocol of detection and estimation of STLRW, developed by the Scientific and Technical Center for the Integrated Management of Radioactive Waste.

The investigation of the STLRW supposes radiation, geophysical, hydrogeological and analytical studies and following special works:
- assessment of the ionizing radiation fields in the investigated area, and collecting samples from the surface soil layer;
- gamma analysis of rocks with help of gamma microprobe;
- well logging, including gamma logging with coring for wells at a penetration depth of 3–5 m
- groundwater sampling by well points under hills and by samplers from wells.

During these studies geological and hydrological characteristics of the repository, contamination level of groundwater other inventory parameters are estimated. The results are recorded to the State Register and State Cadastre of Radioactive waste.

The obtained information is used for the design and implementation of engineering measures, prevention of radionuclides migration into the environment and reburial of radioactive waste from SDRW. The state of the preserved trenches in the SDRW “Buryakivka” is checked every day; modules of the SDRW “Pridlisny” are inspected once a week.

2.5 Routine monitoring

2.5.1 Goals and objectives

The main goal of the routine monitoring in the ChEZ is to protect population and environment from the radiation influence. One of the main objectives is to minimize radionuclide emission outside the ChEZ. It is achieved through the control and forecasting the emissions on the basis of the results of the radiological monitoring of the environment.

2.5.2 Forests

Radiological routine monitoring of forest ecosystems in the Chernobyl Exclusion Zone is conducted by the State Enterprise “Ecocenter” according to the approved Regulations. There are 13 landscaped polygons, where terrestrial contamination density and vertical migration of the main dose-forming radionuclides ($^{137}$Cs, $^{90}$Sr, $^{239+240}$Pu, $^{241}$Am) in the litter and soil are estimated. Sampling of biomass
components such as trees, undergrowth, forest floor plants are also performed on these polygons. Every year 390 soil samples and 110 vegetation samples are collected; and 1200 measurements of radionuclides specific activity are performed.

It should be noted that the number of the observation sites for radioecological investigation is not constant. In 2001 there were 10 sites of regular observations for forest inventory and radioecological monitoring of forest plantations.

2.5.3 Former agricultural lands and fields

The monitoring is carried out at the available landscape polygons of the State Enterprise “Ecocenter” (on the part of the 13 polygons). The control of the contamination density and vertical migration of radionuclides in the soil and plants is conducted at these polygons every year according to the Regulations. The content of $^{90}$Sr, $^{137}$Cs and $^{238-240}$Pu is measured in the collected samples.

This approach doesn’t reflect all the landscape diversity in the Exclusion Zone, and selected samples are not representative. These are the main disadvantages of the valid monitoring. In this regard, network and Regulations of this kind of radioecological monitoring should be optimized. The network should be selected taking into account the diversity and prevalence of landscapes in the Exclusion Zone, and it should contain those elements that are critical in terms of radionuclides migration.

2.5.4 Water bodies

Currently, the routine monitoring of water bodies in the Exclusion Zone is conducted at the definite areas and wells, using approved network and methods for the inspection of geological posts and drainage systems according to the Regulations.

The current network of observations of radiation situation of surface water was formed at the beginning of the 1990’s. The Regulations – which are used for the radiation monitoring of surface water – have been developed on the basis of works of Ukrainian Hydrometeorological Institute and recommendations of Minchernobyl of Ukraine (1992). By this time only measurement of the content of $^{137}$Cs, $^{90}$Sr and some other radionuclides (occasionally) were carried out in the collected water samples.

Since 1993 water consumption from rivers and filtration drains of the ChNPP industrial site is calculated. Currently, there are 40 experimental sites for the routine monitoring of surface waters in the ChEZ. About 650 water samples are collected on these sites, and 1650 measurements of the specific activity of $^{137}$Cs, $^{90}$Sr, $^{238,239,240}$Pu, $^{241}$Am (dissolved in water and suspended in sediments, Bq/l) are carried out during a year.
In 1987-1988 the first stage of a special network of wells was put into operation by the project developed in the Institute “Ukrdniprovdhost”. Since that moment systematic monitoring of groundwater has been started in the ChEZ. The valid monitoring system includes groundwater of the Quaternary, Eocene and Lower Cretaceous aquifer systems, which are related to the zone of free water exchange. The network of wells and sampling frequency are determined by the Regulations of the monitoring of groundwater. The valid radiation monitoring system of groundwater provides control of radioactive contamination of aquifers – which are hydraulically connected with surface waters within and outside the contaminated territory – and groundwater used for water supply. Currently, the network for the monitoring of groundwater is the most developed in the ChEZ and consists of 138 observation sites (Fig. 2). A large number of observation sites are caused by the complicated space structure of the researched objects. Every year, in average, 690 samples of groundwater are collected; and 1100 measurements of the content of $^{137}$Cs, $^{90}$Sr, $^{238,239,240}$Pu, $^{241}$Am are carried out within the radiation routine monitoring.
2.5.5 Settlements

Since 1995 annual inspection of settlements, where people live, is conducted by the SE “Ecocenter”. This monitoring includes radiometric studies of lands and sampling of garden soil, drinking water and staple foods. The content of the gamma-emitting radionuclides and $^{90}$Sr are estimated in the collected samples. Besides it, the terrestrial contamination density is measured at 12 stationary sites in Chernobyl and Pripyat.

2.5.6 Infrastructure facilities

The monitoring of the infrastructure objects in the Exclusion Zone is provided by the Comprehensive Radiation Monitoring and Early Warning System (CRMEWS) [18].

The CRMEWS comprises a network of automated inspection stations that perform monitoring the environment continuously and transmit the data via radio (350 000 measurements a year). The total area of network coverage of the CRMEWS is more than 2000 square kilometers and includes 40 stations of the Automated System for Monitoring the Radiation Situation (Fig. 6). There are:
- 12 stations in the ChNPP industrial site;
- 5 stations in 5-km zone;
- 12 stations in 10-km zone;
- 10 stations in 30-km zone;
- 1 station in Slavutich.
2.5.7 Radioactive waste confinements sites

According to the approved Regulations, radiation contamination of the soil, radioactive fallouts and radionuclides content in the atmospheric air are monitored by the SE “Ecocentr” in the areas, where SDRW are situated. In places PVLRO location made monthly monitoring of 90Sr and 137Cs in ground water wells in accordance with the network. All sites of the radioactive waste confinement are observed by the Comprehensive Radiation Monitoring and Early Warning System. As usual, this network includes: aspiration units, 3 plates for atmospheric fallout, 10 checkpoints for soil sampling, 5–10 wells for groundwater sampling; 3 reservoirs for wastewater sampling. Every month the 90Sr и 137Cs content in groundwater is measured in the areas, where STLRW are situated.

2.5.8 Atmosphere

The monitoring of the ambient air in the Exclusion Zone is carried out by two parameters: radionuclides concentration in the surface air and radionuclides content in the atmospheric fallouts. Currently, the air control system of the CRMEWS includes 14 permanent aspiration units (AU) and 25 plates.

Sampling of the radioactive aerosol in the Near Zone of the ChNPP (area within the 5-km radius around the ChNPP) is conducted by the 5 aspiration units in the conditions of the continuous pumping air through filters. Filters are used for 5–7 days, and their replacement is performed 5 times a month. About 900 samples are collected and 1900 measurements are conducted during a year. In the Far Zone of the ChNPP (area within the 5-30 km radius around the ChNPP) the radiation monitoring of the ambient air is conducted by 9 stations of the CRMEWS situated around the ChNPP (primarily, in the south).

Monitoring of the atmospheric radioactive fallout in the Near Zone is provided by 8 plates oriented on the main directions of air masses movement. In the Far Zone 8 plates of the CRMEWS are involved the air monitoring. Petryanivska material is used for aerosol fixation on the plate. Air filters of the plates are used for 12–15 days, and then they are replaced. During a year about 600 samples are collected and 1000 measurements are conducted.
2.6 Radiation effects in populations and communities of wild organisms

The anthropocentric approach in protection and preservation of the environment has been used in radioecology till the end of the 20th century. The main paradigm of this approach is “If human are protected, other biological objects are protected too” \([19]\). It was based on the fact that human are the most radiosensitive mammalian species. According to this approach priority should be given to evaluating potential risk for humans and to protecting human health \([20]\). The measures in the acute phase of the Chernobyl accident were primarily aimed at the protection of population of settlements and staff of the ChNPP from the exposure. For this reason and difficulties in ecological standards calculation due to the variability of ecosystems, proper attention was not paid to the investigation of the radiation effects on populations and communities of wild organisms. And any routing monitoring of the effects of ionizing radiation on plants and animals was not provided in the ChEZ, excluding the forestry monitoring (see section 2.5.2) \([21]\).

2.7 Emergency (urgent) monitoring

SE “Ecocentr” conducts the emergency monitoring in the case of fire or flood, and during works that can cause radionuclide distribution in the environment and additional exposure of the staff (or population). Emergency monitoring implies control of radionuclides concentration in the air and fallouts, using both stationary and mobile equipment (aspirators, impactors, plates).

Any forest fire in the Chernobyl Exclusion Zone is accompanied by the increase of radionuclides content in the air due to the radioactive aerosol resuspension. Large and intense fire (area of over 200 ha and height of trees charring of over 1.5 m) are particularly dangerous. During such fires the structure of biomass and mortmass of forest ecosystems and radionuclide content in them change for a short time period. Therefore, forest areas affected by the fire should be quickly inspected in order to estimate damages (biological and economic) of forest plantations and to evaluate biogeochemical mobility of radionuclides. In the case of emergency situation (forest fire, accidents at radiation hazardous objects) the ASRS filters are replaced more often, and mobile strategic groups of SE “Ecocenter” with mobile aspiration units are engaged.

In addition to the routine monitoring emergency monitoring is conducted by the contractors during building works in the areas of a higher probability of radioactive aerosol formation (stabilization of the Shelter Object structures and the NSC building). This monitoring provides control of air pollution in the work areas and fugitive emissions.

The aim of the emergency monitoring of water is to provide organizations of the Unified Emergency Prevention and Response State System with information on the status of water bodies. Emergency monitoring of water bodies is carried out through systematic and additional investigations in the zones of influence of possible accidents and natural disasters, and in the case of emergency environmental situation. The contamination of water bodies with definite pollutants is estimated through the comparing of pollutants content with Maximum Permissible Concentration (MPC) and PL-2006. Emergency monitoring is implemented by the special programs that improve routine investigations significantly. In this mode, the sampling is conducted 2-4 times oftener than in normal mode.

2.8 Scientific (precision) monitoring

Scientific monitoring in the ChEZ is conducted by Specialized Enterprise «Ecocenter», NUBiP of Ukraine, International Radiological Laboratory of Chernobyl Center (IRL CC ЧЦ), State Specialized Enterprise «Central Radioactive Waste Management Enterprise » (SSE “CRWME”), Institute of Hydrobiology (IHB), Institute for Nuclear Research (INR), Institute of Geological Sciences (IGN), Institute of Environmental Geochemistry (IEG), Ukrainian Hydrometeorological Institute (UHMI) and other organizations and institutes of different departmental subordination.

2.8.1 Goals and objectives

The primary objectives of scientific monitoring in the ChEZ are to obtain experimental data on radionuclides behavior in the environment and natural conditions; ionizing radiation influence on biota, etc., which are used for the long-term forecast of changes in radiation situation.

2.8.2 Forests
Scientific Radiological monitoring of forest ecosystems in the Chernobyl Exclusion Zone is carried out at the single temporary experimental sites that are created mainly in pine stands. It should be noted, that experimental sites for forest inventory and experimental sites for radioecological monitoring are different sites. Radiological experimental sites are designed by the same algorithm used for forest inventory sites. They differ mainly by the kind of samples collected in these sites and the reasons, why the sampling is conducted. Sampling in the radioecological experimental sites is performed according to the goals of the scientific research. As usual, samples of soil and phytomass are collected for the investigation of specific activity and migration abilities of radionuclides. Number of samples can vary from a few dozen to one thousand.

Over the last decade, new experimental sites for radioecological monitoring were formed by the and (2 sites) and Ukrainian Institute of Agricultural Radiology only (2 sites).

One of the main purposes of the scientific radioecological monitoring in the ChEZ is to study radiobiological effects of radioactive contamination on the forest-forming species of plants. The most studied specie in terms of radiation influence is *Pinus sylvestris* L. There are stationary experimental sites of UIAR within the Western Erase of radioactive fallout in the STLRW “Red Forest” and near the settlement Chystohalivka. These sites are used for the investigation of morphological changes and aberrations of trees (*Pinus sylvestris* L., *Betula Pendula*, etc.) caused by the ionizing radiation influence.

### 2.8.3 Former agricultural lands and fields

The network of the monitoring sites of UIAR covers the main types of soils of former agricultural lands and fields. The study of the $^{90}$Sr, $^{137}$Cs and $^{238-240}$Pu migration in soil profiles and elements of land and vegetation cover are carried out in these sites since 1987.

### 2.8.4 Water bodies

The scientific monitoring of water bodies is primarily conducted as a part of scientific research works and international research projects.

The primary objectives of scientific monitoring in the ChEZ are:

- investigation of radionuclides distribution between biotic and abiotic ecosystems and their components in the water reservoirs;
- estimation of radiation influence on water bodies;
- study of filtration and sorption properties of water dams and soil horizons;
- investigation of radionuclides migration processes caused by groundwater;
- evaluation of long-term trends in contamination of groundwater in the zone of influence of SDRW and STLRW.

The main object of the investigation are cooling pound of the ChNPP, Glyboke about Azbuchin Lakes, territories of SDRW and STLRW.

The main organizations engaged in scientific monitoring investigations are SE “Ecocenter”, Ukrainian Hydrometeorological Institute, Institute of Hydrology of National Academy of Sciences of Ukraine, Institute for Nuclear Research of National Academy of Sciences of Ukraine and UIAR.

### 2.8.5 Settlements

Currently, it is not conducted.

### 2.8.6 Infrastructure facilities

Not conducted.

### 2.8.7 Radioactive waste confinements sites

In the territory of the STLRW “Red Forest” regular scientific studies are conducted by (Trench №22) by the UIAR, Institute of Geological Sciences, IRSN and NMBU. These works are devoted to the investigation of radionuclides migration in in the unsaturated zone and groundwater (at different depths and distance from T22), biogeochemical fluxes of radionuclides, contamination level of vegetation and radiobiological effects of radiation contamination on *Pinus sylvestris* L. (every year).

The aims of the scientific monitoring of radioactive waste confinement sites are:
- study of the hydrological and hydrochemical regimes of SDRW and STLRW;
- research of transfer parameters and migration forms of radionuclides via groundwater;
- study of autorehabilitation processes in groundwater;
- research of dynamic of radionuclide forms presented in STLRW.

Scientific radiological monitoring of the radioactive waste confinement sites is conducted on the basis of scientific research institutions of NAS of Ukraine.

2.8.8 Atmosphere

The chief purposes of the scientific monitoring of radioactive aerosol in the ChEZ are to:
- study parameters of radioactive aerosol (particulate composition of radionuclide bearers) during the fires in the ChEZ;
- found out the correlation between parameters of radioactive aerosol and contamination level of forest plantations and fire scale;
- evaluate the parameters of aerosol resuspension over the reclaimed areas of the ChNPP cooling pound and during different technological operations in the ChEZ.

2.9 Radiation effects in populations and communities of wild organisms

The biota of the ChEZ suffered from the acute radiation exposure in the result of the Chernobyl accident. And it has led to the formation of radio-biological effects at different levels of biological organization, from cell to ecosystem [23].

Despite numerous obtained data, it is noted that the scale and methods of the scientific monitoring in the ChEZ still does not meet the danger level of Chernobyl problems [24]. Single monitoring investigations of radiobiological effects caused by the ionizing radiation influence on plants, soil and water organisms, birds and small mammals were carried out by Ukrainian scientists [4, 25, 26, 27, 28]. At the same time, part of these studies was not accompanied by the correct estimation of dose values for studied objects. For the reason of financial difficulties scientific monitoring of radiobiological effects in the ChEZ is conducted as a part of international scientific research works and is not systemic. There is no uniform strategy and plan for scientific monitoring of radiobiological effects of ionizing radiation influence on populations and communities of wild organisms in the ChEZ.

Herewith, specificity of incorporated radionuclides influence, heterogeneity of radionuclides distribution in the tissues and organs of living organisms, internal and external dosimetry of organisms, mechanisms of adaptation, the impact of radiobiological effects revealed in the definite individuals on the whole population, the effects of the combined influence of ionizing radiation and other abiotic and biotic factors, epigenetic effects, stochastic effects and many other problems and issues are still not clarified and need further investigation.

3. Zone of Unconditional (Obligatory) Resettlement

3.1 Periodic monitoring

3.1.1 Forests

Only periodic forest inventory [7] and scientific monitoring of forest plantations are performed within the Zone of Unconditional (Obligatory) Resettlement (ZUR). Routine monitoring is not carried out.

Scientific monitoring is conducted by Polissya branch Ukrainian Order "Badge of Honor" Vysotskyi Research Institute of Forestry and Agro-Forestry Melioration (URIFEM), UIAR, Zhytomyr State Technological University and Kyiv Research Station of URIFEM. There are about 10 valid experimental sites, where studies are performed.

The last complex radiological inspection of forest plantations of the ZUR was performed in 1993 [29].

3.1.2 Former agricultural lands and fields

The last estimation of the terrestrial contamination density of radionuclides in the ZUR was conducted in 90’s, when the zoning of settlements was performed. The estimation should be repeated, if the status of this territory changes. It is performed according to the protocol [30].
In order to clarify the terrestrial contamination density of \(^{90}\)Sr, \(^{137}\)Cs and \(^{241}\)Am/\(^{238-240}\)Pu the studies are carried out according to the current standards [3,4]:

- the EDR measurement is conducted on a regular network in the tacks way within the test site of 5-100 ha with a GPS reference rotation angle (the distance between routing lines is 100 m). The size of the test site is determined on the base of gradient of the radioactive contamination density, and technical and financial capabilities.

- soil sampling is performed with help of the borer (depth is 20 cm, diameter is 40 mm) at 5 points in the sampling sites, where the EDR values don’t differ by more than 30% (with reference GPS). Specific activities of \(^{90}\)Sr, \(^{137}\)Cs and \(^{241}\)Am/\(^{238-240}\)Pu are measured in the combined soil sample.

Sampling with the purpose of evaluating of terrestrial contamination density is performed according to the standards [5, 10].

3.1.3 Water bodies

Not conducted.

3.1.4 Settlements

The last study of radiation situation in settlements of the ZUR was conducted in 90’s, when the zoning of settlements was performed. The estimation should be repeated, if the status of this territory changes. It is performed with the purpose of estimation of terrestrial contamination density of \(^{90}\)Sr, \(^{137}\)Cs and \(^{238-240}\)Pu according to the standard [3].

In the case of homogeneous contamination of the settlement (if the EDR values don’t differ by more than 30 %) 5 sampling sites are selected. As usual, one sampling site is located in the center of the settlement, and another 4 sites are on the periphery.

In the case of inhomogeneous contamination the territory is divided into homogeneously contaminated sampling sites (not more than 5), where the EDR values don’t differ by more than 30%.

Soil sampling is performed with help of the borer (depth is 20 cm, diameter is 40 mm) at 5 points in the sampling sites, where the EDR values don’t differ by more than 30 % (with reference GPS). Specific activities of \(^{90}\)Sr, \(^{137}\)Cs and \(^{241}\)Am/\(^{238-240}\)Pu are measured in the combined soil sample.

3.1.5 Infrastructure facilities

Not conducted.

3.1.6 Radioactive waste confinements sites

There are radioactive waste confinement sites that have been created after the settlements deactivation and as a result of work of cleaning points. Inventory and monitoring of these places are not conducted now.

3.2 Routine monitoring

3.2.1 Forest

Not conducted.

3.2.2 Former agricultural lands and fields

Not conducted.

3.2.3 Water bodies

Not conducted.

3.2.4 Settlements

The monitoring of radioactive contamination of foods is conducted in those settlements, where the residents are present (every three years since 2012). It is estimated by the \(^{90}\)Sr and \(^{137}\)Cs content in cow milk and potato according to the Dosimetry Certification. There are 86 settlements in the ZUR: one settlement in
Rivne oblast, 63 settlements in Zhytomyr oblast, 20 settlements in Kyiv oblast and 3 settlements in Chernihiv oblast.

3.2.5 Infrastructure facilities
Not conducted.

3.2.6 Radioactive waste confinements sites
Not conducted.

3.2.7 Atmosphere
Not conducted.

3.2.8 Radiation effects in populations and communities of wild organisms
Not conducted.

3.3 Emergency (urgent) monitoring
Not conducted.

3.4 Scientific (precision) monitoring

3.4.1 Forest
Not conducted.

3.4.2 Former agricultural lands and fields
The main aim of the studies in the ZUR is to found out the parameters of $^{137}$Cs migration in the chain “soil-plant”. This kind of studies is conducted by the UIAR, Zhytomyr National Agroecological University, and Institute of agriculture of Polesya of NAAS of Ukraine.

3.4.3 Water bodies
Not conducted.

3.4.4 Settlements
Certain studies of radiological characteristics of agroecosystems and contamination of local agricultural products are conducted by the Zhytomyr National Agroecological University and UIAR.

3.4.5 Infrastructure facilities
Not conducted.

3.4.6 Radioactive waste confinements sites
Not conducted.

3.4.7 Atmosphere
Not conducted.

3.4.8 Radiation effects in populations and communities of wild organisms
Not conducted.
4. System of data collection and storage

Within the framework of the international project of IAEA “Radiological Support for the Rehabilitation of the Areas Affected by the Chernobyl Nuclear Power Plant Accident” the Electronic Register of Highly Contaminated Areas was developed with the purpose of the information support of decision-making on potential economic use of these areas. The Electronic Register reflects the standardized requirements for inventory of highly contaminated areas. The objects of the inventory are decommissioned former agricultural lands (arable lands, cultivated hayfields and pastures), natural meadows, forests and ponds. The list of parameters is determined for each object of study. To international experts’ opinion, background information of Databases is enough for forecasting radiation situation (expected radiation doses for employees and contamination level of products) in different ways of economic use of territories; and for decision-making by authorities. The Electronic Register was developed in order to help organizations involved in the process of economic rehabilitation of lands. It is used as a tool of radiological expertise for support of decisions on economic rehabilitation of lands.

The Electronic Register is integrated in the DBMS Access with a graphical connection of cartographic information and data presentation with help of GIS technology. The database has a function to input, store, organize and look for information (including cartographic data) about the contaminated parts of the territory.

The information distribution and connection with main objects are presented in the scheme (Fig. 4). The main objects of the inventory – which is conducted with purpose of economic rehabilitation of objects – are “Meadow”, “Forest”, “Field”, “Pond”. In order to describe each of these objects, the list of parameters merged into subgroups was developed by the experts. In order to describe objects “Meadow” and “Field” it is necessary to give a general description of object, estimate a level of soil contamination with radionuclides, determine a soil type, evaluate cultural and technical state and assess radioactive contamination of vegetation. For the object “Forest” the following parameters are required: general description, soil contamination with radionuclides, soil type and radioactive contamination of vegetation. For the object “Pond” appropriate parameters for a water reservoir description are required.

GIS technology should be used for a comprehensive assessment of objects and visualization of the environment. GIS technology makes it possible to solve following issues:

- processing of digital cartographic and ecological information obtained during the monitoring and stored in the Electronic Register;
- plotting thematic maps, which reflect current state of ecosystems, on the basis of obtained data;
- forecast of the ecological situation within the inspected area depending on changes in characteristics of contamination sources or other factors;
- statistical analysis of information (to plot graphs, tables and diagrams).
The database of forest plantations of Zhytomyr oblast and ChEZ contaminated in the result of the Chernobyl accident was created on the basis of the Electronic Register for economic rehabilitation of these plantations (to produce bioenergy resources).

The experimental data on radiation monitoring of the territory of Ukraine alienated after the Chernobyl accident are very important, have great scientific and practical value, make it possible to solve many issues, in particular:

- analysis and forecast of radiological state of the environment;
- information and analytical support of decision-making in the field of sustainable use of natural resources and radioecological safety by central and local authorities;
- providing population and international organizations with ecological information.

Routine radiological monitoring in the ChEZ is conducted by the SE “Ecocenter”. The results of this monitoring are partly presented in the site of SAEZ [31]. The obtained information is stored in Microsoft Excel files.

Many institutes, centers, enterprises of Ukraine are involved in the system of scientific ecological monitoring on the alienated territory. Numerous data are accumulated. However, the information is collected and stored separately in different formats and on different media. And access to these data is often closed. There is a necessity to use advanced systems of data storage and transmission. It is advisable to create a new shared data bank “data collection and storage” under the auspices of the International Virtual Science Center. It will make it possible to organize numerous and disordered data, to develop criteria for data collection and storage. The main criteria of such bank are:

- access to the information;
- data reliability;
- data storage.
5. The results of the analysis of the monitoring systems inventory

According to the analysis of published articles in the world science metric database SCOPUS (Fig. 8), number of articles devoted to the monitoring in the ChEZ decreases monotonically since 1996.

At the same time, more than 2/3 of the works are devoted to the radionuclides behavior in the environment and significantly smaller part of articles is focused on radiobiological effects of ionizing radiation (Fig. 9a). The focus is on the aquatic ecosystems (Fig. 9b), however, they are not critical in terms of influence on humans and environment. It is caused by a large number of organizations in Ukraine, engaged in water radiology (State Specialized Enterprise «Ecocenter», NUBIP of Ukraine, International Radiological Laboratory of Chornobyl Center (IRL CC), Institute of Hydrobiology (IHB), Institute for Nuclear Research (INR), Ukrainian Hydrometeorological Institute (UHMI))). More than half of the articles are focused on the behavior of $^{137}\text{Cs}$, $18.3\% - \text{Pu}$ radioisotopes, $13.3\% - ^{90}\text{Sr}$ and $7\% - ^{241}\text{Am}$ (Fig. 9c). Increased attention is paid to the $^{137}\text{Cs}$ activity due to implicitly of its measurement. However, nowadays, the radiation situation in the ChEZ is mainly determined by the $^{90}\text{Sr}$ content. At the same time, the monitoring of super-long-lived and mobile radionuclides such as $^{3}\text{H}$, $^{14}\text{C}$, $^{36}\text{Cl}$, $^{99}\text{Tc}$, $^{129}\text{I}$ is not conducted in the ChEZ (Fig. 9c). Most of all, plants, animals and fish are studied in the ChEZ (Fig. 9d).

It is possible to make the following conclusion by these results:
The routine monitoring of the behavior of super-long-lived radionuclides is not conducted at all, as well as monitoring of radiobiological effects in the reference species.

Probably, the routine monitoring of water ecosystems is excessive, while the monitoring of forest ecosystems should be improved.

Development of criteria, comprehensive revision and analysis of the existing system of routine and scientific monitoring in terms of completeness (coverage of ecosystems), adequacy (set of parameters), and representative information on the levels of content and fluxes of radionuclides ($^{3}\text{H}$, $^{14}\text{C}$, $^{36}\text{Cl}$, $^{90}\text{Sr}$, $^{99}\text{Tc}$, $^{129}\text{I}$, $^{137}\text{Cs}$, $^{238-241}\text{Pu}$, $^{241}\text{Am}$) in the monitoring objects will be conducted on the basis of the survey of various scientific organizations and development of common unified strategy under the auspices of the International Virtual Center.
6. Analysis of landscape diversity and their radioactive contamination and general recommendations for the optimization of the monitoring system the ChEZ

6.1 Forest

Currently, systematic scientific radiological monitoring of forest ecosystems in the Chernobyl Exclusion Zone and Zone of Unconditional (Obligatory) resettlement is not conducted for the reason of chronic lack of funding of the researches in this area. Number of available temporary formed experimental sites is not enough to conduct proper investigation for forest inventory parameters of lands in the ChEZ with forest cover.
A brief analysis of the lands with forest cover by the woody species, age (details in Table 1), taking into account growth conditions and site index, indicates that the total number of experimental sites should be at least 50 pieces. Such number of sites is necessary to find out actual redistribution of biologically mobile radionuclides in the components of forest ecosystems. If abnormal deviation in radionuclides distribution is revealed, these data should serve as a base for future studies. It will make it possible to estimate radioecological state of forests in the ChEZ comprehensively. The designed experimental sites should be used for further scientific monitoring of changes in mobility of biologically active substances in forest ecosystems and other relevant researches (biological, ecological, forestry and so on).

Table 1 – Distribution of forests area in the Chernobyl Exclusion Zone by dominant species and age, thsd ha

<table>
<thead>
<tr>
<th>Species</th>
<th>Years</th>
<th>%</th>
<th>Num ber of sites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>to 20</td>
<td>1- 40</td>
<td>1- 60 1- 80 1- 100 1- 120 over total</td>
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<tr>
<td><em>Alnus glutinosa</em> (Alder)</td>
<td>9</td>
<td>0.7</td>
<td>3.4 1 0.1 0.0</td>
</tr>
<tr>
<td><em>Betula pendula</em> (Birch)</td>
<td>66</td>
<td>13.1</td>
<td>99 7 9 0.0 0.0</td>
</tr>
<tr>
<td><em>Pinus sylvestris</em> (Pine)</td>
<td>6</td>
<td>6.7</td>
<td>1 5 1 7.7 1.5</td>
</tr>
<tr>
<td><em>Populus tremula</em> (Aspen)</td>
<td>6</td>
<td>0.0</td>
<td>0.0 0.0 0.0 0.0 0.0</td>
</tr>
<tr>
<td><em>Quercus robur</em> (Oak)</td>
<td>6</td>
<td>0.1</td>
<td>0.0 0.0 0.0 0.0 0.0</td>
</tr>
<tr>
<td>Other species</td>
<td>4</td>
<td>1.8</td>
<td>59 37 0 0 0</td>
</tr>
<tr>
<td>Total</td>
<td>30</td>
<td>23.3</td>
<td>3.30 8.11 2.74 7.4 2.3 1.43 1.68 100</td>
</tr>
</tbody>
</table>

6.2 Radiation effects in populations and communities of wild organisms

The need for a system able to demonstrate that the environment is adequately protected from the effects of radioactive substances has been recognized by international organizations (e.g. IAEA and ICRP), a number of regulators and many scientists. As a result, the last time has seen considerable international and national effort on this issue with environmental protection now being referred to in the International Atomic Energy Agency’s Fundamental Safety Principles (IAEA, BSS 2011) as well as in the Recommendations of The International Commission on Radiological Protection (ICRP, 2007). The shift in focus from a radiological protection framework based solely on humans to one encompassing impacts on the environment has provided the impetus for the development of radioecological monitoring system the Chernobyl exclusion zone. A key component of the approach is the quantification of environmental risk at the population and ecosystem levels involving the combination of data on environmental transfer of radionuclides, dosimetry and radiobiological effects to provide a measure of wildlife exposure.

For this purpose, it is necessary, first of all, to admit the territory of the ChEZ as a protected area, where regular environmental activity, including monitoring of species biodiversity, research of radiobiological effects on wild organisms, will be performed according to the current legislation of Ukraine in order to find out the degree of the consequences and to develop ways to overcome the crisis, to prevent of the ecological disasters and spread of the radioactive contamination. It should be noted that there are certain preconditions for the preserve regime in the ChEZ such as natural resources, large territory, proximity to preserved areas, the absence of anthropogenic factor, educational, scientific and tourism perspectives.

Despite of the necessity of the environment protection the radioecological standardization is very difficult question because of many problems must be solved before, such as peculiarities of radionuclides distribution into the components of the ecosystem, determination of the critical point where the radiation dose is the highest and radiobiological effects are mostly expressed. Besides it, it is evident that permissible levels for ecosystem will depend on the quality characteristics of this ecosystem, such as landscape, diversity of species, biomass etc. ICRP has proposed to use reference organism approaches as an important first step to characterize doses to biota. According to this approach certain species with high level of radiosensitivity are used for the investigation. And then by the results of this investigation the reaction of the whole ecosystem will be assessed. For this reason, radiobiological effects for biota in the ChEZ must be investigated, first of all, for references species. The list of reference species and choosing criteria (the use of
well-investigated species, availability of special characteristics that are common for the whole type of these living organisms, prevalence) are attached in the document of ICRP [6].

Another important problem of field studies of radiobiological effects is the overestimation of the radiation influence. In the field conditions living organisms are under multiple stressors influence. Not only ionizing radiation influence on the biota in the field conditions, there are also many confounding factors as diet, habitat, predator stress, biological stressors (parasites), presence or absence of competitors, abiotic factors (e.g. temperature, pH), contaminators (metals, chemicals, etc.). It creates difficulties in the results interpretation and often leads to the overestimation of the radiation impact. This problem was discussed in the symposium organized by the International Union of Radioecology in November 2015 and certain recommendations were made [23]. According to these recommendations any results of the field experiments must be carefully interpreted taking into account interconnectedness and interactions between species, results of laboratory experiments and available in literature data on the influence of confounding factors. And priority should be given to the field studies that integrate different trophic levels and look at higher ecosystem levels.

Another problem that can create a false imagination about the radiation influence is the dose estimation. Now different approaches are used for the internal dose calculation on the base of the radionuclides activity using specific dose conversion factors [6]. But the dose assessment approaches, which would take into account changeable radiosensitivity and radionuclides accumulation ability during the life cycle of living organisms, are still being developed now [23, 35]. For this purpose research works of the radiation effects on biota in the ChEZ should be also addressed on the investigation of radiosensitivity and radionuclides accumulation in the different stages of life cycle of the living organisms.

According to the regime of the reserved areas any research activity in the ChEZ should not have deleterious feature. For this reason, the priority should be given to the research methods that allow individuals lives to be solved.

In view of the great variety of plants and animals that could be exposed to radiation at any given site of concern, in 2007 Committee 5 of the ICRP proposed approaches to selection of reference organisms for both terrestrial and aquatic ecosystems (Larsson, 2008). Scientific monitoring of the radiobiological effects in the ChEZ should be accompanied by the correct dosimetry and study radiation influence on reference species of organisms for both terrestrial (amphibian (frog), bird (duck), bird egg (duck egg), detritivorous invertebrate, flying insects (bee), gastropod, grasses and herbs (wild grass), lichen and bryophytes, mammal (rat, deer), reptile, shrub, soil invertebrate (worm) (earthworm), tree (pine tree)) and aquatic (amphibian (frog), benthic fish, bird (duck), bivalve mollusc, crustacean, gastropod, insect larvae, mammal, pelagic fish (salmonid/trout), phytoplankton, vascular plant, zooplankton) ecosystems.

The ChEZ was considered as one of the basic radiation monitoring polygons for the accumulation of empirical data in the natural environment [14, 36].

Conclusion
1. Survey/inventory of areas and objects in the exclusion territory is conducted in accordance with existing procedures and specific objectives of the survey.
2. Routine monitoring in the ChEZ is carried out by SE “Ecocenter” under the Regulations and requires optimization and coordination with scientific monitoring. Currently, there is no consensus about degree of ionizing radiation influence on the accumulation of carbon (biomass growth, decomposition of organic matter, etc.), as well as on the biodiversity changes in aquatic and terrestrial ecosystems of the ChEZ. This problem may be solved in the frame of the scientific ecological monitoring only.
3. Scientific monitoring in the Exclusion Zone is conducted by a number of scientific organizations of different departmental subordination and requires coordination and optimization. For this purpose, questioning of all stakeholders scheduled. Based on this information and taking into account statistical analysis of landscapes, criteria and recommendations for optimization of routine and scientific monitoring of the ChEZ, including the collection and storage of information, will be developed.

In order to optimize systems of routine and scientific radioecological monitoring of terrestrial and aquatic ecosystems in the ChEZ a special questionnaire has been developed and sent to the following organizations: UIAR NUBiP of Ukraine, State Specialized Enterprise «Ecocenter», NUBiP of Ukraine, International Radiological Laboratory of Chornobyl Center (IRL CC ЧЦ), State Specialized Enterprise «Central Radioactive Waste Management Enterprise » (SSE “CRWME”), Institute of Hydrobiology (IHB), Institute for Nuclear Research (INR), Institute of Geological Sciences (IGN), Institute of Environmental Geochemistry (IEG), Ukrainian Hydrometeorological Institute (UHMI):
Scientific ecological monitoring in the Exclusion Zone

<table>
<thead>
<tr>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object of study (soil, water, air, organisms, etc.)</td>
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<td>Observation net (places where the study is conducted)</td>
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<td>Periodicity (when the study started and how often observations are carried out)</td>
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<td>Controlled parameters (activities of radionuclides, heavy metals concentrations, etc.)</td>
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<tr>
<td>Research subject – processes (for example, radionuclides ($^{3}$H, $^{14}$C, $^{35}$Cl, $^{89}$Sr, $^{99}$Tc, $^{125}$I, $^{137}$Cs, $^{238-241}$Pu, $^{241}$Am) and heavy metals migration (accumulation), the frequency of radiobiological effects, diseases, mortality, population dynamics, etc.)</td>
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<tr>
<td>Analytical methods applied (reference to the sampling and measurement methods)</td>
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<td>Information collection, storage and exchange (publication)</td>
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<td>Is the monitoring performed with purpose of evaluation of ionizing radiation influence on the accumulation of carbon in the ecosystem (biomass growth, the rate of organic matter decomposition, etc.)?</td>
</tr>
<tr>
<td>Is the monitoring performed with purpose of evaluation of ionizing radiation influence on biodiversity of ecosystems, population and organisms?</td>
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</tbody>
</table>

The results of the survey will serve as a base for development of criteria and scientific substantiation of optimization of radioecological monitoring objects, networks and schedule for all the most common ecosystems in the ChEZ. Besides it, the results of such kind of cooperation will make it possible to improve and harmonize of existing and additional monitoring polygons with needs of all groups the project (location, landscape type, biodiversity, density of radioactive contamination etc.), and to provide monitoring works with relevant equipment and analytical measurements.
7. The development and support of radiation monitoring systems in the Chernobyl exclusion zone

For the development and support of radiation monitoring systems in the Chernobyl exclusion zone and for the implementation of the main objectives UIAR together with other organization (State Specialized Enterprise «Ecocenter», NUBiP of Ukraine, International Radiological Laboratory of Chernobyl Center (IRL ЧЦ), State Specialized Enterprise «Central Radioactive Waste Management Enterprise » (SSE “CRWME”), Institute of Hydrobiology (IHB), Institute for Nuclear Research (INR), Institute of Geological Sciences (IGN), Institute of Environmental Geochemistry (IEG), Ukrainian Hydrometeorological Institute (UHMI)) will perform following milestones and tasks (Table 2).

The time schedule of the scientific work “Development and support of the radioecological monitoring system in Chernobyl Exclusion Zone” is shown in Table 3.
Table 2. Working program and dedicated milestones on theme of “Development and support of radioecological monitoring system the Chernobyl exclusion zone” with tasks descriptions

<table>
<thead>
<tr>
<th>Stage</th>
<th>Milestones</th>
<th>Tasks description</th>
<th>Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Development of the system of the complex monitoring in the ChEZ</td>
<td>1.1 Allocation of responsibilities on fulfilling routine and scientific monitoring of different ecosystems of the ChEZ between organizations/persons, which are members of the Virtual Center for Environmental Research and Conservation</td>
<td>The list of people/organizations, which are responsible for routine and scientific radioecological monitoring of various objects</td>
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<td>1.2 Approval of the list of monitored parameters, monitoring schedules, methods used for sampling, sample preparation and analysis of samples, data formats, etc.;</td>
<td>The protocol of routine and scientific radioecological monitoring in the ChEZ</td>
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<td>1.3 Selection of research methods suitable for observation of effects in reference plants and animals from radiation exposures and estimation of absorbed dose received by these organisms at chosen experimental polygons;</td>
<td>The protocol of radiobiological researches</td>
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<td>1.4 Preparation of proposals on equipment needs for experimental polygons and analytical laboratories, as well as staff training;</td>
<td>The list of equipment and consumables and staff training program</td>
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<td>1.5 Selection and characterization additional experimental polygons for development monitoring system in the ChEZ: forest, etc.</td>
<td>The description of additional monitoring sites</td>
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<td>1.6 Progress report stage n°1</td>
<td>Progress report up to 31 Jun 2017</td>
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<tr>
<td>2</td>
<td>Support of the system of the complex monitoring in the ChEZ</td>
<td>2.1 Development of procedures and monitoring programs, work schedules, adequate resources;</td>
<td>Protocols and programs of radioecological monitoring</td>
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<td>2.2 Modernization and additional characterization (if necessary) of the network of experimental polygons of radioecological monitoring systems in the ChEZ;</td>
<td>The description of all monitoring sites</td>
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<td></td>
<td>2.3 Development and implementation of Quality Assurance and Quality Control programs for the monitoring systems;</td>
<td>Quality Assurance and Quality Control Requirements</td>
</tr>
<tr>
<td></td>
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<td>2.4 Development and support of unified databases of radioecological monitoring of the Virtual Center for Environmental Research and Conservation;</td>
<td>Databases of radioecological monitoring in ChEZ</td>
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<td>2.5 Development and support of a page on monitoring data at Website of the Virtual Center for Environmental Research and Conservation;</td>
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<td>5</td>
<td>Operation of the system of the complex monitoring in the ChEZ</td>
<td>2.6</td>
<td>Report stage n°1-2</td>
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<td>3.1</td>
<td>Carrying out planned monitoring works (sampling, data collection, maintenance of equipment) within selected experimental sites in the ChEZ. Measurement of radionuclides activity concentrations in collected samples;</td>
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<td>3.2</td>
<td>Providing experimental monitoring data for databases and Website updating;</td>
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<td>3.3</td>
<td>Data analysis and evaluating trends in radiological situation;</td>
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<td>3.4</td>
<td>Preparation of regular newsletters and providing information on radioecological situation for scientists, authorities and the public; Providing operative information and data for authorities and for the public in a case possible emergencies in the ChEZ (forest fires, floods, accidents, etc.);</td>
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<td>3.5</td>
<td>Report stage n°3</td>
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<tr>
<td>4</td>
<td>Creation of the Virtual Center for Environmental Research and Conservation aiming the development and support of radioecological monitoring systems in the Chernobyl exclusion zone</td>
<td>4.1</td>
<td>Preparation of the comprehensive review of the monitoring data aiming planning the current activities and preparation of proposals for the future</td>
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<tr>
<td></td>
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<td>4.2</td>
<td>Participation in the current work of the Virtual Center for Environmental Research and Conservation</td>
</tr>
<tr>
<td>5</td>
<td>Reporting</td>
<td>5.1</td>
<td>Final report stage n°1-4</td>
</tr>
</tbody>
</table>
### 1.2 Time schedule

Table 3. Time schedule for the whole project period of 3 years

<table>
<thead>
<tr>
<th>Year</th>
<th>2017</th>
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<tbody>
<tr>
<td>Stage</td>
<td>Task</td>
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R- Report
8. Reference
1. Концепція реалізації грошової політики в сфері розвитку діяльності в окремих зонах радіаційного загрязнення вслідство Чернобильської катастрофи. КАБІНЕТ МІНІСТРІВ УКРАЇНИ, РОЗПОРЯДЖЕННЯ від 18 липня 2012 р. № 535-р
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8 распоряжение КМ Украины от 18.07.12 г. № 535-р
12 Радіоекологічне обстеження та оцінка земель які виводяться за межі зони відчуження і зони безумовного (обов'язкового) відселення для використання населенням без обмежень
Методика виконання польових досліджень
13 СОУ 74.14-37-425:2006 «Якість ґрунту. Методи відбору проб ґрунту для радіаційного контролю»
15 Звіт про результати 4-ї інвентаризації радіоактивних відходів в Україні, 2010 «ДК УкрДО РАДОН».–2011.
16. Регламент ЧЗО
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**ANNEX**

Radioecological scientific monitoring of forest ecosystems of ChEZ
1. GENERAL CONTEXT AND ISSUES

The long term question on radionuclides redistribution into the environment is particularly important. In that context, different geochemical and radioecological models are developed and must be continuously actualized to adequately simulate the evolution of the contaminated ecosystems. That’s why a better understanding of the biogeochemical cycle of long-lived radionuclides such as $^3$H, $^{14}$C, $^{36}$Cl, $^{90}$Sr, $^{99}$Tc, $^{129}$I, $^{137}$Cs, $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu and $^{241}$Am is necessary to identify in the long term the effective sinks and reservoirs in the environment and the source and extent of exposure.

2. OBJECTIVES

The objective of radioecological scientific monitoring is to determine the eco-physiological and radioecological parameters to be used in assessment codes for evaluating the fluxes of radionuclides recycling by a perennial plant system in response to a surface and/or underground contamination in order to characterize the residence time of radionuclides in the different forest ecosystem compartments. The present radioecological monitoring study shall focus on the acquiring the data set characterizing the root uptake of radionuclides, its distribution in trees parts, bushes, wild herbs, mushrooms, litter and its recycling to the soil through litterfall, throughfall and stemflow processes for the most widespread species of forest plants taking into account their distribution on inventory parameters and site class. It shall also focus on the characterization of radionuclides (bio)availability in soil organic and mineral layers in order to complete the understanding of its recycling dynamic in the soil-tree system as a whole. Radiobiological effects for reference organisms (pine, shrubs, wild grass, etc.) at different doses are studied at the same monitoring sites at the population and ecosystem levels.

3. DATA SET SPECIFICATIONS

3.1 Study location

The dataset will be acquired in the forest stands located at the contaminated area of Chernobyl exclusion zone (ChEZ) near the damaged nuclear power plant which offers an opportunity for in situ studies on long-term impact of perennial vegetation on nuclides biogeochemistry and their transfer in the biosphere. Area of the investigation monitoring site (sample plot) should include not less than 100 trees.

3.2 Studied parameters and sample collections

Key parameters to acquire are intended to feed the modelling of the biogeochemical cycling of radionuclides in forest ecosystems on the basis of the conceptual model used by Van den Hoof and Thiry (2012) and Yoschenko (2016), i.e. compartmental modelling and fluxes according to 1st order kinetics (fluxes between stocks).

The radioecological monitoring system will focus on fluxes occurring within the 3 main components of the soil-tree system: trees (uptake, translocation), returns to forest floor (throughfall, stemflow, litterfall) and soil ((bio)availability dynamics in forest floor vs mineral soil horizon).

Chernobyl contaminated territories are considered in a steady state phase for radionuclides cycling because $^{90}$Sr and $^{137}$Cs redistribution in trees seems having reached an apparent steady state and the fluxes are considered stabilised (Shcheglov et al., 2014).

3.2.1 Forest stand type

Despite the relatively low concentration of $^{137}$Cs, $^{238}$Pu, $^{239-241}$Pu and $^{241}$Am in woody components, tree components are the main long-term reservoir for $^{90}$Sr and $^{137}$Cs in forest vegetation (Calmon et al., 2009). Yet, measured T$_{ag}$ in understory components exhibit higher values than those for trees (Calmon et al., 2009) and fluxes of elements to the understory components are not negligible. They can be considered as a significant source of variability in the total budget. Understory components (shrubs, berries, mushrooms...) will be taken into account in the frame of this study. Fesenko et al. (2001) showed that the $^{90}$Sr and $^{137}$Cs retained by the understory was variable according to species, which implies its characterization and species determination.

3.2.2 Vegetal organs
Biometric data allow the assessment of the total stem volumes, through its modelling as successive truncated cones (Goor and Thiry, 2004), and of the biomass distribution within stems. Biometric data will also allow classifying the forest stand within a productivity category by using local stand productivity tables that return the annual average biomass increment of the different tree compartments. These tables need to take into account all organs of interest. If not available, calculation of biomass annual increment can be performed through the use of allometric equations from literature. In this last case, biometric data allow to check the adequacy of used allometric equations parameters.

Concerning the sampling methodology, first step consists in the characterization of the stands. It will be done through the determination of the frequency distribution of stem diameter at breast height (DBH, at 1.30 m above the ground) and of the trees height.

In a second step, collection of tree samples is performed by cutting model trees. These model trees will be chosen within 5-7 DBH frequency classes that cover the previously obtained distribution. Height of each tree is measured when cut. Branches are separated from the trunk and needles from the branches, and then the separated organs are weighed to acquire the total biomass of each individual. Dead branches and dead needles are also considered. An aliquot of targeted organs are then sampled: living branches (branches > 1 year), twigs (living branches of the year), old living needles (more than 2 years), living needles of the year, dead organs (branches and needles). Then, wood discs are cut off from the trunk at the base of the tree, at the BH, and at the middle of two meter sections: 1 m, 3 m, 5 m, 7 m, 9 m... up to the apex of the tree.

The third step consists in cutting from each individual 2–4 cm trunk discs (including wood and bark) at the trunk base, at BH (1.30 m), 0 H, 0.1 H, 0.25 H, 0.5 H, 0.75 H and 0.9 H up to the top of the trees. Each disc is weighed and measured (thickness, diameter, width of total bark, sapwood rings, heartwood), and the age of each tree is checked by rings using a discs. Scanned pictures of each disc with a scale rule completed this work. All disc components are weighed and densities of wood (fresh weight, dry weight) are determined.

All fresh weights (fw) will be determined after sampling at the field. All samples are then dried at 70°C until constant weight (dw) before treatment for each required analysis, and fw/dw ratios are calculated for all.

3.2.3 Returns to forest floor

Returns to forest floor have to be assessed continuously over 1 year (before trees sampling) for each stand in order to be consistent with the scope of this study. The frequency of samples collection needs to be adjusted according to each implied process and related technical issues, but once a month seems adapted for this purpose.

The litterfall and dead branches are collected by means of dedicated gauges under canopies (classical litter traps, 0.5 m² surface each, N=3 as a minimum) over 1 year. The sampling needs to cover the variability of the stand. Litterfall needs to be separated into its components (barks, needles/leaves, branches).

For throughfall, troughs (vs funnels) are believed to collect more representative volumes, as this type of gauge integrates a larger area and thus a variety of canopy conditions (Thimonier, 1998). However, the sampling strategy (number and location of collectors) is more important than the type of gauge (Thimonier, 1998) and is a key issue for the integration of spatial variability.

The stemflow is collected ideally for trees of each DBH class, and at least cover the variability in the stand. As the composition of precipitations may significantly influence the distribution and turnover of radioactive caesium in forest ecosystems (Thørring et al., 2012), rain amounts outside the influence of canopies will be collected for composition and volume comparison purposes (local scale, same frequency as other returns to forest floor fluxes collection).

3.2.4 Soil parameters

Regarding to mobility and bioavailability of $^{137}$Cs and $^{90}$Sr in forest soil (brown forest soil on podzol), soil profile can be divided into main components: the organic horizons (Oi, Of, Oh), transition horizon (OAh), C enriched mineral horizon (Ah) and mineral horizon (E/B) (cf. Thiry et al., 2000). Marques and Ranger (1997) showed that the soil organic pool and its potential for mineralisation are the main factors that determined the solution chemistry in all layers to different extents. Soil sampling depth depends on the key layers depth which probably won’t exceed 30 cm, as $^{137}$Cs ($^{129}$I, $^{238-241}$Pu and $^{241}$Am didn’t migrate so far. For $^{36}$Cl, $^{90}$Sr and $^{99}$Tc soil sampling depth should be not less than 1 m.

Radionuclides soil profile is determined on undisturbed soil core samples and the classical agro-chemical characterization is performed for each key layer finely separated. The final number of soil layers will be determined according to the configuration of the soil layers on site.
3.3 **Samples and analyses**

After homogenization of dry materials (crushing), samples are divided in several aliquots for analysis and one will be reserved for storage for eventual additional analyses. All samples are analysed for determination of radionuclides activity.