ENVIRONMENTAL PROBLEMS ASSOCIATED WITH DECOMMISSIONING THE CHERNOBYL NUCLEAR POWER PLANT COOLING POND

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ABSTRACT

Decommissioning of nuclear power plants and other nuclear fuel cycle facilities associated with residual radioactive contamination of their territories is an imperative issue. Significant problems may result from decommissioning of cooling ponds with residual radioactive contamination. The Chernobyl Nuclear Power Plant (ChNPP) Cooling Pond is one of the largest self-contained water reservoirs in the Chernobyl Region and Ukrainian and Belorussian Polesye Region. The 1986 ChNPP Reactor Unit Number Four significantly contaminated the ChNPP Cooling Pond. The total radionuclide inventory in the ChNPP Cooling Pond bottom deposits are as follows: ^{137}Cs: 16.28 ± 2.59 TBq; ^{90}Sr: 2.4 ± 0.48 TBq, and $^{239+240}$Pu: 0.00518 ± 0.00148 TBq. The ChNPP Cooling Pond is inhabited by over 500 algae species and subspecies, over 200 invertebrate species and 36 fish species. The total mass of the living organisms in the ChNPP Cooling Pond is estimated to range from about 60,000 to 100,000 tons. The territory adjacent to the ChNPP Cooling Pond attracts many birds and mammals (178 bird species and 47 mammal species were recorded in the Chernobyl Exclusion Zone). This article describes several options for the ChNPP Cooling Pond decommissioning and environmental problems associated with its decommissioning. The article also provides assessments of the existing and potential exposure doses for the shoreline biota. For the 2008 conditions, the estimated total dose rate values were 11.4 40 μGy hr^{-1} for amphibians, 6.3 μGy hr^{-1} for birds, 15.1 μGy hr^{-1} for mammals, and 10.3 μGy hr^{-1} for reptilians, with the recommended maximum dose rate being equal to 40 μGy hr^{-1}. However, drying the ChNPP Cooling Pond may increase the exposure doses to 94.5 μGy hr^{-1} for amphibians, 95.2 μGy hr^{-1} for birds, 284.0 μGy hr^{-1} for mammals, and 847.0 f μGy hr^{-1} for reptilians. All of these anticipated dose rates exceed the recommended values.

Key words: Decommissioning, contamination, cooling pond, Chernobyl Nuclear Power Plant

INTRODUCTION

Decommissioning of nuclear power plants and other nuclear fuel cycle facilities associated with residual radioactive contamination is a fairly pressing issue. In particular, significant problems may result from decommissioning contaminated cooling ponds. Considerable experience and widely accepted recommendations exist on remediation of contaminated lands; however, there is little such understanding, knowledge, or recommendations on remediation of cooling ponds. Previous studies only describe remediation of small reservoirs containing radioactive silt (Brill et al. 2001) or small water reservoirs with the objective of reestablishing natural water flows (Dwyer 2007; Marks 2007). The severity of environmental and economic problems related to the remedial activities has been shown to exceed any potential benefits of these activities (Edelshtejn 1998).

The 1986 Chernobyl Nuclear Power Plant (ChNPP) Reactor Unit Number Four accident significantly contaminated the ChNPP Cooling Pond. According to the 2001 data, the measured radionuclide inventory in the ChNPP Cooling Pond bottom deposits was as follows: ^{137}Cs 16.28 ± 2.59 TBq; ^{90}Sr 2.4 ± 0.48 TBq, and $^{239+240}$Pu 0.00518 ± 0.00148 TBq (Weiss et al. 2000). Because all ChNPP reactors are now shutdown, the Cooling Pond is no longer needed and is currently in the process of being decommissioned. Due to its large size, it is not cost effective to maintain it in the long term. However, shutdown of the water feed to the Cooling Pond would expose the contaminated bottom deposits and change the hydrological features of the area, thus destabilizing the radiological and environmental situation regionally.

METHODS

To assess potential consequences of draining the Cooling Pond, the authors conducted preliminary radioecological studies of its shoreline ecosystems in 2007 – 2008. The radioactive contamination of the Cooling Pond shoreline is variable and ranges from 75 to 7,500 kBq m^{-2}. Three areas with different contamination levels were selected for sampling various environmental media including soils, vegetation, small mammals, birds, amphibians, and reptilians in order to measure their ^{137}Cs and ^{90}Sr content *in vivo*. Using the ERICA (*Environmental Risk from Ionizing Contaminants: Assessment and Management. v. 1.0 2009*) software (Brown et al. 2008), the radiological impact on these systems was estimated.

RESULTS AND DISCUSSION

ChNPP Cooling Pond Characterization

The ChNPP Cooling Pond is a major element of the ChNPP hydraulic engineering system intended for providing continuous water flow for cooling the ChNPP equipment. The Cooling Pond is a stagnant water basin of elongated shape formed in the Pripyat River floodplain near the towns of Pripyat and Chernobyl. The shoreline includes a terrace above the floodplain and a levee with a drainage canal along the perimeter of the levee. There exists a stream separator in the centerline of the Pond to regulate the cooling water flow. The total area of the Cooling Pond is 22.9 km^2 at the normal design level and its volume is 151,200,000 m^3. Apart from the Pond basin, feed and discharge canals, the Cooling Pond hydrological system also includes two canals along the levee: the Northern Drainage Canal that seeps into the Pripyat River and the Southern Drainage Canal that flows into the Glinitsa Creek. Until 1990, the area between the Cooling Pond and the Pripyat River had up to 65 isolated lowland swamps that received water seeping from the Pripyat River, atmospheric precipitation, and water resulting from the Pripyat River floods. During 1991, an additional drainage canal was built to combine all these smaller reservoirs and lowland swamps into one hydrological system to pump the water back into the Cooling Pond.

The major hydrological feature of the Cooling Pond is that its water level is 6 to 7 m higher than the water level in the Pripyat River and its floodplain reservoirs. Significant water seepage from the Pond to the Pripyat River and levee has been observed. Water losses from the Cooling Pond due to the seepage and evaporation are replenished by pumping water from the Pripyat River using the Shoreline Pump Station in the north-western part of the Cooling Pond (Fig. 1) and, to a less extent, by precipitation and an underground water flow from Rodvino Creek and Borschi Creek.

Currently, the ChNPP Cooling Pond is one of the largest self-contained water reservoirs in the Chernobyl region and Ukrainian-Belorussian *Polesye* Region. For 30 years of its operation, a fully fledged ecosystem with a large number of various aqueous and terrestrial species has developed in the Cooling Pond and its shoreline areas. Over 500 algae species and subspecies and over 200 invertebrate species inhabit this ecosystem. During the decade between 1990 and 2000, 36 fish species were observed in the Pond. Fish stock is estimated to be 6,000 to 8,000 tons while the total mass of living organisms is estimated to be between 60,000 and 100,000 tons (Gaschak et al. 2002). The shoreline of the Cooling Pond and its adjacent minor reservoirs abound in vegetation, attracting many birds and mammals. Scientists documented 178 bird species and 47 mammal species in the Chernobyl Exclusion Zone (Gaschak et al. 2002).

In 1986, the Cooling Pond became significantly contaminated due to the accident at the ChNPP Reactor Unit Number Four. According to Kazakov (1995), the primary radionuclide inventory in the Pond was about 7,400 TBq (200,000 Ci). In May of 1986, the Cooling Pond water contained the following percentages of radionuclides: ^{141}Ce – 3.3%, ^{144}Ce – 3.2%, ^{103}Ru – 6.1%, ^{140}Ba – 13.2%, ^{131}I – 28.3%, ^{96}Zr – 7.8%, ^{95}Nb – 9.5%, ^{140}La – 10.7%, ^{134}Cs – 6.8%, and ^{137}Cs – 13.8% (Kazakov et al. 1994). Long-lived radionuclides, including transuranic elements, were mostly associated with the dispersed nuclear fuel. The radioactive fallout absorbed by suspended solid particles settled forming contaminated bottom deposits (Tables 1 and 2).

Since ChNPP is systematically being decommissioned, the large ChNPP Cooling Pond has become unnecessary and its maintenance too expensive. However, shutdown of the water feed to the Cooling Pond will soon expose the contaminated bottom deposits, change the hydrological features of the area, and destabilize the radiological and environmental situation in the ChNPP and adjacent areas.

Earlier Projects Involving the ChNPP Cooling Pond Decommissioning

The ChNPP Cooling Pond contamination caused problems as early as the initial phase of the ChNPP accident mitigation activities started. Specifically, these problems were related to operation of the Cooling Pond as an element of the ChNPP water supply system. To minimize risks of radioactive contamination of the ChNPP utilities and turbine cooling systems (especially, from the northern section of the Cooling Pond considered to be the most contaminated pond area shown in Fig. 1), an additional levee was erected in the mouth of the feed canal and water passages were provided for the stream separator to prevent accumulation of highly contaminated solids in the discharge canal. Due to a relatively fast decrease of the ChNPP water contamination, the risks associated with contamination of the ChNPP process equipment became irrelevant. The Cooling Pond contamination profiles for ^{137}Cs and ^{90}Sr are shown in Fig. 2 (Bondarenko and Kireev 2007).

Another fundamental problem, which is associated with the seepage from the contaminated Cooling Pond to the Pripyat River, is the risk of contaminating the Dnieper River, the major river in Ukraine that crosses a number of large Ukrainian cities. In the summer of 1986, an *interception drainage* system was built, which included 196 wells drilled to use a water collector to accumulate water seeping from the Pond and send it back to the Pond. The capacity of the interception drainage system was designed to be around 100,000,000 $m^3\ y^{-1}$. However, the interception drainage system was not commissioned because no significant increase of the groundwater contamination was observed in the period between 1986 and 1987 and operation of this system could have intensified groundwater radionuclide transport. During the period between 1988 and 1989, although ^{90}Sr concentration in the seeping groundwater significantly increased, but the interception drainage system was still not commissioned because the absolute radionuclide transport values did not appear to present a high risk while intensification of seepage, mass exchange, and radionuclide transport processes in the Cooling Pond caused by the interception drainage system area could have aggravated the radionuclide contamination problem. In addition, the interception drainage system could have affected the salt content of the Cooling Pond, potentially causing an excessive water mineralization beyond the allowable limits.

Studies performed in 1995 regarding the effectiveness of operation of the interception drainage system based on the actual monitoring data showed that, if commissioned, the interception drainage system could have intercepted only about 20% of the seepage flow from the Cooling Pond to the Pripyat River, or less than 30% of the total ^{90}Sr transport from the Cooling Pond to the Pripyat River (Voitchekhovich 2001). Therefore, the interception drainage system was never commissioned and it has currently been dismantled.

Immediately after the 1986 accident, significant radionuclide transport was expected from the Northern Drainage Canal and other minor reservoirs to the Pripyat River; therefore, all of them were bridged with zeolite dykes to capture ^{90}Sr. However, that countermeasure did not prove very effective (Voitchekhovich 2001) and, as an alternative solution, the second interception drainage system was commissioned in November of 1995. This second interception drainage system is still practically non-operational because natural self-remediation of the Cooling Pond water played a critical role in slowing down the radionuclide transport from the Cooling Pond hydrological system. The decrease of the radionuclide concentrations in the ChNPP Cooling Pond water was due to precipitation of the suspended particles that absorbed the bulk of radioactivity (Kazakov 1995; Kononovich et al. 1993).

Immediately after the 1986 accident, a significant radionuclide transport into the Pripyat River was expected due to the surface drain from the Northern Drainage Canal and other minor reservoirs; therefore, in the winter of 1986-1987, all of them were bridged with zeolite dykes to capture ^{90}Sr. However, that countermeasure to remove ^{90}Sr from the water did not prove very effective (Voitchekhovich 2001) and, as an alternative solution, the second surface drainage interception system was commissioned in November of 1995. The second drainage system was intended to intercept the surface drainage of radionuclides whereas the first was intended for interception of the underground drainage. The second interception drainage system is still practically non-operational because natural self-remediation of the ChNPP Cooling Pond water played the crucial role in slowing down the radionuclide transport from the Cooling Pond hydrological system.

Since the Ukrainian Government made a decision to decommission the ChNPP ahead of schedule, the fate of the Cooling Pond stimulated a large number of discussions. Various options for its decontamination and decommissioning were proposed; for example, consolidation of contaminated bottom deposits while maintaining the existing water level, using special custom-made tools and conventional dredges followed by processing, concentrating, and disposal of the radioactive waste generated at the existing radioactive waste disposal sites (e.g., at the Buryakovka site). However, such options were rejected due to their high costs, low efficiency, and relatively high anticipated radiation exposure to personnel. The most attractive option was that of natural drainage and evaporation of the Cooling Pond following shutdown of its water feed with various approaches to decontaminate its bottom areas, specifically (SRR 1992):

- Phased decontamination associated with a gradual decrease of the water level in the Cooling Pond. This was proposed for the most contaminated areas with the contamination density exceeding 18.5 MBq m^{-2}. This was to be followed by removal and disposal of the contaminated soils at the disposal sites;
- Generating a 0.5 m sand layer followed by natural sodding was proposed for less contaminated areas (7.4–18.5 MBq m^{-2});
- Planting vegetation was proposed for areas with a contamination range of 1.85–7.4 MBq m^{-2}. It was further proposed that less contaminated areas would be left alone for natural sodding;

- About 40% of the total radionuclide inventory in the bottom deposits was estimated to be present in deep water silts. After drainage and evaporation of the Cooling Pond, this contamination would have remained under water in newly formed 6 to 8 m deep ponds with the total area of about 4 to 5 km^2. Sorbents were proposed to be introduced into these bottom deposits using rotary drills.

During the time period from 1995 to 1997, the Chernobyl Center in the town of Slavutich and the U.S. Department of Energy's (DOE) Pacific Northwest National Laboratory performed a comprehensive evaluation of all problems associated with the Cooling Pond and developed an action plan for additional studies and decommissioning strategies (Oskolkov et al. 1997). Unfortunately, due to a lack of funding, this project was never completed.

During the period of time between 1998 and 2000, under the European Commission Directorate General "Environment" project (Weiss et al. 2000; Buckley et al. 2002) some additional data on the status of the Cooling Pond were collected and recommendations on how to handle the Cooling Pond were developed. Scientists performed a new detailed bathymetric survey of the Cooling Pond, updated bottom deposits distribution maps and radionuclide profiles in the bottom deposits, and assessed potential secondary contamination due to dust generation and re-suspension from the dried bottom areas. Mathematical models, used to simulate the natural drainage and evaporation of the Cooling Pond associated with shutdown of its water feed, were developed and included new bathymetric and dose consequence data. Using these models, it was demonstrated that shutdown of the water feed and decrease of the water level would cause the Cooling Pond to break down into a number of smaller pools. It was also demonstrated that the pond's drying rate would mostly depend on weather conditions.

According to the "normal[‡]" scenario, water levels in the residual water pools would range from 105.5 m (above the Baltic Sea level based on the Baltic System of Elevations) in the north-western part of the Cooling Pond to 104.2 m in the southern part, while the dried bottom area will encompass 12.9 km^2. According to the "dry" scenario, these values will be 103.3 m, 101.2 m, and 18.5 km^2, respectively. The estimated time required for a natural drainage and evaporation down to the level of 104.7 m ranges from three years (for the "driest" scenario) to 8 years (for the "normal" scenario). After a dynamic groundwater level balance is established, the Cooling Pond area will present a terrain with a few pools, shallow water areas, and swampy areas separated by levees from all sides. The dried areas will mostly contain silty fine sand and original soils covered with dead algae and clams. The internal slope of the levees and slopes of the stream separator will mostly be covered with fine and coarse sand, and occasionally with silty sand. The maximum thickness of the dried silt layers will range from 1 to 6 cm; however, silts found deeper than 7 m with the thickness greater than 26 cm will remain under water on the bottom of the newly formed ponds and pools (Fig. 3).

The total activity of the dried bottom deposits will be about 42.3 TBq (1,144 Ci), while the ^{137}Cs specific activity will range from 5 to 30 kBq kg^{-1}, which, according to the Ministry of Health of Ukraine (MHU 2005), classifies them as radioactive waste. Redistribution of contaminated deposits towards deeper areas is likely due to a decrease in the ChNPP Cooling Pond water level.

It should be noted that the bulk of radionuclides in the bottom deposits is bonded with so called "hot particles," i.e., a finely dispersed fuel matrix preserved in the neutral underwater media. In ground level soils, hot particles have practically decayed and have become biologically accessible due to a physical degradation of fuel particles (e.g., oxidation) (Buckley et al. 2002).

The studies described above made it possible to identify the following major factors that directly affect the selection of a strategy for decommissioning the ChNPP Cooling Pond:

- Assessment of radiation risks for the personnel and public, resulting from air exposure of the contaminated bottom deposits, including assessment of dust and resuspension, water level changes, and escape of hot particles from the Pond water;
- Assessment of environmental consequences associated with an increased intake of radionuclides by plants and animals and increase of biological accessibility of the radionuclides;
- Assessment of the environmental consequences associated with drastic transformation of the terrain and changes in quantities and speciation of the biota.

During the time period between 1999 and 2000, studies were performed (Weiss et al. 2000; Buckley et al. 2002) to assess the dust re-suspension under various meteorological conditions, including dust storms (with the exception of tornados). A potential additional increase of contamination in the ChNPP area resulting from the dust re-suspension was shown to be insignificant; specifically, it would range from 0.001 kBq m^{-2} to 0.05 kBq m^{-2} for ^{137}Cs and from 0.001 kBq m^{-2} to 0.005 kBq m^{-2} for ^{90}Sr.

A decrease of the radionuclide transport is due to a decrease of the velocities and volumes of the underground water flows and due to the improved hydrogeological conditions of the radioactive waste disposal sites provided during the post-Chernobyl period as a mitigation activity. A decrease in the groundwater level is estimated to decrease underground radionuclide transport into the Pripyat River. In 2008, the total ^{90}Sr seepage was equal to 120 GBq y^{-1}, and, after drying the ChNPP Cooling Pond, the total ^{90}Sr seepage is estimated to range from 1 to 10 GBq y^{-1}. A significant improvement of hydro-geological conditions is predicted for interim radioactive waste disposal sites. Specifically, the Cooling Pond drainage will decrease by 1 to 2 m at the Shelter Facility and at the Spent Nuclear Fuel Storage Facility (SNFSF-2) and by 2 to 4 m at the *Kompleksny* radioactive waste disposal site. Therefore, the Cooling Pond decommissioning is not expected to aggravate the radiological situation within or beyond the Chernobyl Exclusion Zone area.

However, radiological risks associated with air exposure of the contaminated bottom deposits for the biota have not been thoroughly studied. Effects of these changes on species that will inhabit the residual water reservoirs, where a slight increase of the radionuclide concentration up to 60 Bq L^{-1} is expected, also have not been studied.

Radiological Aspects of ChNPP Cooling Pond Decommissioning

The radioactive contamination of the Cooling Pond shoreline is fairly variable and ranges from 75 to 7,500 kBq m^{-2}. After the Cooling Pond dries, its loose bottom deposits free from vegetation will be easily susceptible to wind erosion and accessible to terrestrial animals. A short-term decrease of the water level in the process reservoirs at the U.S. DOE's Savannah River Site (SRS) from 1991 through 1994 was known to cause a significant contamination of birds, mammals, and vegetation [Whicker et al. 1997; Whicker et al. 1999]. A similar increase is likely to be expected in the Chernobyl area as well. In addition, studies performed at SRS also indicate that a replacement of one large water reservoir with several smaller ones and decrease of the water level is attractive to birds, which may also cause an increased intake of radionuclides via those food chains (Whicker et al. 1997) including birds.

To evaluate potential consequences of the Cooling Pond evaporation and drainage, the International Radioecology Laboratory (IRL) located in Slavutich, Ukraine, assessed the current radiation situation in the shoreline and aqueous ecosystems of the ChNPP Cooling Pond from 2007 through 2008. For this purpose, IRL scientists selected three 200x200 m areas with various radioactive contamination levels, sampled soils and vegetation there, and caught small mammals, reptilians, amphibians and birds to measure their radionuclide content. The radionuclide content in animals was measured using the *in vivo* spectrometry method described by Makluk et al. (2007) and Bondarkov et al. (2001). The studied areas have a fairly heterogeneous spatial radionuclide distribution, which proves to be a very typical radiological feature of the Chernobyl Exclusion Zone observed by practically all researchers. The biota contamination appears to be equally heterogeneous as shown in Table 3.

The obtained data and the ERICA Assessment Tool Code (Environmental Risk from Ionizing Contaminants: Assessment and Management. v. 1.0 2009) made it possible to assess the exposure of the shoreline biota. The maximum measured values of ^{137}Cs (29.9 kBq kg^{-1}) and ^{90}Sr (12.3 kBq kg^{-1}) soil content were used as the baseline data (conservative approach). The limiting dose rate values, i.e., 40 μGy h^{-1} for terrestrial animals and 400 μGy h^{-1} for plants, were selected as those recommended by IAEA (1992) and UNSCEAR (1996) as baseline criteria, below which undesirable radiation related consequences are fairly low. These criteria also correspond to the maximum allowable dose rates recommended by the DOE of 10 mGy d^{-1} (417 μGy h^{-1}) for aquatic animals and terrestrial plants and 1 mGy d^{-1} (41.7 μGy h^{-1}) for terrestrial animals, respectively (DOE 2002; IAEA 1992; TS 2002; ICRP 2003; UNSCEAR 1996).

Amphibians, birds, mammals (rodents), and reptilians were selected as reference species. The concentration ratio (CR) was calculated as the ratio of the radionuclide specific activity in a raw mass of the biological species and the specific activity of the subsurface 0 to 20 cm soil layer (dry mass) (Table 4). The risk factor was calculated using the following equation:

$$RQ = M_n/EMC_n, \quad (1)$$

where RQ is the risk coefficient; M_n is the measured value of the radionuclide specific activity in the species in Bq kg^{-1}; and EMC_n is the established maximum concentration in the species in Bq kg^{-1}.

Total dose rates currently received by animals in the shoreline areas (Table 5) do not exceed the recommended values. However, the conservative risk assessment value for rodents is higher than 1.0, which means that the doses recommended as safe can be exceeded. It should be noted that the accumulation coefficients based on our data significantly differ from those obtained using the probabilistic analysis between 2 and 17. The assessment using the probabilistic risk analysis provides for a twofold increase of the dose rate for amphibians and a five time increase for reptilians, but the recommended doses are still not exceeded.

Using the ERICA software, predictive assessments of the radioecological consequences associated with drying the Cooling Pond were made. The data provided by Buckley et al. (2002) were utilized as the input data. The isotopic composition and the specific concentrations of radionuclides in the soil correspond to the maximum values of contamination of the bottom deposits in the part of the Cooling Pond to be evaporated (Table 6). The predicted dose rates and risks are shown in Table 7.

The highest dose rates are shown to be associated with mammals (murine) and reptilians, 284 and 847 µGy h^{-1}, respectively, which considerably exceeds the recommended value (40 µGy

h^{-1} for terrestrial animals - UNSCEAR 1996). The risk coefficients for all species exceed 1, and, for reptilians and mammals, they are equal to 63.5 and 21.3, respectively.

However, it should be noted that these predictions are very conservative and they do not take into account the time for the ecotone succession and changes in the biological accessibility of the radionuclides, which will necessarily take place after the Cooling Pond evaporates.

CONCLUSIONS

The review of the published data regarding the radioecological status of the ChNPP Cooling Pond and results of the studies completed by IRL make it possible to draw the following conclusions:

Problems associated with remediation of cooling ponds of nuclear facilities, including cooling ponds of nuclear power plants, significantly differ from those associated with remediation of land-based production sites.

Decommissioning of large nuclear plants cooling ponds, which became radioactively contaminated, and which are stand-alone full-scale biocenoses during the operation of these nuclear power plants, appears to be a complex and comprehensive task. The strategies developed will clearly impact radiation safety and the environmental status quo potentially resulting in drastic changes in the regional ecosystem and established land use practices.

The ChNPP Cooling Pond and its shoreline areas present a complex ecosystem in the succession phase with well-established radioecological properties associated with the accidental radioactive material contamination. The assessment of the current radioecological situation indicates its relative stability and predictability. However, evaporation of the Cooling Pond will destabilize the radioecological situation and increase risks for the biota. According to the preliminary estimates, the total doses for various animal species (mammals and reptilians) may exceed the maximum allowable doses that are currently considered safe by a factor of several times.

Analysis of a possible strategy for Cooling Pond decommissioning shows that the best option would be its natural evaporation and drainage accompanied by continuous radioecological monitoring and, if necessary, implementing steps for an expedited recovery of vegetation in the exposed areas.

Since the radioactive contamination is unevenly distributed in the area, the data on the shoreline biota contamination obtained so far should be considered preliminary and insufficient for an adequate radioecological assessment of the Cooling Pond evaporation and drainage. Such studies will have to continue on a larger scale, covering new shoreline areas. Development of a strategy for the Cooling Pond decommissioning and prediction of its potential environmental consequences require a more thorough study of the existing biological speciation and rate of transformation (succession) of the shoreline cenoses. Comprehensive radioecological studies of the Cooling Pond will make it possible to develop recommendations on assessment of radiation characteristics of water reservoirs with residual radioactive contamination and their adequate decommissioning.

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REFERENCES

Bondarenko ON, Kireev CI. Report on Radiation Status in the Territory of the Exclusion Zone in 2006//Specialized State Scientific and Industrial Enterprise “Chernobyl Radioecological Center” (DSNVP “Ecocenter”), Chernobyl, 2007.

Bondarkov M, Gaschak S, Goryanaya Ju, Maximenko A, Ryabushkin A, Salyi O, Shulga A, Saba Awan, Chesser R, Rodgers B. 2002. Parameters of bank vole decontamination from radiocesium and radiostrontium: Proceedings Volume 1 of the International Congress "ECORAD 2001", Aix-en-Provence (France), 3-7 September, 2001: Radioprotection. Colloques, Vol. 37, C1: 385-390; 2001.

Brill E, Krispin L, Whitehead J. Remediation of two basins containing radioactive sludge at Oak Ridge National Laboratory – Low Tech Meets High Tech. WM 2001 Conference, Tucson, AZ. February 25-March 1, 2001.

Brown JE, Alfonso B, Avila R. The ERICA Tool. - Journal of Environmental Radioactivity Amsterdam: Vol. 99 № 9 Elsevier, - ISSN 0265-931X. C.1371-1383; 2008.

Buckley MJ, Bugai D, Dutton LM, Gerchikov MY, Kashparov VA, Ledenev A, Voitzehovich O, Weiss D, Zheleznyak M. Drawing up and evaluating remediation strategies for the Chernobyl Cooling Pond. Final Report: C6476/TR/001. Service Contract No. B7-5230/2000/306958/MAR/C2; 2002.

Department of Energy DOE 2002. Technical Standard: A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota; STD-1153-2002; Washington, DC; DOE Office of Environment, Safety, and Health; July 2002.

Dwyer C. Honeysuckle Reservoir decommissioning. Earth Tech, Wangaratta; 2007. Available at http://www.csu.edu.au/research/ilws/news/events/5asm/docs/proceedings/Dwyer_Christopher_73.pdf. Accessed 24 September 2009.

Edelshtejn K. Russian water reservoirs: environmental problems and their solutions. M: GEOS; 1998.

Gaschak S, Zalisky O, Buntova O, Vishnevsky D, Kotlyarov O. Fauna of vertebrae species in the Ukrainian Chernobyl Zone. International Radioecology Laboratory. Slavutich; 2002.

International Atomic Energy Agency (IAEA). Effects of ionizing radiation on plants and animals at levels implied by current radiation protection standards. Vienna: IAEA Technical Reports Series No. 332; 1992.

International Commission on Radiological Protection (ICRP). A framework for assessing the impact of ionizing radiation on non-human species. New York: Pergamon Press; ICRP Publication 91; 2003.

Kazakov S, Vovk P, Filchagov L. Radioecological status of the ChNPP Cooling Pond: Problems of the Chernobyl Exclusion Zone. Kiev, Naukova Dumka: INIS-UA-0227: 129-138; 1994.

Kazakov SV, Radiation Management of NPP Cooling Ponds. Kiev, Technika; 1995.

Kononovich A, Oskolkov B, Ryabov I, Kryshev I. et al. Justification of the status for the ChNPP Cooling Pond: Scientific Research Report approved on September 8, 1993: Chernobyl; 1993.

Makluk Yu, Gaschak S, Maximenko A, Bondarkov M. Evaluation of parameters of in vivo removal of ^{90}Sr and ^{137}Cs from bodies of wild and laboratory small mammals animals after their natural contamination in the Chernobyl Zone. Radiobiology: Radioecology 47(4): 444-456; 2007.

Marks J. Down Go the Dams. Scientific American Magazine; 2007.

Ministry of Health of Ukraine (MHU). Major sanitary regulations for providing radiation safety of Ukraine. Order # 54 of February 2, 2005.

Oskolkov BYa, Nosovskiy AV, Zhepo SP, Bugai DA, Skalskii AC, Hersonskii ES, Derevets BB, Kononovich AL, Drapeko GF, Kubko YuU, Borozan AT. Report: Plan for studies of characteristics of the ChNPP Cooling Pond as a source of radiation risk to collect data for justification of activities on its decommissioning. Slavutich Laboratory of International Studies and Technologies; PA Chernobyl NPP; US Pacific Northwest National Laboratory, Program: Improving the Safety of Soviet-Designed Nuclear Power Plants, Contract # 321210 - A - R7, DOE USA; 1997.

Scientific Research Report/SRR 1992. Analysis of solutions for protection of the environment and activities on localization of radionuclides in the ChNPP Cooling Pond bottom deposits and soils of the floodplain areas of the ChNPP site: Agreement # 180-N: Zheltye Vody; 1992.

Technical Standard (TS) DOE-STD-1153-2002. A graded approach for evaluating radiation doses to aquatic and terrestrial biota. Washington: US Department of Energy, Project number ENVR-0011/ US Department of Energy; 2002.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Report to the General Assembly, Scientific Annex. Effects of radiation on the environment. United Nations. New York; 1996.

Voitchekhovich O. Surface water quality control in the area affected by the ChNPP accident: Ukrainian Scientific Research Gydrometeorological Institute (krNIGMI) Kiev; 2001.

Weiss D, Larue PJ, Bogorinski P, Watermeyer V, Voitsekhovitch O, Sobotovich E, Bugai D, Oskolkov B. Collection and analysis of information and data related to the contamination of the Chernobyl cooling pond. Final report on CEC-Contract No.: B7-5350/99/6241/MAR/C2; 2000.

Whicker FW, Hinton TG, Niquette DJ. Effects of a partial drawdown on the dynamics of ^{137}Cs in an abandoned reactor cooling reservoir Studies in Environmental Science, Volume 68, Pages 193-202; 1997.

Whicker FW, Hinton TG, Orlandini KA, Clark SB. Uptake of natural and anthropogenic actinides in vegetable crops grown on a contaminated lake bed. Journal of Environmental Radioactivity, Volume 45, Issue 1, Pages 1-12; October 1999.

Figures:

Fig. 1. General view of the ChNPP Cooling Pond.

Fig. 2. Contamination profile of the ChNPP Cooling Pond water (Bondarenko et al. 2007).

Fig. 3. Outlines of residual water reservoirs of the evaporated ChNPP Cooling Pond under the "normal" Scenario (the numbers indicate the areas of the residual water reservoirs in m^2 and elevation in m).

Fig. 4. Radioactive contamination distribution for the ChNPP Cooling Pond bottom deposits (Weiss et al. 2000).

Footnotes (Text):

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[‡] The "normal" scenario is a scenario consistent with average meteorological and hydrological conditions in the ChNPP area. The "dry" scenario is consistent with extreme conditions, i.e., minimum precipitation, maximum evaporation, minimum seepage feed, and minimum water levels in the entire local hydrographic system.

Table 1. Estimated radioactive contamination of ChNPP Cooling Pond bottom deposits in TBq (Ci) (Kazakov et al. 1994; Kononovich et al. 1993; Voitchekhovich 2001).

Time of measurements	^{137}Cs	^{90}Sr	$^{239,240}Pu$
1990	170.2 (4,600)	28.5 (770)	–
1991	167.2 (4,518)	35.4 (956)	0.81 (22)
2001	1.628 ± 25.9 (4,400 ± 700)	24.1 ± 4.81 (650 ± 130)	0.518 ± 0.148 (14 ± 4)

Table 2. Estimated radionuclide inventory in the ChNPP Cooling Pond bottom deposits in TBq (Ci) (Weiss et al. 2000).

Depth (m), characteristics of the bottom deposits	**Area, km^2, (%)**		**Average contamination density of the bottom deposits, TBq km^{-2} (Ci km^{-2})**			**Total radionuclide inventory, TBq (Ci)**		
			^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{137}Cs,	^{90}Sr	$^{239+240}Pu$
0-3.7 m, sand	3.4 (15.5%)	15.8 (72.3%)	1.39 (37.5)	0.204 (5.5)	0.007 (0.19)	4.74±0.37 (128±10)	0.7±0.2 (19±6)	0.11 (2.94)
3.7 - 7 m, sandy silt	12.4 (56.8%)		2.78 (75)	0.69 (18.7)		34.4±1.9 (930±50)	8.58±2.96 (232±80)	
0 - 6 m, discharge canal, silty sand	0.5 (2.2%)		7.4 (200)	5.92 (160)	0.007 (0.19)	3.7±1.48 (100±40)	2.96±1.30 (80±35)	0.03 (0.82)
7 – 13 m, silt with occasional sand, silt layers up to 10 cm thick	4.4 (17.7%)		74 (200)	0.69 (18.7)	0.059 (1.6)	32.6±9.26 (880±250)	3.03±1.48 (82±40)	0.03 (0.83)
Over 10 m, deep water areas, lutite silt over 30 cm thick	1.75 (7.8%)		50.06 (1353)	>4.92 (133)	0.203 (5.5)	87.3±18.5 (2360±500)	8.62±2.78 (233±75)	0.35 (9.6)

Table 3. ^{90}Sr and ^{137}Cs specific activity in samples of ChNPP Cooling Pond shoreline ecosystem, Bq g^{-1}.

Object of study	^{137}Cs					^{90}Sr				
	mean	**SD**	**min**	**max**	**n**	**mean**	**SD**	**min**	**max**	**n**
Area 1										
Amphibians	1.70	1.46	0.55	4.15	5	13.00	20.77	2.27	55.27	6
Birds (small)	2.16	3.68	0.04	22.86	85	6.60	9.48	0.06	50.87	91
Bottom deposits	23.88	24.21	5.78	69.40	6	11.62	18.55	0.29	48.23	6
Cereal crops	8.24	18.01	0.41	52.67	8	53.09	36.22	18.60	109.10	8
Small mammals	7.97	10.80	0.49	49.20	39	9.12	8.34	0.22	35.50	38
Cane	3.16	1.12	1.43	4.73	6	0.78	0.66	0.08	2.03	6
Reptilians	13.69		7.99	19.39	2	7.06		6.30	7.81	2
Soil (0-20 cm)	20.89	18.77	3.39	62.80	12	12.31	14.38	0.27	53.26	12
Arboreal leaves	14.73	14.61	0.59	38.67	11	253.03	126.58	5.93	451.53	11
Area 2										
Amphibians	20.49				1	32.11				1
Birds (small)	1.46	1.01	0.02	4.93	52	3.99	4.52	0.00	23.17	52
Bottom deposits	7.03	4.71	2.13	15.80	6	0.86	0.85	0.15	2.47	6
Cereal crops	2.99	2.61	1.22	10.33	11	127.02	72.13	3.38	235.47	11
Small mammals	16.84	30.20	0.29	151.69	40	12.89	10.32	0.52	55.16	40
Cane	0.96	0.47	0.63	1.88	6	0.48	0.13	0.26	0.64	6
Reptilians	3.56		1.35	5.77	2	2.09		0.42	3.77	2
Soil (0-20 cm)	35.04	37.24	0.07	107.00	12	16.23	16.65	0.06	52.57	12
Arboreal leaves	4.69	7.32	0.18	26.87	12	277.50	209.33	26.93	656.73	12
Area 3										
Birds (small)	0.35	0.32	0.01	1.63	40	2.78	7.26	0.08	46.88	44
Bottom deposits	3.10	1.64	1.57	6.04	6	0.37	0.58	0.09	1.55	6
Cereal crops	1.48	3.02	0.12	10.87	12	12.28	11.42	0.97	32.07	12
Small mammals	2.40	3.23	0.14	14.76	37	2.43	2.50	0.26	12.01	37
Cane	0.72	0.18	0.38	0.88	6	0.31	0.12	0.17	0.50	6
Reptilians	0.47	0.19	0.30	0.67	3	0.91	0.90	0.22	1.93	3
Soil (0 -20 cm)	2.84	2.22	0.15	6.29	12	1.37	0.94	0.22	3.20	12
Arboreal leaves	0.59	0.74	0.07	2.44	12	34.47	38.16	1.34	109.40	12

Table 4. Comparison between Concentration Ratios (CR) obtained from this study and ERICA assessments.

Species	CR	ERICA probabilistic assessment	CR	ERICA probabilistic assessment
	^{137}Cs		^{90}Sr	
Amphibians	1.03x10^{-01}	5.29x10^{-01}	5.36x10^{-01}	8.42x10^{-01}
Birds	3.94x10^{-01}	6.80x10^{-01}	4.31x10^{+00}	4.95x10^{-01}
Mammals	8.06x10^{-01}	2.81x10^{+00}	1.05x10^{+00}	1.64x10^{+00}
Reptilians	6.55x10^{-01}	3.67x10^{+00}	5.74x10^{-01}	1.10x10^{+01}

Table 5. Dose risk coefficient calculations for reference species in the ChNPP Cooling Pond shoreline areas for 2008 conditions.

Assessment criteria	Reference species			
	Amphibians	**Birds**	**Mammals**	**Reptilians**
Total dose rate, μGy hr^{-1}	11.4	6.3	15.1	10.3
Baseline dose rate limit, μGy hr^{-1}	40.0	40.0	40.0	40.0
Total dose rate associated with the most probable accumulation coefficient CR, μGy hr^{-1}	24.31	6.86	16.70	8.86
Expected risk coefficient, conventional units	0.607908	0.171658	0.417595	0.22153
Conservative values of the risk coefficient, conventional units	1.823723	0.514973	1.252785	0.66459

Table 6. Expected specific activity of radionuclides in soil, kBq kg^{-1} (dry mass).

Isotope	Specific activity
^{137}Cs	230
^{90}Sr	96
^{240}Pu	0.94
^{241}Pu	40
^{241}Am	2.5

Table 7. Predicted dose rates for biota and risk assessments associated with the evaporation of the ChNPP Cooling Pond.

Assessment criteria	**Reference species**			
	Amphibians	**Birds**	**Mammals**	**Reptilians**
Total dose rate, μGy h^{-1}	94.5	95.2	284.0	847.0
Baseline dose rate limit, μGy h^{-1}	40.0	40.0	40.0	40.0
Total dose rate associated with the most probable accumulation coefficient CR, μGy h^{-1}	2.36	2.38	7.11	21.2
Expected risk coefficient, conventional units	7.08	7.14	21.3	63.5

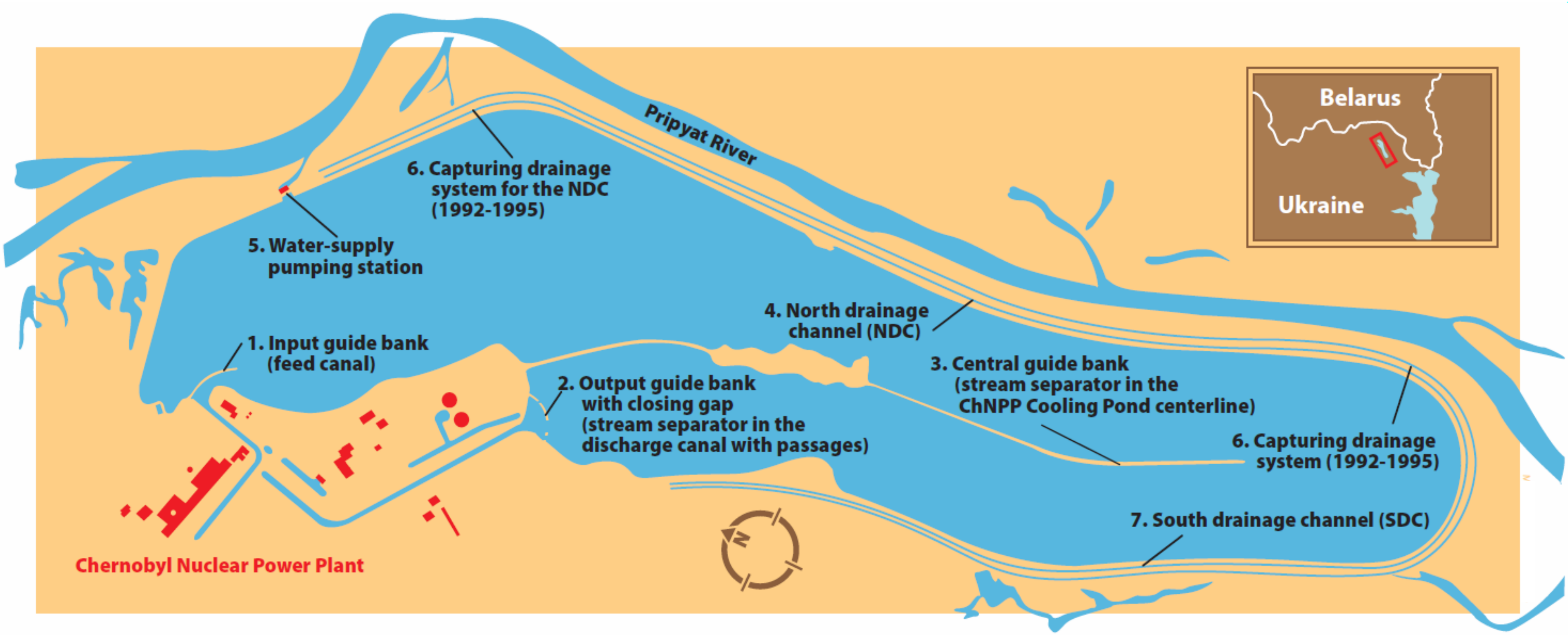


Fig. 1. General view of the ChNPP Cooling Pond.

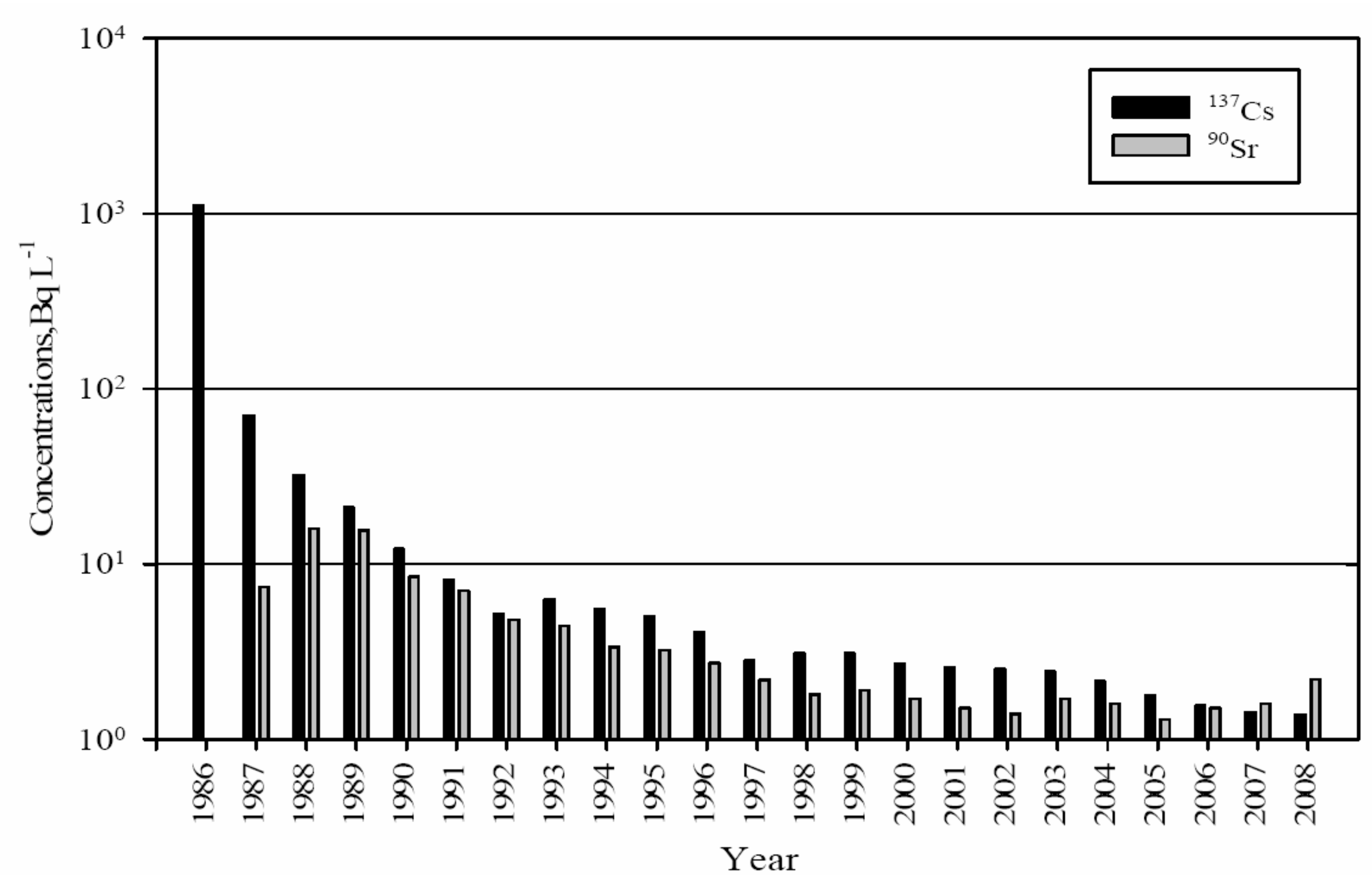


Fig. 2. Contamination profile of the ChNPP Cooling Pond water (Bondarenko et al. 2007).

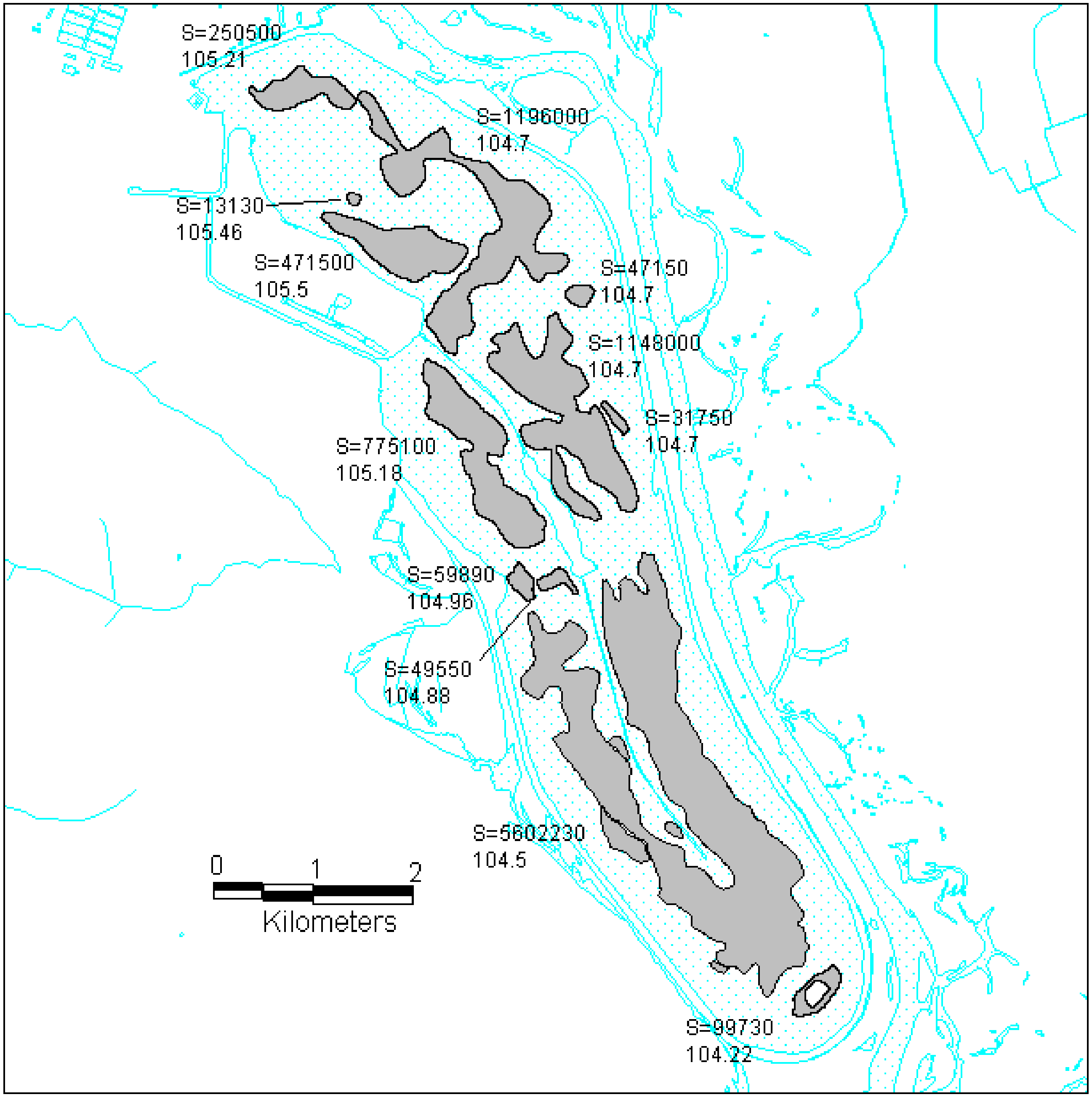
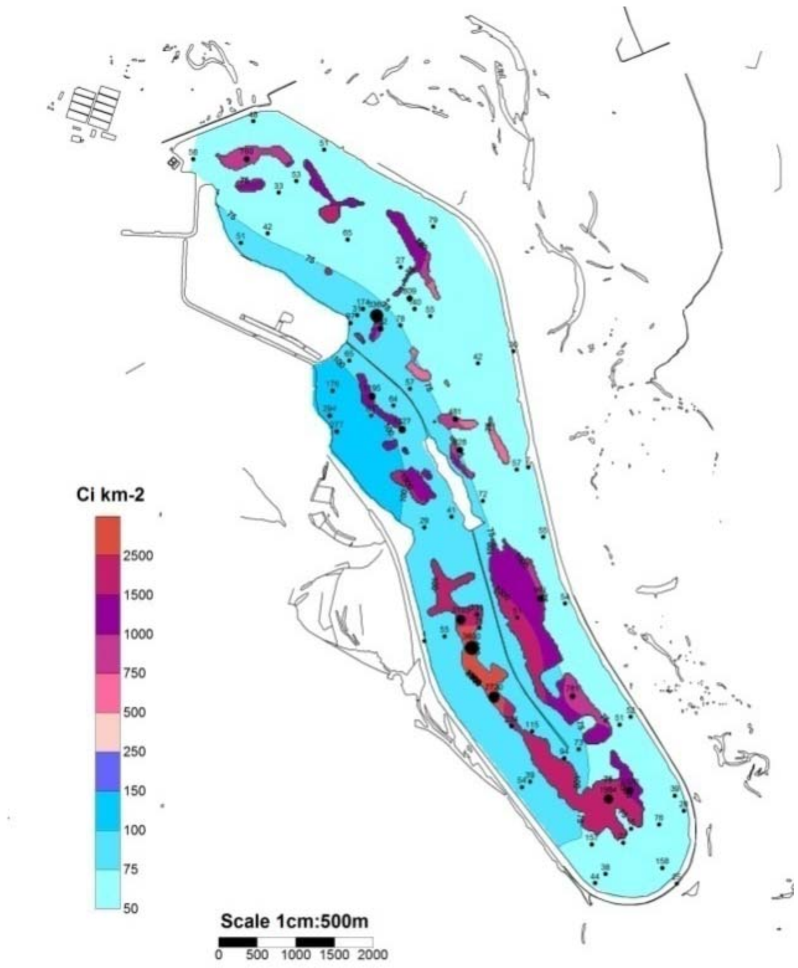
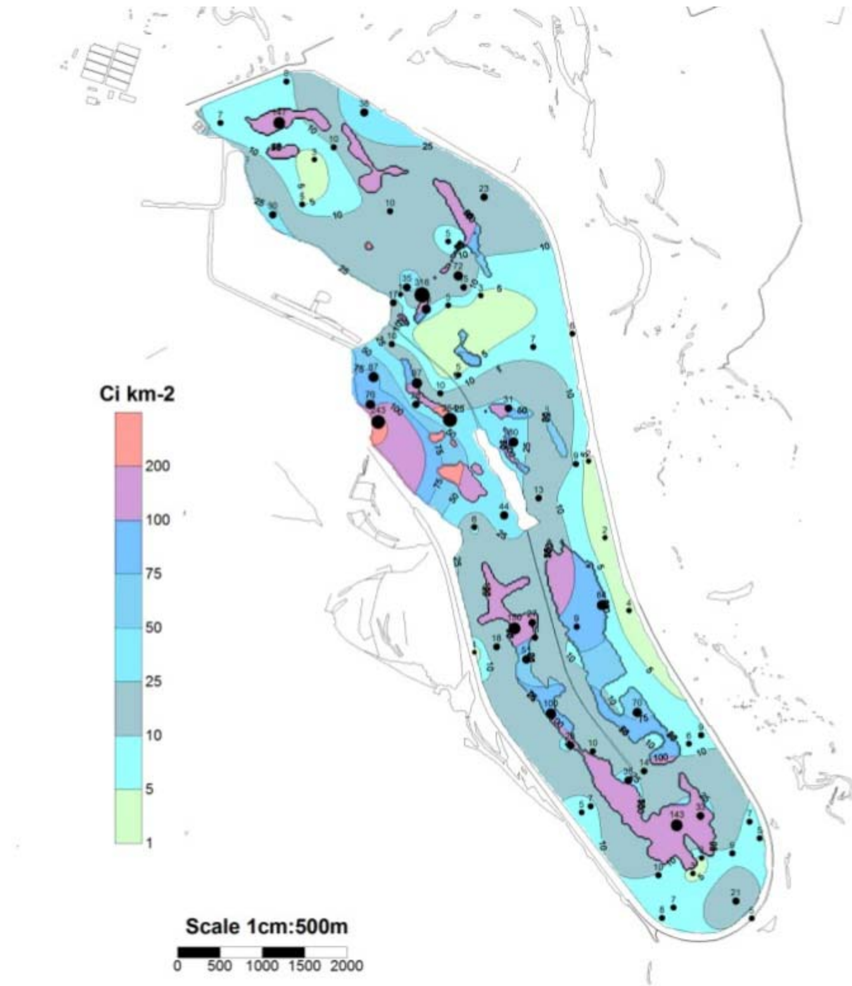


Fig. 3. Outlines of residual water reservoirs of the evaporated ChNPP Cooling Pond under the "normal" Scenario (the numbers indicate the areas of the residual water reservoirs in m2 and elevation in m).



^{137}Cs Contamination Density



^{90}Sr Contamination Density

Fig. 4. Radioactive contamination distribution for the ChNPP Cooling Pond bottom deposits (Weiss et al. 2000).