Long-Term Observation of Radioactivity Contamination in Fish around Chernobyl

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Abstract

Dynamics of ^{137}Cs accumulation by marketable fishes in different kinds of water bodies (cooling pond, water reservoir, lake) polluted by radionuclides after the Chernobyl accident has been studied. The highest concentration of ^{137}Cs, reaching 500 kBq/kg w.w. (wet weight) was registered in fish inhabiting the cooling pond of ChNPP in 1986. During the last 15 years the level of radionuclides in fishes of all water bodies came down, but rates of lowering are different. Peculiarities of ^{137}Cs accumulation by fishes depending on the trophic level have been revealed. During the first months after the Chernobyl accident the concentration of ^{137}Cs in peaceable species of fishes in Kiev Reservoir was by 10 times higher than in pike. After 1987 predatory fishes have the concentration of ^{137}Cs by 2-3 times higher than peaceable fishes. Higher indices have been marked in pike and large perches. By 2001 the content of ^{137}Cs in fishes in the cooling pond did not exceed 5 kBq/kg w.w., in River Teterev – 0.09 kBq/kg w.w., in Kiev Reservoir – 0.5 kBq/kg w.w. High content of ^{137}Cs remained in the lakes of Bryansk region of Russia and in Mogilev region of Belorussia, which have low content of +K in water and stagnant water, although these lakes are situated 100 - 200 km from the place of the accident. Biological effects of fishes in morphology of body and reproductive system have been marked in all studied water bodies. The largest quantity of abnormalities in the reproductive system has been marked in predatory fishes.

Introduction

The Chernobyl accident of 1986 resulted in contamination of many bodies of water around Europe. Three branches of radioactive plume dispersed radionuclides over northern, southern and western Europe. Radioactivity from man-made nuclides increased considerably in freshwater bodies of Scandinavian countries, England and in mountain lakes in Germany [1]. Forests and water bodies, located in close proximity of Chernobyl NPP (*i.e.* within 30-km zone) appeared to be the most heavily contaminated along with Gomel' and Mogilev region of Belarus, and Bryansk region in Russia [2,3].

A Combined Radioecological Expedition of USSR Academy of Sciences attached to the A.N.Severtsov Institute of Evolutionary Animal Morphology and Ecology (now A.N.Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences) started its activity in the field of radioecology of fish directly at the cooling pond of Chernobyl NPP in June, 1986. Later on, some other heavily contaminated bodies of water, such as Kiev Reservoir, River Teterev, Lake Kozhanovskoe (Russia) and Lake Svyatoe (Belarus) have been studied (Fig. 1).

The main objectives of our activity were:

(a) To study the dynamics of radionuclide accumulation in fish after the Chernobyl accident in different ecosystems such as cooling pond, river, lake, and reservoir;
(b) To reveal peculiar features of ^{137}Cs and ^{90}Sr accumulation in fish of different trophic level;
(c) To evaluate doses of radiation and to find out their biological effects in fish living under the influence of chronic irradiation.

Studied bodies of water differ by their hydrology, hydrochemistry and by the distance from the site of

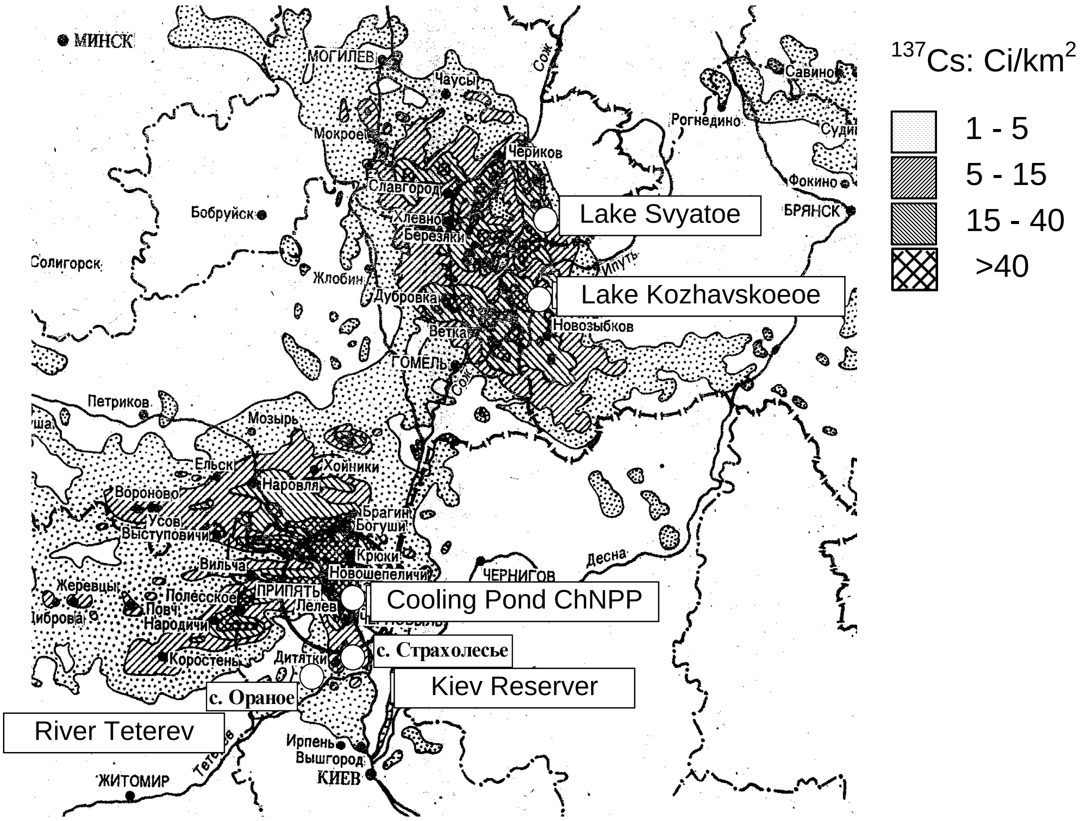

Fig.1. Regions of expedition activity at water bodies contaminated by radionuclides after the Chernobyl accident.

release (Table 1).

In all, 45 species of fish from 12 families and one species of Cyclostomata have been registered during multiple fish surveys (Table 2). The highest number of fish species was registered in River Teterev. Natural water bodies are populated by a set of species, typical of this part of Europe. Different from the natural bodies of water, the cooling pond of Chernobyl NPP was used before the accident as a raising pond for a fish farm and contained several introduced species. These were grass carp, silver carp and spotted silver carp of Chinese origin as well as North American bigmouth buffalo and bullhead. The isolated individuals of grass carp and silver carp may be found in Kiev Reservoir.

Altogether, more than six thousand individuals belonging to 46 species have been studied morphologically. More than four thousand samples have been analyzed in a laboratory of radiation spectrometry. Scintillometer RTF 20026 (made in Germany) has been used to evaluate the concentration of ^{137}Cs in different samples. Dose assessment has been done using the data on radionuclide concentration in muscles and the gut content of fish according to the method suggested by S.V.Kazakov [4], taking into account the main biological parameters, such as size and weight, of every studied individual.

Table 1. Hydrological and hydrochemical characteristics of studied bodies of water.

Water body	Area, km^2	Max. depth, m	Volume, m^3	Distance from ChNPP, km	K^+, mg/l	Ca^{++}, mg/l
Cooling pond of ChNPP	22	18	150×10^6	1.5	3.4-4.0	37.0-64.0
Kiev Reservoir	922	14.5	3.7×10^9	60	2.9-3.4	32.4-60.0
River Teterev	-	20	-	80	3.1-3.4	35.5-40.5
Lake Kozhanovskoe	6	2.5	9×10^6	210	2.6-2.7	24.6-44.3
Lake Svyatoe	0.25	5.1	7×10^4	225	0.9-1.0	17.4-19.8

Table 2. List of species Cyclostomata and fishes registered during work of the Complex Radioecological expedition of A.N. Severtsov Institute of Ecology and Evolution RAS.

	Species	Cooling pond	Kiev Reser-voir	River Teterev	Lake Kozha-novskoe	Lake Svyatoe
I. Petromyzontidae	1. Ukrainian lamprey - Eudontomyzon mariae (Berg) **x**	+		+		
II. Clupeidae	2. Common kilka – Clupeonella cultriventris cultriventris (Nord.)	+	++			
III. Esocidae	3. Pike – Esox lucius L.	+	+++	+++	+++	++
IV. Cyprinidae	4. Roach – Rutilus rutilus (L.)	+	+++	+++	+++	+++
	5. Dace – Leuciscus leuciscus (L.)	+	+	++		
	6. Chub - Leuciscus cephalus (L.)	+	+	++		
	7. Orfe Leuciscus idus (L.)	+	+	++		
	8. Rudd – Scardinius erythrophthalmus (L.)	+	+++	+++		+++
	9. Grass carp – Ctenopharyngodon idella (Val.) •	+	+			
	10. Asp - Aspius aspius (L.)	+	+	+		
	11. Verkhovka – Leucaspius delineatus (Heck.)	+	+	+		
	12. Tench Tinca tinca (L.)	+	+++	+		+
	13. Undermouth – Chondrostoma nasus (L.)	+	+	+		
	14. Stone moroco – Pseudorasbora parva (Temm. and Schl.) •	+	+	+		
	15. Gudgeon - Gobio gobio (L.)	+	+	+++		+
	16. White – finned gudgeon Pomanogobio albipinnatus (Lukasch)	+		+++		
	17. Bleak – Alburnus alburnus (L.)	+++	+++	+++	+	
	18. Bystranka – Alburnoides bipunctatus (Bloch) **x**			+		
	19. Silver bream -Blicca bjoerkna (L.)	+++	+++	+++	+	
	20. Bream – Abramis brama (L.)	++	+++	+++	+	
	21. White eye – Abramis sapa (Pall.)	+	+			
	22. Blue bream – Abramis ballerus (L.)	+	+	+		
	23. Vimba – Vimba vimba vimba (L.) **x**		+	+		
	24. Sabrefish - Pelecus cultratus (L.)	+++	++	+		
	25. Bitterlings - Rhodeus sericeus amarus (Bloch)	+	+	+++		++
	26. Crucian carp – Carassius carassius (L.)	+	+	+	+	+
	27. Golden carp - Carassius auratus gibelio (Bloch) •	++	+++	+++	+++	+++
	28. European carp – Cyprinus carpio L.	++	+	+		
	29. Silver carp – Hypophthalmichthys molitrix (Val.) •	+++	+			
	30. Spotted silver carp – Aristichthys nobilis (Rich.) •	+				
V. Catostomidae	31. Bigmouth buffalo – Ictiobus cyprinellus (Val.)	+				
VI.Cobitidae	32. Spiny loach – Cobitis taenia L.			+++	+	
	33. Loach – Misgurnus fossilis (L.)			+++	+	
VII. Siluridae	34. Wels - Silurus glanis L.	++	+	+		
VIII. Ictaluridae	35. Bullhead – Ictalurus punctatus (Raf.) •	+++				
IX. Gadidae	36. Burbot - Lota lota (L.)	+	+	+		
X. Gasterosteidae	37. Nine spined stickleback – Pungitius pungitius (L.)	+	+	+		
	38. Three spined stickleback – Gasterosteus aculeatus L.	+	+	+		
XI. Percidae	39. Sander – Stizostedion lucioperca (L.)		+++	+++		
	40. Perch - Perca fluviatilis L.	+	+++	+++	+++	+++
	41. Ruffe – Gymnocephalus cernuus (L.)		+	+	+++	+++
	42. Don ruffe – Gymnocephalus acerinus (Guld.)		+	+		
XII. Gobiidae	43. Monkey goby – Neogobius fluviatilis (Pall.)	+++	+	+++		
	44. Tube nosed goby – Proterorhinus marmoratus (Pall.)	+++	+	+++		
	45. Round goby – Neogobius melanostomus (Pall.)	+	+	+		
XIII. Syngnathidae	46. Black striped pipefhish – Syngnathus nigrolineatus (Eichw.)		+			

Note: + occurrence of different species +; low, ++; medium, +++; high,
•; species populated in reservoirs because of fishing measures; **x**; species carried in the list of rare fishes.

Cooling pond of Chernobyl NPP

Chernobyl NPP is situated in the eastern part of the natural region called Poles'e, which means "marshy woodlands", at the bank of River Pripyat, emptying into Kiev Reservoir. The source of water supply for plant operation was the cooling pond that was made artificially along River Pripyat and located at 1.5 km southeast from the power site.

The highest concentration of radionuclides, reaching 500 kBq/kg wet weight (w.w.) was registered in fish inhabiting the cooling pond in 1986. During the first months after the accident non-predatious fishes, feeding on zoo- and phyto-plankton, were the most contaminated, but later predatious fishes accumulated more radionuclides [5,6]. During the after-accident period the average concentration of radionuclides in silver carp decreased from 400 kBq/kg w.w. to 5 kBq/kg.

Aggregate dose for silver carp during the whole after-accident period reaches 10-12 Gy. Fish has absorbed the main part of irradiation dose, 7-8 Gy, during the first two years after the accident. In recent years internal dose was mainly obtained through intestine irradiation and amounted about 0.4 Gy per year, while internal dose for muscles averaged only 0.02 Gy per year (Fig. 2).

During special studies of reproductive organs of fish, different abnormalities in anatomy of gonads and morphology of reproductive cells have been found in silver carp. Gonad pathology included hermaphroditism, gonad asymmetry and other anatomical defect [7]. A number of fish, surviving the accident, had sterile gonads. Destruction of some amount of generative cells and contraction of generative tissue volume were registered in 48% of males. 35% of females had disturbances in oocyte morphology during vitellogenesis. In spite of various disturbances observed in generative organs, it was possible to obtain viable offspring from some fish in 1989-1990.

Silver carp, surviving the accident, could be easily bred, showing a high percentage of egg insemination and high survival rates for embryos, larvae and fry [8]. Anatomical abnormalities became apparent in the second and, especially, in the third year of life. There were curvature and length shortage of the dorsal or one of the pelvic fins, deformations of oral and gill structures, deformations of swim-bladder and epidermal neoplasia (*i.e.* tissue overgrowth) in anal region of females, forming a kind of genital papillae.

Ten individuals of silver carp, belonging to generation $F_{1\text{-}91}$, were analyzed in 1996 and only two mature carp have been found; a male and female. Unusual was the fact of their maturation at amazingly small size for this species; female was only 24 cm long, weighing 250 g, and a male was 31 cm long with a total weight of 461 g [9].

In 1991 during ichthyological survey of the cooling pond an abnormal young individual of tube-

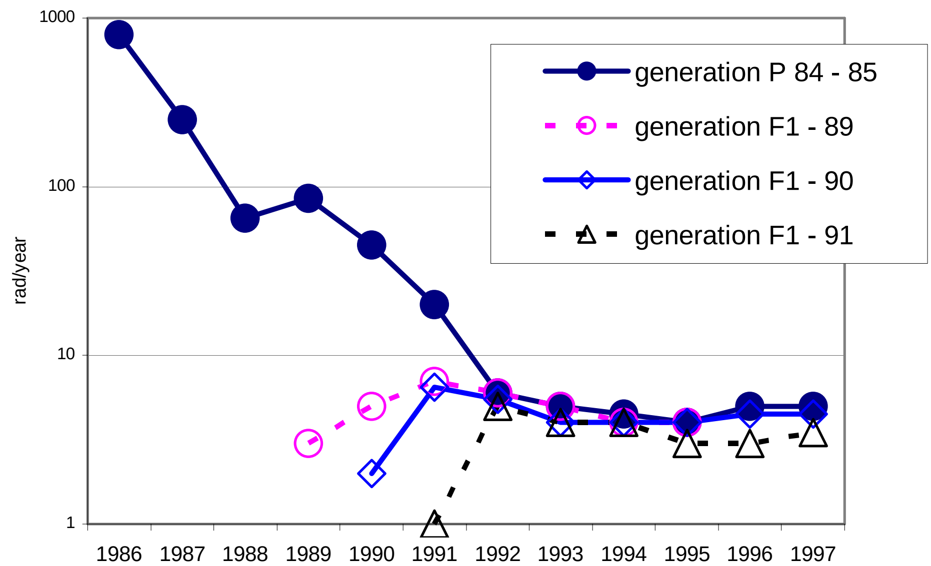

Fig.2. Internal committed dose for muscles of grass carp of different generations

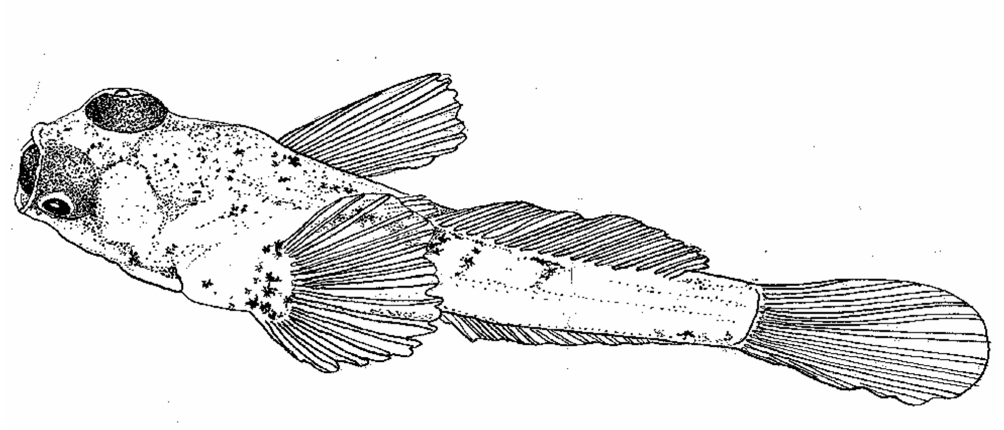

Fig.3. Abnormal fry of tube-nosed goby caught in the cooling pond of ChNPP (11.05.92).

nosed goby was found, having an eyeball developed inside the mouth cavity (Fig. 3). But the rest of the collected young fish of this species had no morphologic defects. During young fish collection in the cooling pond in 1992, a larval silver bream was found with spinal pathology and with primordial malformed pectoral fins. The larva was found among pondweeds and evidently could feed without swimming but keeping itself at the surface of weeds. It is obvious that individuals having such severe pathology cannot survive in the natural environment.

In spite of high dose rates during several years after the accident, no significant changes in fish community at population level have been observed. Comparison of the degree of abnormality in developing reproductive cells in both sexes reveals that structural damages are more pronounced in males than in females.

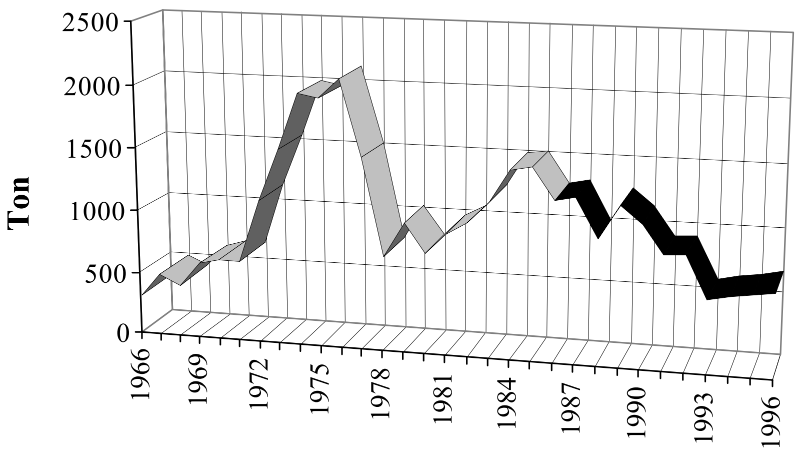

Fig.4. Dynamics of commercial catches in Kiev reservoir from 1966 to 1996.

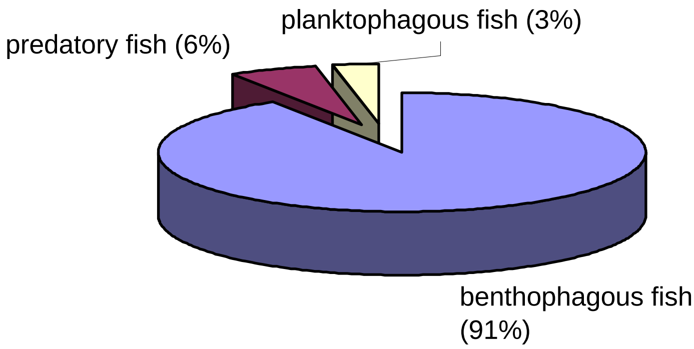

Fig. 5. Distribution of commercial fishes of Kiev Reservoir according to their food.

Kiev Reservoir

Kiev Reservoir is the first one in the Dnieper cascade into which run rivers Pripyat, Teterev and Uzh, flowing across the contaminated areas. During the after-accident period of 1986-1996, 10,245 ton of fish were harvested in Kiev Reservoir. Such benthophagous species as bream, roach, silver bream and European carp formed more than 90% of the total catch (Fig. 4, 5).

Radioecological monitoring of Kiev Reservoir revealed a decrease of ^{137}Cs concentration in muscles of predatory fish from 1500-2000 to 200-400 Bq/kg w.w. during 1987-2000 (Fig. 6, 7). But in the autumn of 2001, perches were met having 550 Bq/kg w.w. In muscles of non-predatory fish, constituting the bulk

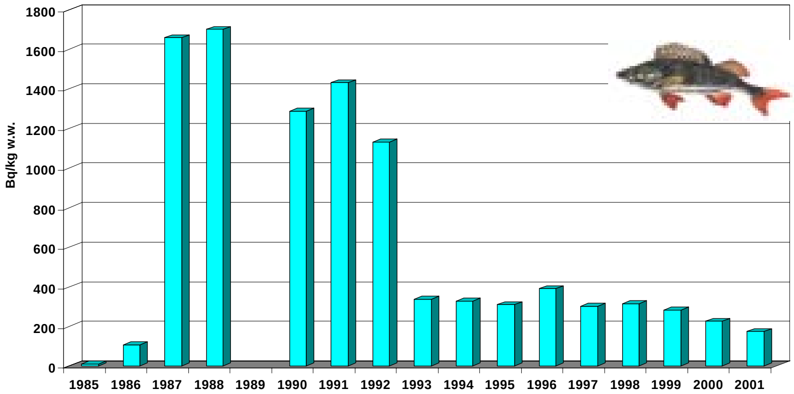

Fig. 6. Dynamics of Cs-137 accumulation in muscles of perch from Kiev reservoir

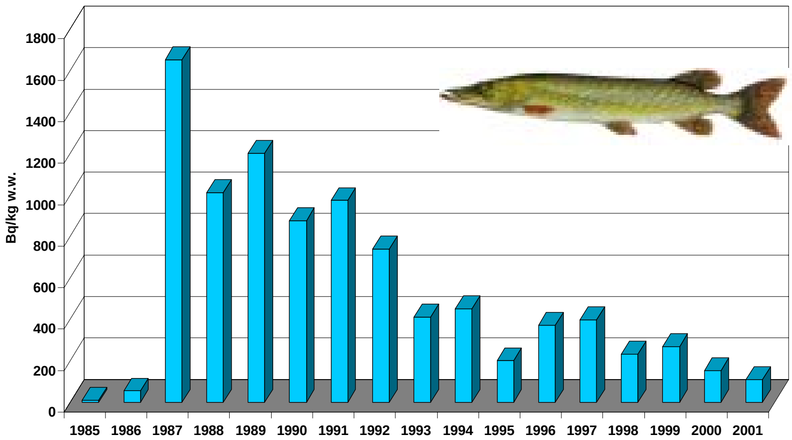

Fig. 7. Dynamics of Cs-137 accumulation in muscles of pike from Kiev reservoir

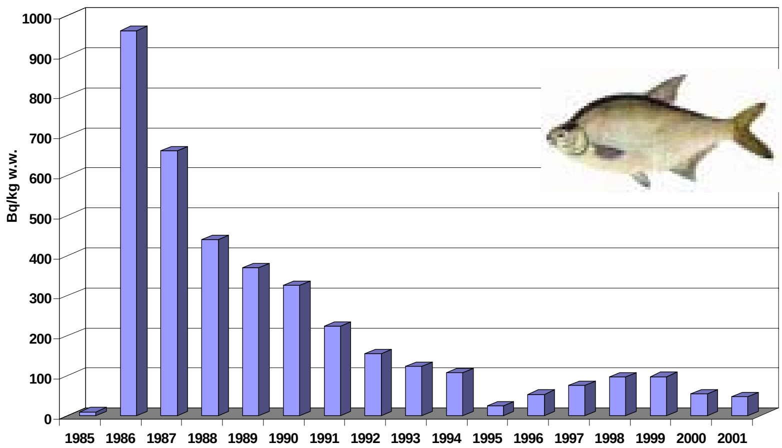

Fig. 8. Dynamics of Cs-137 accumulation in muscles of bream from Kiev reservoir

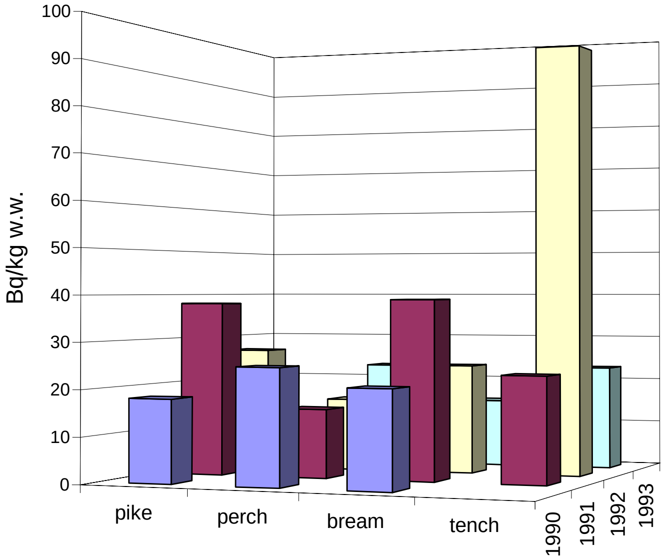

Fig. 9. Dynamics of Sr-90 accumulation in muscles of fish from Kiev reservoir

Table 3. The incidence of gonad malformations in pike females of different generations, (%).

Year of generation origin	Type of gonad malformations		
	Gonad asymmetry	Grain of roe resorption	Gonad hydration
1986	20.0	20.0	20.0
1987	33.3	0	16.6
1988	45.0	0	9.0
1989	0	0	0
1990	29.0	0	0
1991	46.0	23.0	0
1992	40.0	40.0	0
1993	65.0	10.0	0
1994	13.0	13.0	0
1995	33.0	22.0	0
1996	17.0	17.0	0

Note: the data on the before-accident generations are not cited because of their scarcity.

of commercial catch, bream for example, the concentration of ^{137}Cs was two-three times lower than in predators; pike and perch (Fig. 8). In the autumn of 2001, the highest figures for ^{137}Cs in bream muscles ranged between 40 and 70 Bq/kg w.w., averaging 55 Bq/kg.

Fishes of different trophic levels also accumulate in their muscles different amounts of ^{90}Sr, sometimes equivalent to 100 Bq/kg w.w. In 1991-1993 radionuclide concentration in muscles of bream, the main commercial fish species, ranged between 15 and 50 Bq/kg w.w. (Fig. 9).

In order to evaluate the biological effect of deposited radionuclides on fish from Kiev Reservoir, 209 pikes, belonging to 17 generations, have been analyzed during 1987-2000. Three types of abnormality in morphology of the reproductive system were registered: gonad asymmetry (34.1%), total resorption of eggs (12.5%) and gonad hydration (2.5%). Gonad asymmetry, the most common imperfection, was frequently accompanied by constrictions. There were instances that the weight difference between right and left gonad lobes was very high. Most frequently, this difference ranged from 1.5 to 3.0 times [10].

The first maximum in the number of malformations was observed in pikes born in 1986-1988. Another rise in malformation number was noted for the second after-accidental pike generation born in 1991-1993 (Table 3). In pike females, born before the accident in years 1982-1985, no gonad abnormalities was found, but one individual with asymmetric gonads, belonging to the generation of 1981, has been registered.

In 1986 internal dose from ^{137}Cs and ^{134}Cs for pikes in Kiev Reservoir was about 0.1 – 0.2 Gy, in 1993-1997 it decreased to 0.001 – 0.002 Gy per year.

Lake Kozhanovskoe

During water bodies monitoring in Bryansk region, scientists from Combined Radioecological Expedition of USSR Academy of Sciences in 1993 discovered abnormally high content of ^{137}Cs in fishes from Lake Kozhanovskoe. This lake, located at a distance of 210 km from Chernobyl NPP, has a square about 6 km^2, average depth of 1.5 m, maximum depth of 2.5 m. Lake sides are swampy and overgrown with coastal vegetation. Its bottom is covered with thick sapropel deposits. According to limnological classification, this lake may be attributed to eutrophic type. The concentration of K^+ in water varies from 2.6 to 2.7 mg/l during a year, and the concentration of Ca^{++} is from 24.6 to 44.3 mg/l. One liter of lake water during different seasons of 1993 contained ^{137}Cs activity from 6.1 to 8.5 Bq. The lowest index was registered in autumn. Seasonal measurements of pH showed the lowest figure for March (5.8) and the highest (7.7) – for autumn [11].

Eleven species of fish were registered in the lake. They were: pike, roach, bleak, silver bream, bream, crucian carp, golden carp, spiny loach, loach, perch and ruffe. Golden carp is dominating species. The concentration of ^{137}Cs in different fish species changed depending on their trophic level and size. The highest figure, equivalent to 70 kBq/kg w.w., was registered in 1993 for big pike, and the lowest, from 5 to 8 kBq/kg w.w., for ruffe and roach. The concentration of ^{137}Cs in muscles of golden carp, the main commercial fish species in the lake, ranged from 6.5 to 15.6 kBq/kg w.w., being 10.4 kBq/kg in average. The concentration of ^{90}Sr in this species varied between 160 and 530 Bq/kg w.w. with the average figure of 260 Bq/kg w.w. At the same time, in River Iput', very close to Lake Kozhanovskoe, the concentration of ^{137}Cs was almost 100 times lower.

According to the data of 2000, the content of ^{137}Cs in fish flesh was retained at the level of 1993, and for golden carp averaged at 8.14 kBq/kg w.w. Main factors, determining such high level of fish contamination with radionuclides in Lake Kozhanovskoe, are the high content of radiocesium in lake water and, accordingly, in feeding objects of fish, as well as low water exchange in the lake and the low content of K^+ in lake water.

Taking into account that the permitted level of ^{137}Cs content in fish products in Russia is 120 Bq/kg w.w. [12], it can be suggested with certainty that for such lakes as Kozhanovskoe with internal drainage, fish purification up to the permitted level will take 60-90 years, *i.e.* two-three half lives of ^{137}Cs and ^{90}Sr.

Analyses of gonad condition revealed that serious disturbances in gonad morphology were found only in predatory fish; pike and perch. In other species, like roach and golden carp, only small amount of germinal cells was damaged [13].

River Teterev

River Teterev flows across Kiev region of Ukraine at a distance about 80 km from ChNPP. Contamination of the river with radionuclides happened primarily by radioactive fallouts from the atmosphere just after the accident, and later, as a result of wash out of radionuclides from the contaminated river watershed. Ichthyofauna of lower reaches of the river, around settlement Oranoe, is very similar to that of Kiev Reservoir and includes 38 species. The river supports active but mainly illegal fishing by local peasants.

The highest indices of ^{137}Cs content during study period (1990-2001) were registered for predatory species; pike and perch. Monitoring of the contamination dynamics in pike revealed maximal levels of ^{137}Cs concentration in the first year of investigation in this region (1990) with the average value in muscles of 728 Bq/kg w.w. In the summer of 2001 this index became 7-8 times lower with the average figure of 90 Bq/kg w.w. (Fig.10).

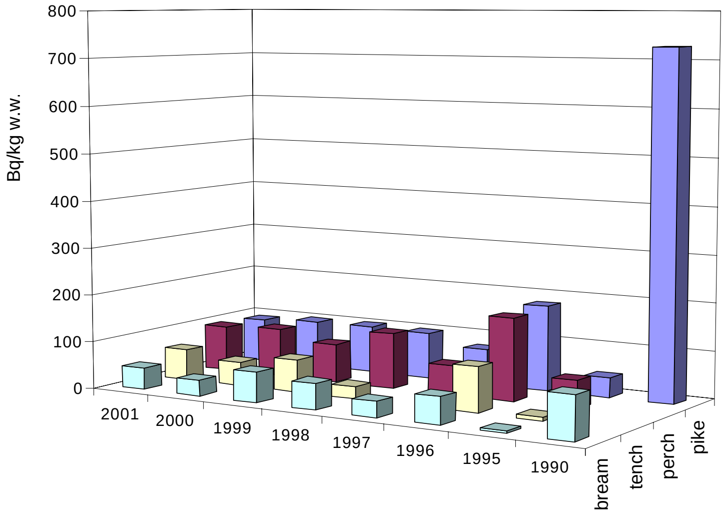

Fig.10. Average concentration of Cs-137 in different species of fish from river Teterev

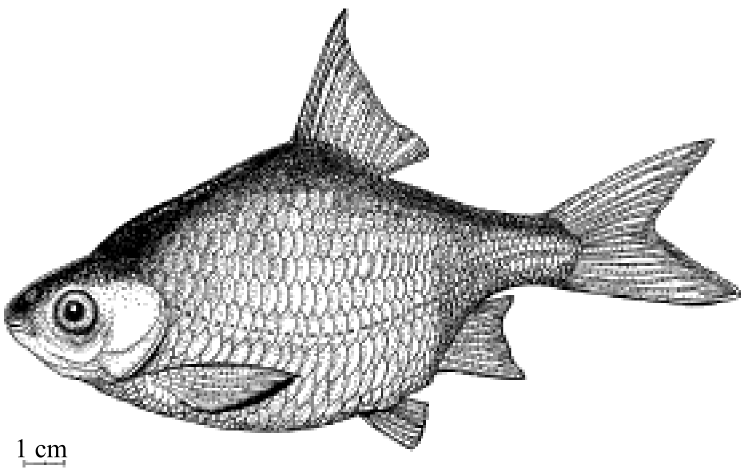

Fig.11. Abnormal roach from river Teterev, SL – 183 mm, age – 6+, caught in February 1998.

Several morphologically abnormal fish have been found during regular surveys of River Teterev. Four abnormal roaches were caught in 1998. One of them had unusual body proportions – caudal peduncle was very short, and relative body depth was almost twice higher than in normal fish (45% of standard length). The age of the fish was 6+ years and it represented, most likely, the second after-accident generation (Fig. 11). One more abnormal individual, aged 10+ had deformed scales. The rest two fish had anomalies in body proportion combined with damages of scales. One of these fish in its right pelvic fin had two more soft rays as compared with the left pelvic fin.

During next three years, 1999-2001 no more fish bearing morphological deformities were found in River Teterev.

Lake Svyatoe

Studies of this lake, situated in Mogilev region of Belarus, have been launched in 1997 [14]. It turned out that in this lake, located at the distance of 225 km from Chernobyl Power Plant, the concentration of ^{137}Cs in muscles of perch was equivalent to activity of 120 kBq/kg w.w. It was twice bigger than in muscles of predatory fish from lake Kozhanovskoe and 24 times higher than in muscles of fish from the cooling pond of ChNPP. Activity of ^{137}Cs in muscles of non-predatory fish such as roach and rudd achieved 15 – 20 kBq/kg w.w.; their average values are 15.3 and 14.8 kBq/kg w.w., respectively (Fig. 12). Maximum accumulated dose was found in perch to be 0.4 Gy per year.

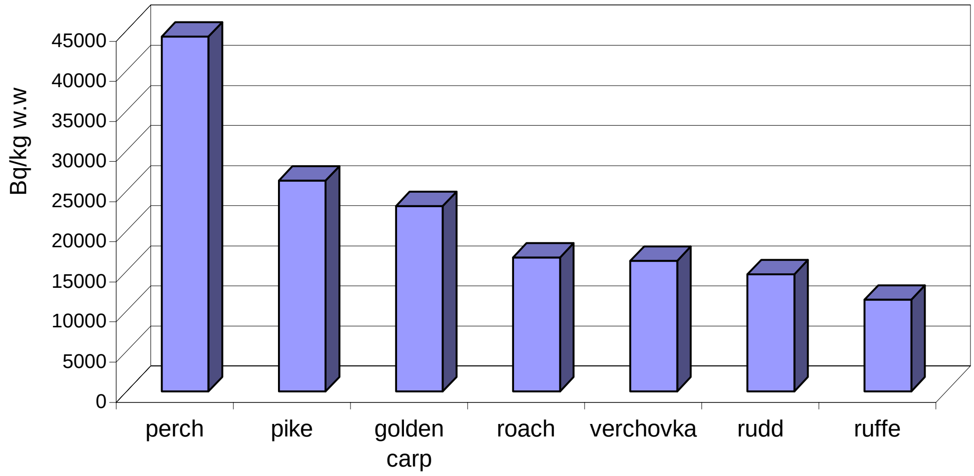

Fig.12. Average concentration of Cs-137 in different species of fish from Lake Svyatoe in May,1998

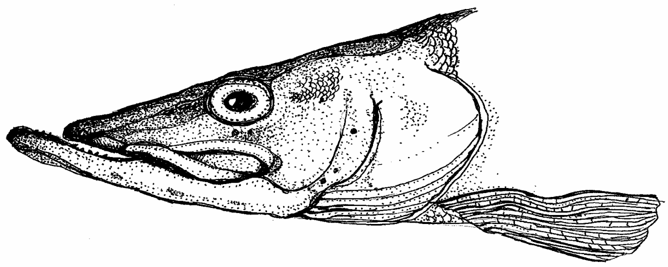

Fig. 13. Head of pike with deformed upper jaw and pectoral fin rays SL – 453 mm age – 4+. Lake Svyatoe, Mogilev region, Belarus, 16.05.98.

During fish survey of Lake Svyatoe in May 1998 only one pike was caught. It was four years old and had several anatomical defects: shortened upper jaw (Fig. 13) and four deformed rays in the left pelvic fin. Gonad imperfections included gonad asymmetry and constrictions in the right gonad. Calculated internal dose for this pike was 2.5 Gy for all its life. One of the reasons of morphologic deformities in the after-Chernobyl fish generations may be the phenomenon called "extended mutagenesis". It means that mutations are manifested in the offspring of parents, subjected to some negative influence. In our instance, the initial impacts were given during the first days after the Chernobyl accident in 1986.

Conclusion

A considerable reduction of radionuclide content in fishes, inhabiting the most part of contaminated bodies of water, took place during 15 years, passing from the time of the Chernobyl accident. After 1993, the concentration of ^{137}Cs in flesh of fish, living in rivers and reservoirs, does not exceed 600 Bq/kg w.w. Only the cooling pond of ChNPP and some lakes in Russia and Belarus are the exception [15].

The rate of fish decontamination from radionuclides is connected with the initial amount of deposited radionuclides, and also with hydrology and hydrochemistry of the water body. Main reasons for the high concentration of ^{137}Cs in water, sediments and fish of Lake Kozhanovskoe are low content of K^+ in water and very slow water exchange. High level of contamination of this and some other lakes can last tens of years, decreasing only as a result of natural decay of ^{137}Cs with half-life about 30 years. Since the rate of natural decontamination of Lakes Kozhanovskoe and Svyatoe is very low, the process of fish decontamination or "purification" may also take several tens of years.

Predatory fish concentrate 2-3 times more ^{137}Cs than non-predatory ones; in the process of ^{90}Sr accumulation this effect of trophic level is not expressed so evidently.

Biological diversity of fish in water bodies contaminated as a result of the Chernobyl accident does not show significant changes, but the abundance of some species, representing the highest trophic level, may decrease during the next 10-20 years because of disturbances in their reproductive system.

Considering the lack of proven practice and even any experience in rehabilitation of large fishery bodies of water such as rivers, lakes and reservoirs, there is a need in urgent development of scientific recommendations for safe and rational fishing and fish processing in contaminated bodies of water, with the help of international scientific community.

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