LAKE KARACHAY AS A SOURCE OF GROUNDWATER POLLUTION

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ABSTRACT

The purpose of this Bachelor's thesis was to study the problem of groundwater contamination by radionuclides in Lake Karachay which is an industrial reservoir V-9 of the Mayak Production Association, the first and largest enterprise in the fuel and energy complex in Russia.

For more than 50 years, the reservoir was used to discharge liquid radioactive (including highly radioactive) waste from the enterprise, which led to large-scale radioactive contamination of Lake Karachay and the surrounding area. Despite the fact that in 2015 the water area of V-9 was completely eliminated, the migration of radionuclides into groundwater continues. This led to the relevance of this study to improve environmental safety measures of nuclear industry enterprises.

The theoretical methods used in the thesis were analysis, synthesis, classification, generalization and forecasting.

Based on the study of scientific literature and other open sources, a comprehensive analysis of the causes and consequences of pollution of Lake Karachay with radioactive waste was carried out, ways to solve the problem of radioactive pollution and further prospects of the ecological state of the region were considered.

Based on the study carried out in the thesis it can be concluded that the main production facilities of Mayak Production Association have created a large amount of liquid radioactive waste, a significant part of which has been dumped into Lake Karachay for a long time, leading to a severe radioactive pollution of the lake's open body and the groundwater of the region. The elimination of Lake Karachay made it possible to exclude both the probability of aerosol dispersal from the surface of the water area and the lake shores, as well as the possibility of a significant influx of radionuclides into the open hydrographic network through groundwater.

Keywords Pollution, environment, radiation

Pages 55 pages

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1. INTRODUCTION

One of the main dangers that mankind has encountered when using nuclear fission energy is the problem of biosphere contamination by radionuclides.

The activities of the nuclear industry are characterized by a high consumption of water resources. The reservoirs used in the technological cycle serve not only as a source of water for production needs, but also as dumping sites for radioactive and other types of liquid waste. The highest levels of radioactive contamination of industrial reservoirs in Russia and, probably, around the world, belong to the technological water reservoirs at «Mayak» Production Association («Mayak» PA), the first industrial complex specialized in production of weapons-grade plutonium in Russia, which began its operation in June 1948 in the north of the Chelyabinsk Region. (Smagin, 2008)

The «Mayak» Production Association was built immediately after the end of World War II to solve the unprecedentedly complex scientific, technical and production tasks of creating nuclear weapons in the Soviet Union. Extremely high rates of unique technological equipment development, construction and commissioning of new industries, lack of scientific knowledge and technological experience have created serious problems in the field of environmental protection and human health. In conditions of acute shortage of resources and time, simplified schemes for managing radioactive waste were adopted. (Larin, 2001)

As a result of the discharge of liquid radioactive waste into water reservoirs, as well as several radiation incidents that occurred in the first decades of production, there was extensive radioactive contamination, the effects of which are still visible even today. In the area of «Mayak» PA, a technogenic radionuclide geochemical anomaly, the East Ural Radioactive Trace (EURT), was formed. Numerous lakes located in the zone of influence of the enterprise were exposed to radioactive contamination. The maximum levels of radioactive contamination belong to the liquid waste storage reservoirs, and, in particular, to Lake Karachay (V-9). The long-term nature of the pollution was determined by the most biologically dangerous long-lived radionuclides $_{90}$Sr and $_{137}$Cs. (Smagin, 2008; Dmitreva, 2012) The problem of deactivation of numerous bodies of water contaminated with radionuclides remains unsolved. (Dmitreva, 2012)

Lake Karachay, despite the fact that in 2015 its water area was completely liquidated, remains a source of radioactive pollution of the environment near FSUE «Mayak» PA. As a result of filtration, radioactive and chemical pollution of groundwater around the reservoir occurs, therefore, the problem of studying groundwater pollution by radionuclides from Lake Karachay is relevant up until this day.

2. CHARACTERISTICS OF THE MAYAK ENTERPRISE

The Federal State Unitary Enterprise “Mayak Production Association” (FSUE “Mayak” Production Association) is the largest nuclear fuel cycle enterprise in Russia, which incorporates radiochemical, radioisotope, reactor, and chemical and metallurgical production. (Slyunchov, 2004)

The company was set up in the late 1940s of the last century to obtain weapons-grade plutonium and the processing of fissile materials. At present, the production of weapons-grade plutonium has been discontinued, and civilian production of the nuclear fuel cycle, radioactive sources and drugs has been established. (Obninsk, 2019)

2.1 History reference

The Government of the USSR decided to begin to work on the creation of atomic weapons in 1943. Organizational and survey work began to be carried out to create the scientific and technical base of the nuclear industry. (Larin, 2001)

In 1945, in order to implement an atomic project to ensure the country's defense and security, the government of the Soviet Union decided to create one of the special industrial facilities in the South Urals, now known as the Mayak Production Association. The decree adopted by the Soviet government on December 1, 1945 defined the site for the construction of the first reactor plant, plant number 817 (the future chemical plant Mayak). On April 24, 1946, the general construction plan was approved, and after 26 months, on June 19, 1948, the launch was carried out. The first Eurasian uranium-graphite industrial nuclear reactor was founded to produce weapons-grade plutonium; for reasons of secrecy, it was designated as the industrial reactor "A" ("Annushka"). The operation of the 100 MW reactor was carried out with a direct flow-through water cooling system. It was stopped on June 16, 1987.

In addition to the reactor production, the project included a radiochemical plant (facility B), which was put into operation on December 22, 1948, a chemical and metallurgical plant (facility B), launched on February 26, 1949, as well as other industries, which formed a powerful nuclear weapons complex. At the radiochemical plant (facility B), the second stage of plutonium production was carried out - the processing of uranium irradiation in the reactor.

On February 26, 1949, the first batch of plutonium in the form of liquid paste, the final product of facility B, was received for further processing at a chemical and metallurgical plant.

The final stage in the creation of the Mayak chemical plant was the organization of a unique in its complexity experimental-industrial chemical-metallurgical and foundry-mechanical production of ultrapure metallic plutonium and the manufacture of nuclear charge parts needed for the first Soviet atomic bomb.

It was necessary to bring plutonium to a spectrally pure state, turn it into metal, give it an appropriate shape, and fabricate a charge for the atomic bomb. In June 1949, the required amount of plutonium was obtained for the manufacture of the atomic bomb, the tests of which were passed on August 29, 1949 at the Semipalatinsk test site. (Bochkareva, 2018)

The second reactor AB-1 was launched in April 1950. Altogether, seven reactors were put to full capacity for the production of weapon-grade plutonium. By the mid-60s the combinate consisted of three plants and a total of eight atomic reactors. The last atomic reactor at PA Mayak was shut down on the 1st of November, 1990.

In 1955, a pilot industrial workshop was established for the production of radioactive isotopes, and on June 8, 1962, a factory for the production of radioactive isotopes began its operation.

In 1959, a new radiochemical plant was built and commissioned. It had distinct advantages over the old plant. The rational placement of more advanced equipment was provided; technological processes were controlled remotely and the personnel radiation protection system underwent radical changes. (Bochkareva, 2018)

In 1977, the RT-1 complex was put into operation on the basis of the first radiochemical plant for the processing of fuel elements containing spent nuclear fuel. The nuclear fuel regeneration capacity was 400 tons per year. In the 1980s, the Ruslan reactors (03/09/1982) and LF-2 (02/05/1988) were commissioned.

On June 25, 1991, the first furnace was launched in the active liquid waste vitrification workshop. This furnace was eventually shut down in 1997.

In 2003, a fissile material repository (CDM) was commissioned. In 2010, commissioning of the first stage of the all-alloy sewage system took place. In 2012, the Lf-2 reactor installation was modernized in order to extend the operation. On November 25 in 2015 work was completed to eliminate the water area of the special industrial water reservoir Karachay.

In 2017, the industrial processing of VVER-1000 SFAs, as well as the construction of the New Source facility, were launched.

In 2018, a branch (an enterprise of FSUE Bazalt) was joined to FSUE PA «Mayak». (Larin, 2001)

One of the modern problems of the enterprise is the elimination of nuclear heritage, which mainly consists of facilities that no longer meet modern requirements of nuclear and radiation safety. The territory of FSUE PA Mayak includes 5 industrial uranium-graphite reactors; 8 objects of industrial reservoirs, 45 objects of industrial buildings and structures withdrawn from technological processes, 167 objects of mothballed storage facilities and repositories of solid radioactive waste.

2.2 Location of FSUE PA Mayak

When designing the plant, a sparsely populated place with a large amount of water resources and not very distant infrastructure was chosen. The large industrial center of Chelyabinsk with a developed metallurgical and machine-building industry and a railway fully met the conditions. An industrial site near the city of Ozersk was chosen for the construction of the plant. (Muratov, n.d.)

FSUE “PA Mayak” is located in the north of the Chelyabinsk region, 70 kilometers from the city of Chelyabinsk, on the territory of the closed administrative-territorial formation of the Ozersk city district, near the cities of Kyshtym and Kasli. The official name of the city of Ozersk, in which the most of the plant’s personnel lived, was approved on January 4, 1994 by an order of the Russian government. Previously, the settlement had different names, the most used among which was Chelyabinsk-65.

The industrial site of FSUE PA Mayak, the border of which coincides with the external border of the sanitary protection zone, covers an area of around 247.8 km^2. (Obninsk, 2019)

The company is located on the eastern slope of the South Urals. The territory of the location is a slightly wavy plain with a general direction of the slope to the east, a watershed of up to 250 m. The site is located between the Techa and Michelyak rivers, surrounded by lakes Ulagach, Tatysh and surface water bodies - storages of liquid radioactive waste. (Belkin, Ivanov & Tananev, 2016, p.58-65)

In accordance with the requirements of NRB-99/2009 and OSPORB-99/2010, a sanitary protection zone with an area of 248 km^2 and an observation zone with an area of 1800 km^2 were established around the industrial zone of the enterprise. The dimensions of this zone were agreed with the Sanitary Inspection authorities. (FMBA of the Russian Federation) Within the sanitary protection zone, the boundaries of which coincide with the boundaries of the industrial site, there are many settlements, separate residential buildings and social facilities.

The influence zone of PA Mayak is comprised of a sanitary protection zone, a surveillance zone and zones of accidental pollution: the EURT, the cesium trace of 1967, and the floodplain of the Techa river. (Federal Center for Hygiene and Epidemiology of Rospotrebnadzor, 2009; Gosatomnadzor, 2010) The East Ural Reserve is a territory contaminated after the 1957 accident. All plants are located in the sanitary protection zone and are spread over rather large distances (Figure 1).

Figure 1. Location of FSUE PA Mayak. (Muratov, 2017)

2.3 Structure of FSUE PA Mayak

FSUE PA Mayak is a part of the State Atomic Energy Corporation «Rosatom» and is a production complex that includes a reactor, chemical, chemical and metallurgical, radiochemical, radioisotope production, instrument-mechanical plant, an environmental protection service, «Bazalt» branch and a number of support units. (Ozersk: RIC VRB; Printing house of FSUE PA, 2019)

Figure 2 below represents a structural diagram of the units of the "Mayak " PA.

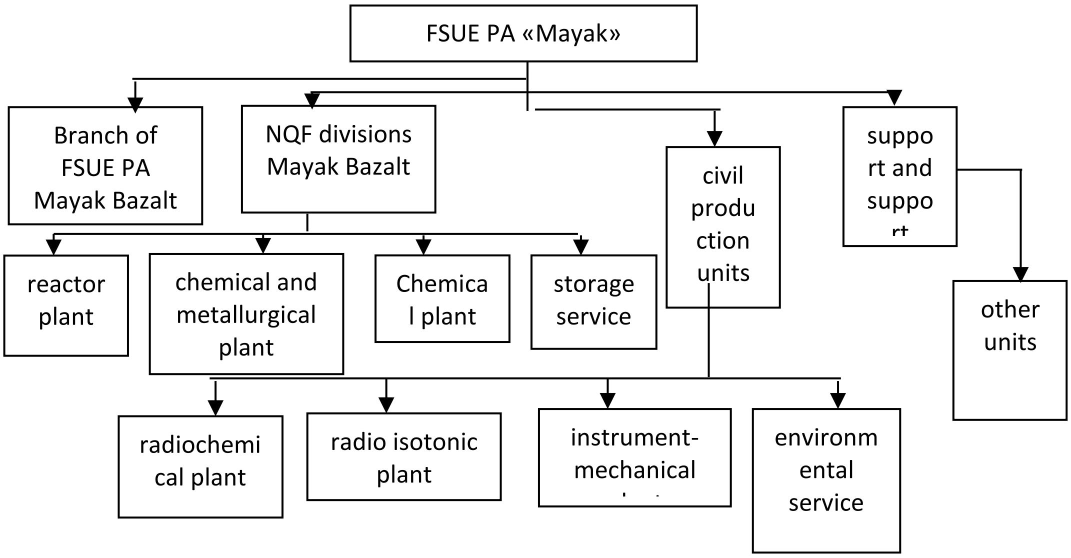


Figure 2. Structural subdivisions of PA «Mayak»

Reactor production of the Mayak Production Association is the only industrial reactor complex in the country that has the technologies for developing the products of the State Defense Order necessary for the nuclear weapons complex of the Russian Federation.

Two operating reactors - light-water RUSLAN and heavy-water LF-2 possess unique neutron-physical characteristics, which make it possible to obtain a wide range of radioactive isotopes for military and civil purposes. At present, the reactor plant is a platform for the implementation of the project for the construction of a new multifunctional reactor complex with an industrial reactor inside of it.

In addition to the existing reactor facilities, the reactor complex of the enterprise includes five shutdown industrial uranium-graphite reactors - A, AI, AV-1, AV-2 and AV-3, which are currently in the mode of long after-service soaking and preparation for decommissioning.

Chemical production is one of the main divisions of the nuclear weapons complex of the enterprise. PA «Mayak» is the only serial manufacturer of the entire range of special products in its direction for state defense orders.

Chemical and metallurgical production ensures the implementation of the state defense order for the development of special products. The plant also processes recycling of special items as part of a program for the disposal of excess weapons-grade nuclear materials. The plant successfully participated in the Russian-American "Megatons to Megawatts" program. Since 2014, the enterprise has been developing the entire range of products for fulfilling the state defense order.

The main objectives of radiochemical production are the reception, temporary storage and processing of various types of spent nuclear fuel. RT-1 Plant is the only nuclear fuel regeneration enterprise in Russia. Due to the joint work of the enterprise and TVEL JSC, one of the most important achievements in the nuclear industry has been achieved - the closure of the nuclear fuel cycle. Uranium regenerates obtained at the RT-1 plant and delivered to the fuel company enterprises have been returning to the energy sector in the form of “fresh” fuel for many years.

Currently, the plant is reprocessing spent nuclear fuel (SNF) from power reactors of nuclear power plants (VVER-440, BN-600, RBMK-1000), research reactors of Russian and foreign scientific centers, as well as transport power plants of the underwater and surface marine fleet. An important aspect of SNF reprocessing is the organization of the safe management of radioactive waste. The plant vitrifies liquid high-level waste in direct electric heating furnaces and ensures their safe long-term storage.

The Radioactive Isotope Plant is one of the world's largest manufacturers of radionuclide sources of ionizing radiation, heat, and radioactive preparations; its nomenclature includes more than 300 items. The plant produces more than 50% of the total volume of isotope products manufactured in Russia. Most of the products (over 90%) are exported to 20 countries.

Sources of ionizing radiation based on various radionuclides are widely used in many industries, science and technology. They are most widely used in instrumentation, radiation technology, agriculture, medicine and the food industry.

The Instrument-Mechanical Plant incorporates the design and production service of instrumentation and automation, and was created primarily to solve the problems of instrument control of defense production. Possessing the necessary design and experimental research base, the plant carries out industrial production of non-standard means of control, regulation and control of technological processes for Mayak Production Association and for other enterprises of the Russian nuclear industry. The plant's products are sensors, signaling devices, level meters, detection units, radiometers, spectrometers. The production of alarm systems, technological control, radiation control and monitoring systems has also been launched.

The main functions of the ecology service unit include the processing of liquid radioactive waste from the enterprise, the operation of hydraulic structures of industrial reservoirs and lakes of the Irtyash-Kasli system, landfills for the disposal of solid radioactive and hazardous waste from production and consumption, radiation rehabilitation of the industrial site and the sanitary protection zone of the enterprise.

The FSUE Mayak branch - «Basalt», as part of the reorganization of the Russian nuclear industry, was merged with the PA «Mayak» FSUE in 2018-2019. The main task of the branch is to provide enterprises of the nuclear industry with the products manufactured from strategically important beryllium metal.

Stable operation of the main industries is ensured by auxiliary services: the railway department, the department of motor vehicles, the department of information technology, the department of networks and substations, the repair and construction department, the department of work supply, the warehouse storage department, etc.
The entire production complex of the enterprise is supported by the scientific and methodological activities of the Central Plant Laboratory.

3. ENVIRONMENTAL IMPACTS OF THE PA «MAYAK»

The location area of FSUE PA Mayak is situated in the foothill plain of the eastern slope of the Southern Urals and is represented by a slightly hilly plain with the general direction of the slope to the east. According to physical and geographical zoning, the western territory belongs to the lake-forest subzone of pine-deciduous species of the province of eastern foothills.

3.1 Geographic and climatic characteristics of the territory PA Mayak

The terrain of the industrial site is a gently sloping plain with absolute elevations of 248.3-258.4 m. The relief is weakly rugged, the hills are mostly small, with flat peaks and gentle slopes. The slopes are convex, less often of a straight shape with a steepness of 10 to 100, an average of 2 ° -5 °. Watershed spaces and peaks in most cases have small outcrops of bedrock. The slopes and bases of the hills are usually sod. Expressed special relief elements, such as ravines, cliffs, depressions, karst funnels, etc. are absent.

Hydrographically, the territory belongs to the upper part of the Techa river's basin. The industrial site of "PA" Mayak is located in the northern part of the watershed area, between the Techa and Michelyak rivers, capturing the southern shore of Lake Kyzyltash.

In the region under consideration, upland-type swamps are developed on the watersheds, the inter-hilly spaces are often swamped and the river valleys together with the coastal strip of lakes are occupied by low-lying swamps.

The area is characterized by a temperate continental climate. The average annual air temperature is +2.6 ° C. The coldest period of the year begins in October and ends in May. The coldest month is January with an average temperature of -14.7 ° C, the hottest is July with an average temperature of + 18.7 ° C. The absolute minimum is -43.2 ° C (December 1955), the absolute maximum + 37.3 ° C (July 1952).

The first frosts, on average, occur on September 15, the earliest – on September 3, and the latest – on October 5. Soil temperature in a soil layer down to 0.5 m deep usually corresponds to the air temperature. At a depth of more than 1 m, there is a shift in the calendar graph of the temperature of the soil compared to air temperature: the maximum temperature is observed in August, and the minimum in March. At a depth of 2.0 m, the highest average monthly soil temperature reaches + 15.8 ° C, and the lowest -4.2 ° C. The greatest depths of soil freezing vary from 1.8 to 2.0 m (registered in March).

The average annual absolute humidity is 6.8 g / m^3, and the average annual relative humidity is 72%. The highest absolute humidity values are observed in summer and range from 25 to 27 g / m^3, the highest relative humidity recorded in the cold season varies from 68 to 88%. The lowest absolute humidity observed in January-February ranges from 0.1 to 3.0 g / m^3. Daily fluctuations in absolute humidity in winter are negligible. The largest number of dry days (with relative humidity less than 30%) is observed in May and ranges from 10 to 12 days. In the cold season, humidity below 30% is rare.

The first snow falls in mid-October, and a permanent snow cover is established in early November. The number of days with snow cover ranger from 150 to 170. In open areas, snow depth can reach from 30 to 35 cm, and in the forests from 45 to 55 cm. Usually, snow begins to melt at the end of March and the melting lasts from 15 to 20 days. The average snowmelt in the area is from 2 to 6 mm / day.

In the area around PA «Mayak» such natural phenomena as fogs, icing, thunderstorms, hails, snowfalls and snowstorms are quite typical. Fogs can be observed at any time of the year, while the average number of days with fog in a year is 15. The number of days with snowstorms can vary significantly from year to year. On average, up to 33 days with snowstorms are recorded during one year, and the maximum number of such days is 58. Thunderstorms are usually observed in summer, less often in spring and autumn, the average number of days with thunderstorms in the year is 25, and the largest is 38. The hail is usually observed during rainfall time. The average number of days with hail is 1.8, and the largest is 4 days a year. The diameter of hailstones can reach 4-5 cm.

In winter, the southern ridge of the Asian anticyclone has the main influence on the hydrometeorological conditions of the Southern Urals. Therefore, westerly winds with a southern component prevail (50-65%).

In summer, the Azores anticyclone leads to an increase in atmospheric pressure in the west of the Southern Urals; therefore, the winds of the western and northern directions begin to prevail (50%). The average annual wind speed is 4.1 m / s, and the average monthly wind speed is almost the same and quite stable. The maximum wind speed is 24 m / s.

The atmospheric phenomena that affect the migration of radioactive substances include not only the moderate and strong winds, but also dust storms and dusty snow drifts, dry winds during droughts, dusty whirlwinds and squalls. (Teterin, 2000)

During the centennial observation period (1886 - 1986), 6 hurricanes and 12 tornadoes of varying intensity degrees were recorded in the Perm, Sverdlovsk and Chelyabinsk regions, as well as the Republic of Bashkortostan. The intensity of the tornadoes that were observed near the PA Mayak location did not exceed the F2 class on the Fujita scale.

Adverse features of the physical and geographical location and climate include high air and soil temperatures in the warm season, relatively high wind speeds, significant amplitudes in precipitation, high evaporation, minimal water flow in rivers, significant fluctuations in lake levels, high frequency of thunderstorms, droughts, dry winds, dust storms and dusty snow drifts, squalls, dusty whirlwinds and tornadoes; most manifest in the area of the PA Mayak (according to the weather stations Argayash and Brodokalmak). In terms of climate characteristics, the Mayak industrial site is located in the most unfavorable place in the region.

3.2 Chronology of events associated with radioactive pollution of the environment as a result of the activities at PA «Mayak»

Most of the radiation accidents and incidents occurred at the initial stage of the first domestic nuclear production. It was necessary to master complex and extremely dangerous production and to obtain nuclear weapons in the shortest possible time and in the conditions of secrecy. Incidents at the Mayak Production Association related to radiation pollution of the environment, exposure of personnel and the public occurred due to imperfection of technological processes, tight time limits, lack of working experience and also the mistakes of scientists, designers and production personnel. All work on the design, testing, commissioning and commissioning of a uranium-graphite reactor and other facilities was carried out in a hurry, as they say, “on the go”, sometimes even without letting the equipment to cool down.

The first accident officially occurred already on the first day of operation (June 1948), when the reactor was brought to its full capacity. The cooling water supply stopped in the center of the reactor core, the reactor was stopped and the remaining uranium blocks remaining in the graphite masonry were removed. (Bekman, 2005, p.19)

According to the data of Larin (2001) and Bekman (2005), the following radiation incidents and accidents were registered at the Mayak Production Association (Table 1).

Table 1. Radiation incidents and accidents at the Mayak Production Association in the period 1948-2000. (Larin, 2001)

Date	**Event description**
19.06.48	A reactor was shut down due to refrigerant deficiency
15.03.53	The occurrence of a self-sustaining chain reaction (SCR) at the factory followed by irradiation of the working personnel
13.10.54	The explosion of technological equipment and the destruction of parts of the building
21.04.57	Self-sustaining chain reaction (SCR) at plant No. 20 in the uranium oxalate collector. The working personnel was irradiated, one person died
29.09.57	Kyshtym nuclear disaster: explosion of a container with highly radioactive liquid waste of radiochemical production in a storage facility with a radioactivity emission of about 20 million Ci.
02.10.58	The occurrence of a self-sustaining chain reaction (SCR) due to a worker’s mistake. The working personnel was irradiated, three people died, and one case of radiation sickness was registered
28.07.59	Technological equipment blackout
05.12.60	Self-sustaining chain reaction (SCR) at the factory followed by irradiation of the working personnel
26.02.62	Explosion inside of sorption column, destruction of equipment
07.09.62	Another self-sustaining reaction (SCR) at the plant No. 20
January 1965	Heavy water began to leak from the OK-180 reactor. The reactor was shut down on 03.03.1966.

Date	Event description
16.12.65	Self-sustaining chain reaction (SCR) at the plant No. 20 that lasted for 14 hours
autumn 1966	Heavy water leak from OK-190M reactor detected
10.12.68	The plutonium solution was poured into a cylindrical container with a dangerous geometry. One death, one case of acute radiation sickness
1975	Mass failures of heat-emitting elements at the OK-190M heavy-water reactor
11.02.76	Development of an autocatalytic reaction at the radiochemical plant. Due to unqualified actions of personnel, nitric acid reacted with complex organic matter, an explosion of the apparatus and radioactive contamination of the premises of the repair zone and the adjacent area of the plant territory occurred
April 1983	Depressurization of the inner wall of the water protection tank and mixing of this water with heavy water leaks at the OK-190M heavy-water reactor
02.10.84	Explosion at a reactor vacuum equipment
16.11.90	Explosive reaction in the reagent containers. One man died, two got chemical burns
17.07.93	The destruction of the sorption column at the radioisotope plant and the release of a small number of α-aerosols localized within the workshop
02.08.93	Spilling 2 m^3 of radioactive pulp with an activity of about 0.3 Ci onto the ground due to the depressurization of a pipeline, followed by contamination of about 100 m^2 of surface). The radioactive trail was localized, contaminated soil removed
27.12.93	Radioactive aerosols were released into the atmosphere at the radioisotope plant during the replacement of a filter. The emission scale: 0.033 Ci for α-activity, 0.36 mCi for β-activity
04.02.94	Excess of daily release of radioactive aerosols by 137Cs and 2-day emission by β-activity, total activity 15.7 mCi
30.03.94	An increase in the daily release of radioactive aerosols was registered
May 1994	β-aerosols with the total activity of 10.4 mCi were accidentally released through the ventilation system of the plant building
07.07.94	Leakage from a sealed sewer followed by the formation of a radioactive spot with an exposure dose rate of 500 μR / s and a total area of several square decimeters
31.08.94	An uncontrolled electric arc arose when the workers were cutting off the idle ends of the SFA and the VVER-440 fuel elements depressurized, which led to an increased release of radioactive aerosols with a total activity of 238.8 mCi into the atmosphere
24.03.95	Nuclear hazard incident: 19% excess of plutonium loading rate
15.09.95	Leakage of cooling water from one of the vitrification furnaces. Operation of the furnace in a scheduled mode was discontinued.
21.12.95	Violation of technological regulations when cutting a thermometric channel. Staff exposure to radiation.
24.07.95	Increased emissions of 137Cs aerosols due to the inflammation of a filter cloth

Date	Event description
14.09.95	Air pollution of the working area with α-nuclides
22.10.96	Depressurization of the cooling water coil of one of the storage tanks for high-level waste. As a result, contamination of the pipelines of the storage cooling system occurred.
20.11.96	An increased aerosol release of radionuclides into the atmosphere at the chemical plant
27.08.97	Floor contamination with an area of about 2 m^2, with a dose rate of γ radiation from 40 to 200 μR / s was detected in the building of RT-1 plant
06.10.97	An increase in the radioactive background to 300 μR / s was recorded inside the installation building of the RT-1 plant
23.09.98	After the capacity of the LF-2 reactor (Ludmila) was raised, the permissible power level was exceeded by 10%. As a result, depressurization of a part of the fuel elements occurred in three channels, which led to contamination of the equipment and pipelines of the primary circuit
09.09.2000	Nuclear hazard incident: disconnection of power supply at Mayak software for 1.5 hours

Tolstikov (2016) notes that all radiation accidents related to environmental pollution around the territory of PA «Mayak» were, to one degree or another, related to the unresolved problem of radioactive waste management. Numerous attempts of specialists to find effective ways to neutralize them, to make them safe for all living things, did not lead to the desired results. (Tolstikov & Bochkareva, 2016, p.137-141 & 405)

In the summer of 1951, as a result of floods, about 80 km^2 of floodplain lands were contaminated with radionuclides sorbed by bottom sediments of the Techa river. Discharge of liquid radioactive waste into the river during the period between 1949-1956 was estimated at 76 million m^3 of wastewater with a total activity of 2.75 MKi. This data was obtained by a calculation method, because all documentation on accounting for the discharge from the radiochemical plant in the Techa river during its commissioning and development (1948–1951) was destroyed. (The National Information Agency, 2013)

The results of radiation monitoring of plutonium ($_{238}$Pu and $_{239+240}$Pu isotopes) showed that, in addition to emergency situations, one of the main sources of plutonium in the environment around the plant are the technological emissions into the atmosphere. (Bakurov & Equal, 2006)

Radionuclides of activation origin ($_{14}$C, $_{41}$Ar, $_{51}$Cr, $_{54}$Mn, etc.), fission products (inert radioactive gases, $_{90}$Sr, $_{89}$Sr, $_{95}$Zr + $_{95}$Nb, $_{106}$Ru + $_{106}$Rh, $_{131}$I, $_{137}$Cs, $_{144}$Ce + $_{144}$Pr, etc.) and alpha-emitting nuclides ($_{239}$Pu, $_{241}$Am, etc.) were discharged into the atmosphere through 150 m tall pipes. Several low emission sources have also been used. At the same time, in the initial period of the enterprise's operation there was no direct control of emissions; their level was judged by measurements of the specific β-activity of vegetation cover, snow, and soil. Aerosol emissions of radionuclides from the pipes of the Mayak production plants in the 1950–1960s led to soil pollution in the enterprise area to levels of 13^{10} Bq / km^2 for $_{90}Sr$ and $_{137}Cs$.

The events which occurred in 1957 and 1967 have led to extensive pollution of the territory outside the Mayak PA - The Kyshtym nuclear disaster and the formation of the Karachaevsky trace.

3.3 Kyshtym nuclear disaster

In September 1957, the Kyshtym nuclear disaster occurred - the largest accident in the history of PA «Mayak». On 29 Sep 1957 at 16:22 in the storage of a radiochemical plant, a container (bank No. 14) with a volume of 300 m^3 exploded, in which 70-80 tons of liquid radioactive waste with radioactivity of at least 20 million curies ($7.4 \cdot 10^{17}$ Bq) were stored. The cause of the explosion was the failure of the cooling system. No one died directly from the explosion.

The blast power of the explosion was estimated at tens of tons of TNT. As a result, the container with liquid radioactive waste was destroyed, a concrete slab 1 m thick weighing 160 tons was thrown to the side.

A large amount of radioactive substances was released into the atmosphere ($_{144}Ce$ + $_{144}Pr$, $_{95}Nb$ + $_{95}Zr$, $_{90}Sr$, $_{137}Cs$, plutonium isotopes, etc.), 18 million curies were scattered on the industrial site.

Some of the radioactive substances (about 2 million curie) were raised by an explosion to a height of 1–2 km and formed a cloud consisting of liquid and solid aerosols. Within 10–11 hours, radioactive substances fell 300–350 km northeast of the site of the explosion, forming the East Ural Radioactive Trace (EURT) with a total area of 23 thousand km^2.

A radioactive cloud of radioactive dust and droplets of solution covered many industrial facilities, roads, military camps. As a result of the explosion, the territories of the Chelyabinsk, Sverdlovsk, Kurgan and Tyumen regions were exposed to radioactive contamination.

The results of the first radiation survey near the storage facility and at remote points of the Mayak industrial site were obtained by the night of September 30, 1957. They showed extremely high values of the exposure dose of γ-radiation in the surveyed area. In the period of October 10–20, 1957, the first radiation survey was taken of the territories exposed to radioactive contamination located in a zone remote from the explosion. It was carried out using radiometers mounted on cars. The extent of pollution of the territories of the Chelyabinsk, Sverdlovsk, Kurgan and Tyumen regions was pre-established.

In November - December 1957, the actual scale of radiation pollution in the territory from the enterprise to the city of Kamensk-Uralsky, Sverdlovsk Region (105 km) was clarified. (Khokhryakov, 2002, p.39-44)

Terrestrial and aquatic ecosystems of the EURT area (lakes Uruskul, Berdenish, Kozhakul, the Karabolka river, Bugai swamp, etc.) were contaminated with radioactive substances. An extinction of individual ecosystem links was registered (pines, a number of species of herbaceous plants, soil fauna, etc.) in the head part of the trace. The total beta activity of water in the initial period reached 1000–10 000 Bq / l; soil pollution levels in the head part of the EURT reached 2000 Ci / km^2 and higher. The main role in long-term pollution of land and water systems was played by $_{90}$Sr. (Stukalov & Rovny, 2009, p.5-13)

In order to prevent the spread of radionuclides in 1959, a sanitary protection zone on the most contaminated part of the radioactive trail was created and the economic activities were prohibited. The official status of “radioactively contaminated area” subject to radiation protection measures was extended to the territory within the zone of 2 Ci / km^2 by $_{90}$Sr. The territory was 4-6 km wide and 105 km long and had a total area of about 1000 km^2 (Chelyabinsk: South Ural Book Publishing House, 2006)

A total 59 thousand hectares of land in the Chelyabinsk region and 47 thousand hectares in the Sverdlovsk region were withdrawn from economic circulation. The settlements from the contaminated territory were evacuated.

As a result of special measures developed with the participation of the Experimental Station, by 1967 most of the territory of the EURT was returned to economic use. Only the most contaminated parts remained unusable. (The National Information Agency, 2013)

Industrial activity of the Mayak Production Association has led to large-scale radioactive contamination of the components of terrestrial and aquatic ecosystems in the Southern Urals. Terrestrial and aquatic ecosystems of the EURT territory (lakes Uruskul, Berdenish, Kozhakul, the Karabolka river, Bugai swamp, etc.) were contaminated with radioactive substances up to lethal levels of exposure to individual links of biocenoses (the head part of the EURT, the Techa, Karachay, and Staroe Boloto).

3.4 Karachaevsky trace

The Karachaevsky trace is the radioactive contamination of the territory resulting from the wind dispersal of radioactive substances in the spring of 1967. It arose due to the specific arid weather conditions of the spring of 1967 and poor control over the level of Lake Karachay (V-9), which since 1951 was used as a storage for liquid radioactive waste. In the spring of 1967, an adverse set of weather conditions developed:

- insufficient rainfall during the winter period
- early and dry spring
- strong gusty winds

From December 1966 to March 1967, precipitation level was about 36 mm, which is only 10% of the average norm for this period. Early spring led to the fact that by March 20 there was no snow cover. The topsoil was dry, and a further increase in temperature caused warming and drying of the soil. This has led to an increased dust formation. Due to the small amount of precipitation in Lake Karachay, the water level dropped rapidly, the coastal strip of the reservoir was exposed, and radioactive bottom sediments were involved in the process of dust formation.

During April 1967, strong winds were repeatedly observed, especially in the sectors of south-south-west and west-north-west. On April 18 and 19, the gusts of wind reached 23 m / s.

The wind transfer of exposed bottom sediments of Lake Karachay contaminated with long-lived radionuclides (mainly 90Sr, 137Cs and 144Ce) led to the spread of radionuclides not only all over the area directly adjacent to the lake, but also all over the area located in the northeast-east sector (NE-E) from the industrial site of Mayak PA. The main direction of wind migration of exposed radioactive bottom sediments was from the south-west to north-east up to the city of Kamensk-Uralsky, located 105 km from Lake Karachay, and from west to east. (Teterin, 2000)

On April 18–19, 1967, high concentrations of radioactive aerosols in the surface air layer were observed. On 18 April 1967 at a distance of 2 km from the Karachay reservoir in the direction of the wind from the storage, concentrations of β-emitting nuclides in the air were observed up to 4 · 10-12 Ci / l; 04/19/1967 at a distance of 500 m from the storage, the concentration was 4 · 10-9 Ci / l, and at a distance of 12 km - 4 · 10-10 Ci / l.

At the same time, an increase in the level of exposure dose rate was observed (measurements were taken at a height of 1 m above the soil surface) at stationary observation points located in the areas of ONIS, Khudaiberdinsk, Kirov branch, Argayash TPP, by 2–3 times.

In April – May 1967 and for the following months, researches of the radioactive contamination of the territories around Lake Karachay were conducted. The values of the exposure dose rate on the territory of the surveyed areas were also measured. At the same time, the intensity and radionuclide composition of the radioactive fallout were determined.

By radiochemical and gamma-spectrometric determinations of the composition of pollution carried out on various samples of environmental objects (filters, tablets, natural and cultural vegetation, soil), it was found that the radioactive substance was represented by long-lived radionuclides. The isotopic composition of the mixture of radioactive substances in various samples of environmental objects was approximately the same and for further calculations (according to the results of control measurements of soil samples) was adopted as follows: $_{90}$Sr + $_{90}$Y - 34%; $_{137}$Cs - 48%; $_{144}$Ce + $_{144}$Pr - 18%. Difficult meteorological conditions and the long emitting capacity of the source of radioactive substances into the atmosphere caused pollution of the territory. (Khokhryakov, 2002, p.39-44)

The total activity of radionuclides released into the atmosphere was estimated at 0.6 MKi, and the area of pollution was approximated to 2700 km^2 (outside the production area of Mayak Production Center) (Figure 3).

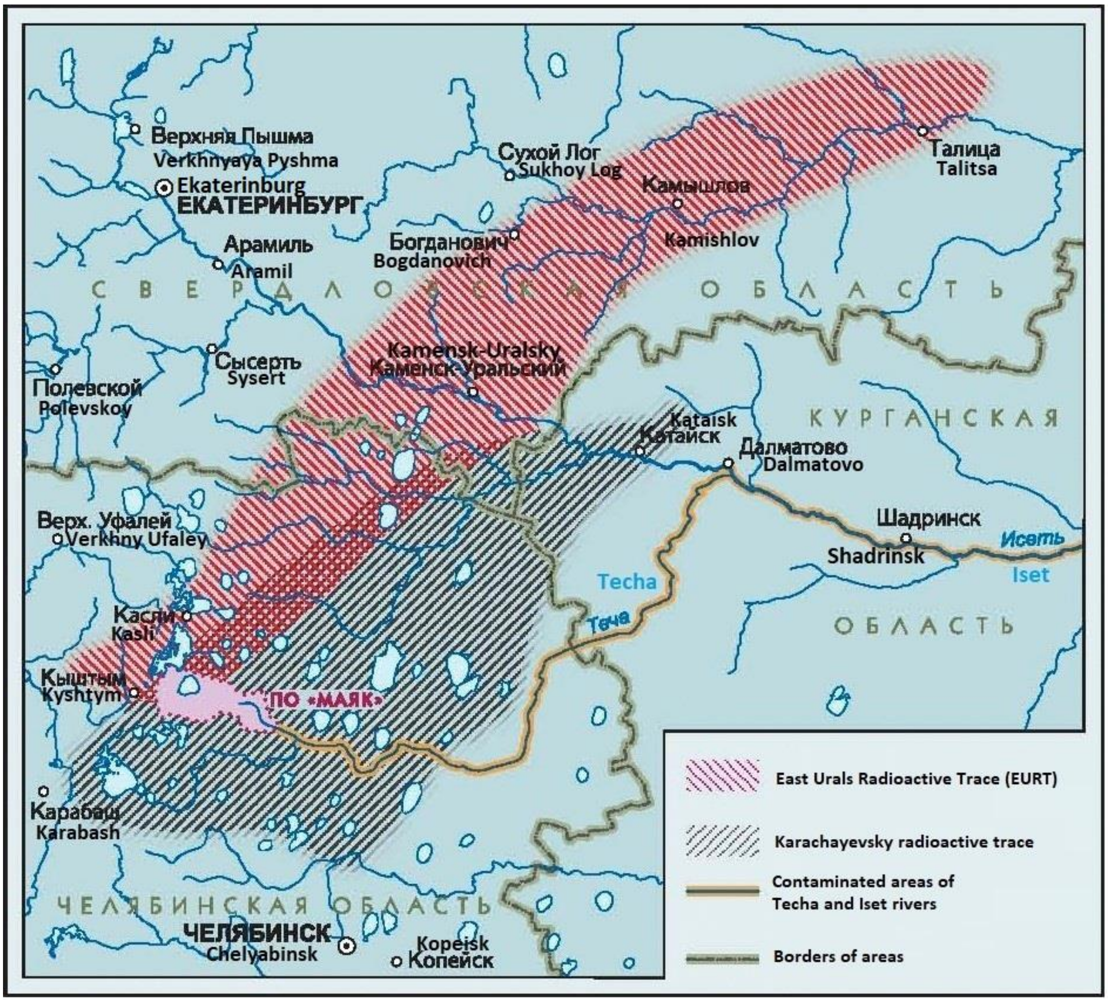


Figure 3. The pattern of contamination of the territory resulting from the incidents of 1957 and 1967

As of 1 January 2018, the total area around FSUE PA «Mayak» contaminated with radionuclides is 446.8 km^2, of which 195.96 km^2 are located in the sanitary protection zone.

4. ANALYSIS OF RADIOACTIVE CONTAMINATION OF WATER BODIES IN THE REGION

The main environmental problem of PA Mayak is related to the operation and maintenance of the special industrial reservoirs of the enterprise, which are used to dump the enterprise’s waste. Radiation pollution of the environment, especially in the first decades of the enterprise’s operation, was associated with the unresolved problem of the management of liquid radioactive waste, which was generated in large volumes, especially when plutonium was released.

4.1 The problem of liquid radioactive waste "PA" Mayak"

In order to obtain incomplete 100 g of plutonium at the radiochemical production, it was necessary to process 1 ton of uranium blocks. This required 11.6 tons of nitric acid, 56 tons of industrial water and 2000 tons of cooling water. Therefore, the problem of liquid radioactive waste has become one of the most acute and dangerous, especially for the PA «Mayak» water system.

Depending on their activity, liquid radioactive waste generated at PA «Mayak» is divided into the following categories as shown in Table 2.

Table 2. Categories of liquid radioactive waste

Waste category	Activity	
Very low activity	α, Bq	$8{,}13 \cdot 10^{8}$
	β, Bq	$2{,}40 \cdot 10^{12}$
Low activity	α, Bq	$1{,}63 \cdot 10^{10}$
	β, Bq	$6{,}21 \cdot 10^{13}$
Medium active	α, Bq	$2{,}53 \cdot 10^{11}$
	β, Bq	$1{,}85 \cdot 10^{16}$
Medium active	α, Bq	$6{,}67 \cdot 10^{16}$
	β, Bq	$1{,}97 \cdot 10^{18}$

A special technology has been created for the neutralization of liquid radioactive waste from radiochemical production with a high level of activity. It implied a reduction in waste by evaporation. In order to localize waste from radiochemical production, a special expensive storage facility was designed with a volume of 15 thousand m^3 per year. Liquid wastes with low and medium levels of radioactivity were generated in such quantities that they could not fit into any storage facilities.

Medium-level waste is presented by liquid environments (containing sodium nitrate, pulps of ion-exchange resins, alkaline and acid stripping solutions, etc.) with various physicochemical properties. Stopping the dumping of medium-level waste is still a difficult task, which requires the modernization of many industries, the creation of concentration technologies, curing (vitrification or cementing) and the infrastructure for subsequent safe storage.

In 1948 there was no normal technology for the disposal of radioactive waste. After the commissioning of the reactor, radiochemical and other major plants of the chemical plant, a forced decision was made to discharge liquid radioactive waste into open water bodies. (Tolstikov & Bochkareva, 2016, p. 137-141 & 405)

4.2 Hydrographic network of the impact zone of PA "Mayak"

The reservoirs located in the impact zone of the Mayak Production Association belong to several lake groups and water systems. The influence of the wastewater from FSUE Mayak PA on the pollution of the river bed with $_{90}$Sr can be traced all along the entire length of the Techa and Iset rivers until the point where the Iset river joins the Tobol river. The Karabolka and Sinara rivers are also located in the influence zone of FSUE PA Mayak (Figure 4).

Figure 4. A schematic map of an open hydrographic network in the zone of influence of FSUE PA Mayak

The largest lake system is Kaslinsko – Kyshtym. It is located in the northern part of the Chelyabinsk region, in the upper part of the Techa river. The Kaslinsko-Kyshtym lakes fill up the foothill faults of the Potanin and Granin mountains on the eastern slope of the South Ural Range. The total area of water bodies is 280 km^2. All the lakes in the system can be divided in two types: the flow-through lakes and open (exorheic) lakes.

The lakes located to the north from the town of Kasli belong to the northern (Kaslinsky) stock chain, and the lakes located to the south from the city of Kyshtym - to the southern stock chain. The final element in the water system is Lake Irtyash, from which the water was transferred to Lake Kyzyltash and then into the Techa river. Lake basins are saucer-shaped and shallow. The hydrological regime is characterized by seasonal and perennial fluctuations in water level. As a result of many years of activity at PA Mayak, a part of the open reservoirs of the nearby territory was turned into industrial reservoirs.
Figure 5 shows a diagram of industrial reservoirs in the period up to 1956. (The National Information Agency, 2013)

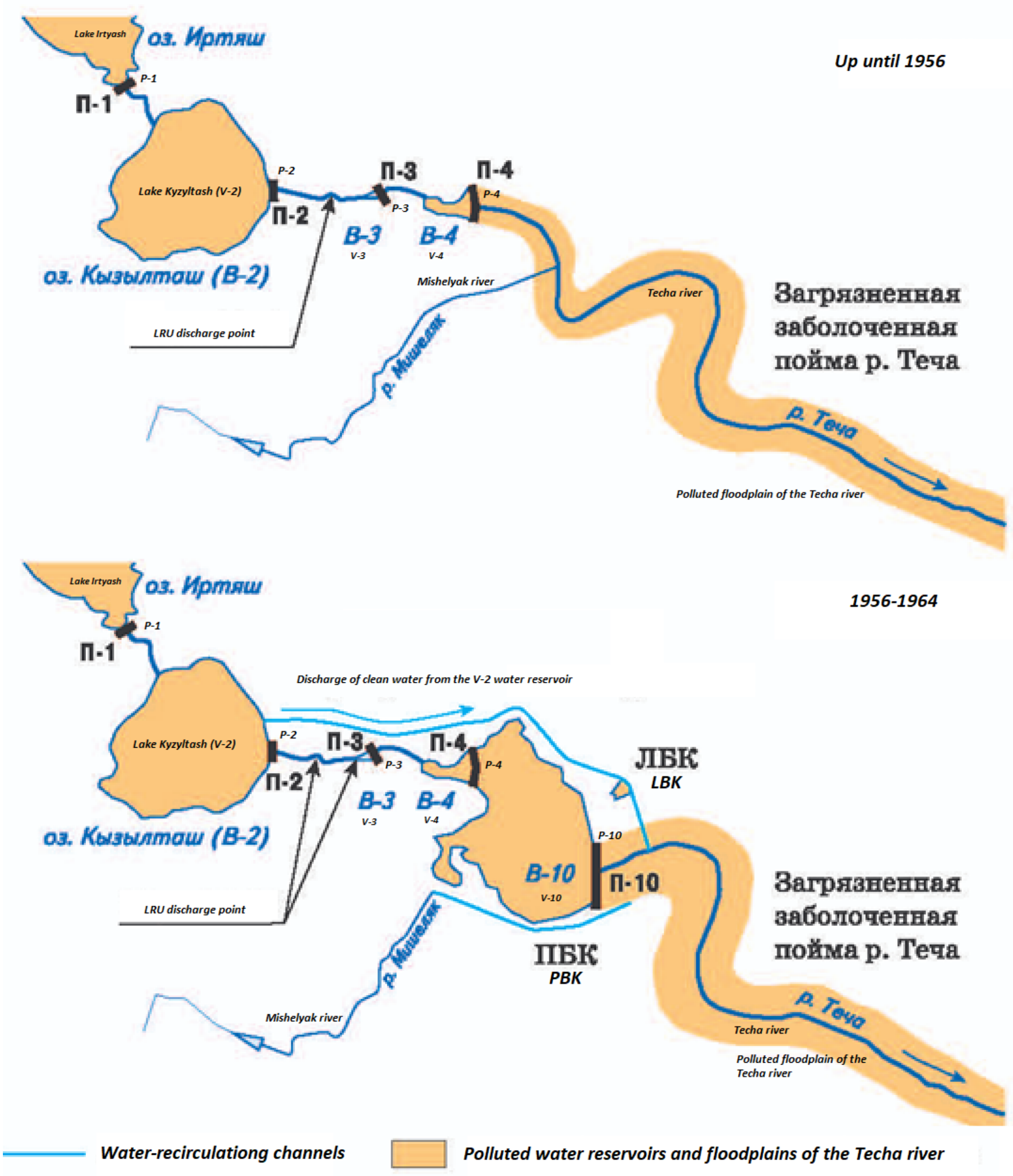


Figure 5. The scheme of industrial reservoirs in different years: V-1 – V-11 - reservoirs; P-1 – P-11 - dams; LBK - left-bank channel, PBC - right-bank channel

At present, industrial reservoirs of the PA Mayak include the following shown in Figure 6 below.

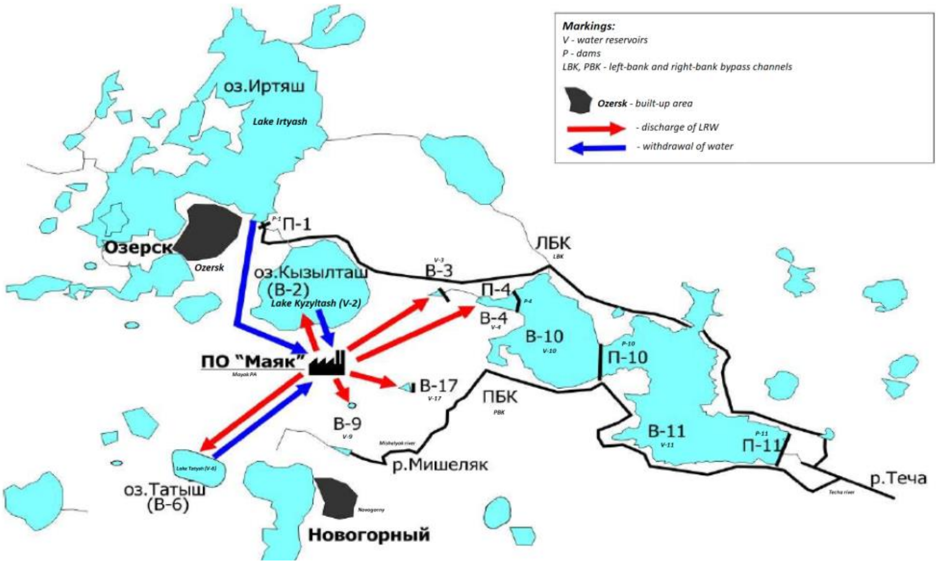


Figure 6. The scheme of discharges of liquid radioactive waste of FSUE "PA «Mayak»" (as of 2013). (Mokrov, Batorshin & Aleksakhin, 2013)

V-2 (Lake Kyzyltash) - a reservoir-cooler for reactor production, used for recycled water supply and sewage.

V-3 and V-4 - industrial reservoirs on the site of ponds that existed before the start of the chemical plant (Koksharovsky pond and Metlinsky pond).

V-10 and V-11 - reservoirs in the riverbed of the Techa river; both are included in the TKV system. These reservoirs serve as storages of water masses and radionuclides coming from upstream reservoirs V-3 and V-4, as well as from the catchment areas of the former river bed of the Techa river. Direct discharge from the Mayak production facilities is not performed.

V-6 (Lake Tatysh) - used for recycled water supply and sewage;
V-9 (Lake Karachay) - a storage reservoir at the site of the Karachay swamp, was used as a storage for medium-level waste (absent since 2015);
V-17 (Old Swamp) - an artificial reservoir in the interfluve of the Techa and Michelyak rivers, used as a dumpster for medium-level radioactive waste.

Figure 7 presents the characteristic of water reservoirs at "PA" Mayak

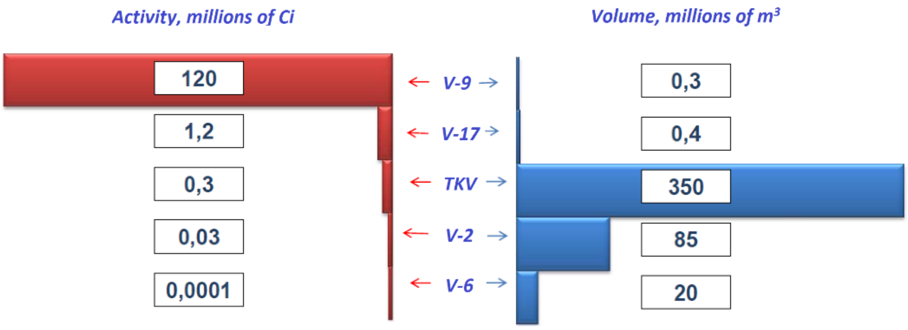


Figure 7. Characteristics of water reservoirs at "PA" Mayak" (Mokrov, Batorshin & Aleksakhin, 2013)

4.3 Contamination of the Techa river

The waters of the Techa river are the most polluted waters in Russia, mainly by $_{90}$Sr. This radionuclide is present in a water-soluble state, so it easily migrates over long distances through the hydrographic system.

The Techa river takes its start from Lake Irtyash and flows in the directions of east and northeast. The river spreads for 243 km and eventually falls into the river system Iset - Tobol - Irtysh - Ob. According to the structural features of the valley and the riverbed, as well as the distribution of radionuclides, two landscape zones are distinguished: the upper zone (Asanovsky swamps, length 35 km) and lower zone (Muslyumovo village - Nizhnepetropavlovskoye village, 100 km long).

There are many coastal swamps in the upper landscape zone; the floodplain is bilateral, with an average width of 2.0–2.5 km, in narrowing up to 0.4 km. The river depth at rifts is 0.3–0.8 m and the flow velocity is 0.1–0.4 m / s. The surface of the floodplain is swampy, hummocky and annually flooded during flood with a layer of water 0.2–1.0 m (up to 2 m in high flood). The river emerges from the marshes in the vicinity of the Muslyumovo station.

Lower landscape zone: The floodplain is double-sided, asymmetric, with an average width of 300–400 m, with fluctuations from 30–35 m at the beginning of the zone to 700 m at the end. The depth of the river on the rifts is 0.4–0.6 m, on the reaches - 2-3 m. The flow velocity on the rifts is up to 1.2 m / s, on the reaches up to 0.4 m / s. The floodplain is flooded along its entire length during normal floods to a depth of 0.5–2.5 m.

Since the founding of the Mayak PA in 1949, the Techa river has been used for scheduled and emergency discharges of liquid radioactive waste. The discharge of liquid waste into the Techa river was limited, and the limits were set in the initial waste disposal plan. The amount of low and medium activity liquid waste could not exceed 40 Ki / day, and the amount of highly active liquid waste could not exceed 3 Ki / day.

However, in 1949, the technology for the evaporation of highly active liquid waste was never launched at its designed capacity. Soon, the evaporators were completely stopped due to inefficiency and the threat of the corrosion. There was not enough capacity to store large volumes of unpaired highly active liquid waste; radiochemical production was under the threat of being shut down. This could not be allowed.

Between December 1948 and October 1951 only a small part of the radioactive waste was discharged into Lake Staroe Boloto and chromate pits. The waste inside the pits was drained through the soil in the direction of the Michelyak river. As a result of sorption of radionuclides on soils, these waters entered relatively open reservoirs relatively clean.

Most of the radioactive liquid waste was discharged into the Techa river without any cleaning. The biggest volumes of discharges of radioactive solutions were the contribution from the radiochemical plant, but also radioactive discharges came from industrial uranium-graphite reactors. The discharge was carried out directly into the existing Koksharovsky pond, which was subsequently included in the system of industrial reservoirs (V-3).

In 1949-1951 in the ecosystem of the Techa river was dumped the bulk of the radioactive nuclides. During this period, about 76 million m^3 of radioactive wastewater of various compositions, with a total activity of β-radiation of more than 2.8 MKi, entered the reservoir. (Tables 3 and 4)

Table 3. Average annual discharges of liquid radioactive waste in 1949–1956

Year	**Sum of α-emitters TBq / year (Ki / year)**	**The sum of β-emitters PBq / year (kCi / year)**
1949	0,44 (12)	1,8 (50)
1950	0,81(22)	52 (1400)
1951	0,74(20)	52 (1400)
1952	-	0,35 (9,5)
1953	-	0,074 (2,0)
1954		0,03 (0,8)
1955	-	0,018 (0,5)
1956	-	0,048 (1,3)
Total	2,0 (54)	106 (2860)

Table 4 provides information on the radionuclide composition of liquid radioactive waste discharged into V-3 in 1949–1956.

Table 4. The radionuclide composition of liquid radioactive waste discharged into V-3 in 1949-1956. (The National Information Agency, 2013)

Radionuclides	**Total activity**	
	picobecquerel	**kilo curie**
$_{89}$Sr + $_{140}$Ba	10	270
$_{90}$ Sr	12	330
$_{95}$ Zr + $_{95}$Nb	14	390
$_{103}$Ru+$_{106}$Ru	28	760
$_{137}$Cs	13	35
Rare earth elements	28	760

Until mid-1951, no measures were taken to reduce the level of danger caused by radioactive contamination of the river system. Protection against the effects of radiation from the population living in the affected areas was not provided.

In October 1951, it was decided to transfer the discharges of all technological waste to Lake Karachay, located 400 meters from the radiochemical plant. As a result, the discharge of liquid waste into the Techa river in 1951-1956 was reduced by almost 100 times (to 100-200 ki / day). After 1956, medium-level waste began to flow into the open hydro-grid in very small quantities.

However, the concentration of radionuclides in the waters of the Techa river decreased only slightly. The process of leaching radioactivity from contaminated floodplain and bottom sediments was the main source of the water pollution.

Of the total number of technogenic radionuclides dumped into the open hydrographic network, about 75% were retained in the marshy floodplain and bottom sediments in the upper river. The greatest accumulation of radionuclides in the upper river occurred due to the presence of a swampy floodplain, in which there were significant peat deposits with a maximum sorption capacity (compared with loams and sandy loams).

About 80% of the total area of the river floodplain was isolated by creating a cascade of reservoirs. In 1956, the valley was blocked by a dead dam, and the release of radioactive substances into the lower parts of the river decreased to levels of about 0.5 Ci / day. The construction of another dam in 1963–1964 almost completely isolated the hydro-chemical facilities of the enterprise, and the Techensky cascade of reservoirs (TKV) was formed.

From 1964 to the present, i.e. at a time when the discharge of liquid radioactive waste into the Techa river is completely stopped and the most polluted part of the river is practically isolated from the downstream sections by dams, the main sources of radionuclide entry into the river are the following:
- TKV bypass channels;
- filtration of water from the console reservoir of TKV through the body of the dam No. 11;
- floodplain sections of the river, located below the dam of reservoir No. 11, previously contaminated as a result of the spill of the river. These include, in particular, a boggy area of about 30-40 km^2 on both sides of the river with an activity margin of about 6 KCi for 90Sr, 9 KCi for 137Cs and 11 Ci for plutonium isotopes.

The increased sorption capacity of the marshy soils has led to high levels of pollution during river spills, and currently the Asanovskie bogs are a constant source of secondary pollution of river water as a result of washing out of the radionuclides by floods and surface waters. (The National Information Agency, 2013)

4.4 Techen cascade of water bodies

For a long time, the Techen cascade of water bodies (TKV), built in the early 1960s, has been posing a serious threat to the environment. TKV serves to protect an open hydrographic network from liquid radioactive waste in the upper part of the Techa river. TKV consists of four sequentially artificially created reservoirs (V-3, V-4, V-10 and V-11) bounded by dams, and two bypass channels necessary for diverting ordinary water from shallow streams into the Techa river, bypassing these reservoirs, shallow water and rain streams.

In order to prevent the washing out of radionuclides and accumulation of incoming low-level liquid radioactive waste in 1956, the Techa river was blocked by an earthen dam (P-10) and the filling of a new reservoir, the V-10 waste storage, began. The water from the Michelyak river was intercepted and sent to bypass the newly created reservoir along the right-bank bypass channel (PBC).

After the accident of 1957, the EURT crossed Lake Berdenish, and the channel was decommissioned. The left bypass channel (LBK) was built along the left shore of Lake Kyzyltash in order to transfer the clean water from Lake Irtyash.

Dam No. 10 was built in 1956, but due to the high rate of filling of the V-10 reservoir in 1964, an additional dam (No. 11) was constructed, which formed the new V-11 reservoir. The filling of the reservoir V-11 with liquid radioactive waste began in 1966.

The creation of TKV was the first stage of radiation rehabilitation of the Techa river.
Bypass channels serve to discharge river and flood waters around the Techen cascade of water bodies, as well as under the body of dam No. 11; LBK regulates the flow of water from the Irtyash-Kasli system of lakes, and PBC regulates the flow of the Michelyak river.

A total of 350 million m^3 of radioactive water, containing about 8 · 1015 Bq of long-lived β-active radionuclides, was accumulated in the TKV. The ponds are the source of radionuclides in the surface layer of air, surface and groundwater. Filtration of polluted waters into the open hydrographic system of the Techa river occurs through and under the side wall dams into the bypass channels.

In 2004-2005 a weakening of the upper part of dam No. 11 was discovered, which posed a real threat to the influx of radioactive water into the open hydrographic system as a result of leakage or breakthrough of the dam. This could lead to an environmental disaster, since the TKV is connected to the hydrological network of the entire Ural-Siberian region. To prevent an accident, during 2066-2007 in the body of Dam No. 11, a concrete wall with a depth of 7 to 13 meters was built.
The commissioning of the general alloy sewage system (2009–2011) made it possible to reduce the discharges of wastewater into the sewage disposal pipes by 5 million m^3 per year, since non-radioactive wastewater began to flow into the Techa river.

However, the storage of accumulated high-level waste in a liquid form in special containers, and the ongoing discharge of medium-level and low-level waste from the

Mayak chemical plant into open storage reservoirs still pose a potential threat to the population and the natural environment of the region. (Bochkareva, 2018)

The bottom sediments and underlying soils accumulate the most of the radioactive substances in water bodies exposed to radioactive contamination and also play a geochemical barrier role in the processes of radionuclide migration. The semi-purification rate of water in reservoirs under steady-state dynamic equilibrium (90Sr and 137Cs) is 6–10 years. This exceeds the rate of the physical half-life of radionuclides by several times. The processes of self-purification of water occur due to the redistribution of radionuclides in the water-bottom sediment system. A significant role in the processes of water self-purification of hydrocenoses in a number of reservoirs is played by aquatic vegetation. (Smagin, 2008)

4.5 Lake Kyzyltash

Lake Kyzyltash (V-2) is located at a distance of 2 km southeast of the city of Ozersk. The mirror area of the reservoir is 18.6 km^2, the volume of water is 84.4 million m^3 and the prevailing depth is 4 m.

The facilities of the Mayak industrial site are located on the southern and southeastern shores of the lake. In the coastal zone and in most of the catchment area, the natural landscape is disturbed due to ongoing construction works.

Water from Lake Irtyash (V-1) entered Lake Kyzyltash (V-2) along the wide shallow channel Karagai-Kuel. In the 50s the duct was blocked by a continuous earthen dam equipped with a water divider, which lets the water from V-1 enter the V-2 or the LBK. To ensure the circulation of superheated waters along the eastern shore of V-2, a 3 km long jet separation channel was built.

In the 1950s and 1980s the water temperature at the channel exit was 50-70 ° C. Evaporation from the surface of the lake doubled, and V-2 did not freeze even in the most severe winters. The water balance of the reservoir-cooler consisted of the flow of water from a uranium-graphite reactor in the amount of 20 to 50 million m3 / year and a local flow of 5 to 13 million m3 / year.

Water consumption occurred due to evaporation processes (8 to 22 million m^3 / year) and losses for technological needs (8 to 13 million m^3 / year). Water releases from V-2 to the Techa river were carried out until 1953 and periodically in the period between 1953-1957.

By 1990, after the decommissioning of five straight-through uranium-graphite reactors, thermal discharges to V-2 sharply decreased; at present, the reservoir is completely covered with ice in winter.

From the beginning of operation, neutron activation products ($_{13}$N, $_{14}$C, $_{24}$Na, $_{27}$Mg, $_{31}$Si, $_{32}$P, etc.) and long-lived $_{90}$Sr and $_{137}$Cs began to enter V-2 together with the cooling waters. In 1950, $_{24}$Na accounted for 45%, and $_{32}$P accounted for 36% of the total radioactivity of nuclides entering the water body. Short-lived radionuclides played a leading role in the radioactive contamination of the cooling pond. The total β-activity of water after 10 days of exposure decreased by 100 times.

Most of the radionuclides were concentrated in the upper layer of bottom sediments at a depth of 10 cm. The specific activity of bottom suspensions during this period reached 7400 kBq / kg from the dry weight of sediments with an average specific activity of water equal to 1.5 kBq / l.

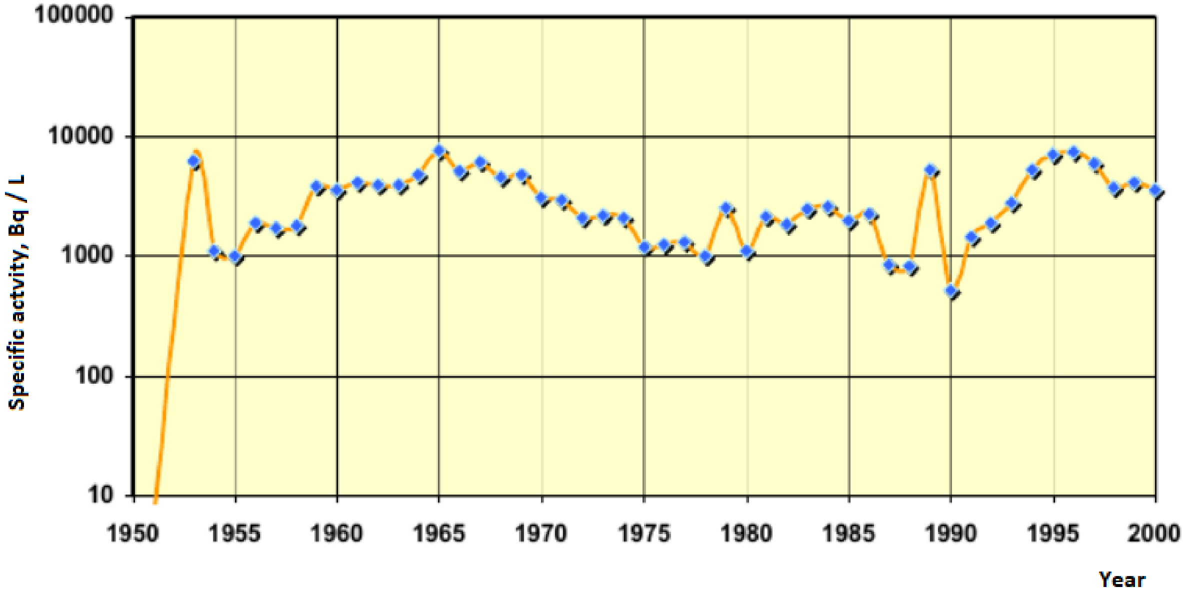


Figure 8. Dynamics of the specific activity of β - emitting radionuclides in V-2 water (Smagin, 2008)

Currently, the reservoir, considered to be the storage of liquid radioactive waste, is in the self-decontamination mode, due to the reduced discharges of radionuclides. Thus, the long-term water pollution was caused by the most biologically dangerous long-lived radionuclides $_{90}$Sr and $_{137}$Cs.

Industrial reservoirs included in the production cycle of FSUE PA Mayak were subjected to maximum radiation exposure. The reservoirs include: Lake Karachay (V-9) and the Old Swamp (V-17), Koksharovsky pond (V-3), Metlinsky pond (V-4), reservoirs No. 10 (V-10) and No. 11 (V-11).

5. LAKE KARACHAY AS A SOURCE OF GROUNDWATER POLLUTION

Lake Karachay is one of the most environmentally hazardous sources of radiation pollution of the environment on the territory of PA «Mayak». The water area of the lake was formed in the process of the regular discharge of medium-level liquid radioactive waste into the open surface water body - the Karachay swamp – which has taken place since 1951. As a result, Lake Karachay turned into an artificial lake called “V-9 Pond”.

5.1 Characteristics of Lake Karachay

Lake Karachay is a natural drainage swamp located in the central part of the watershed space of the lakes Ulagach, Tatysh, Malaya Nanoga, Kyzyltash and the Michelyak river. At that time, Karachay was a marsh of the upper type, which in rare periods completely dried up, and for some time remained a meadow.

According to the results of studies conducted in August 1951 (before the start of operation), the Karachay swamp had a water surface of 265 thousand m^2 (length 750 m, width 450 m) with an average depth of 0.8 m and a maximum depth of 1.25 m (Figure 9).

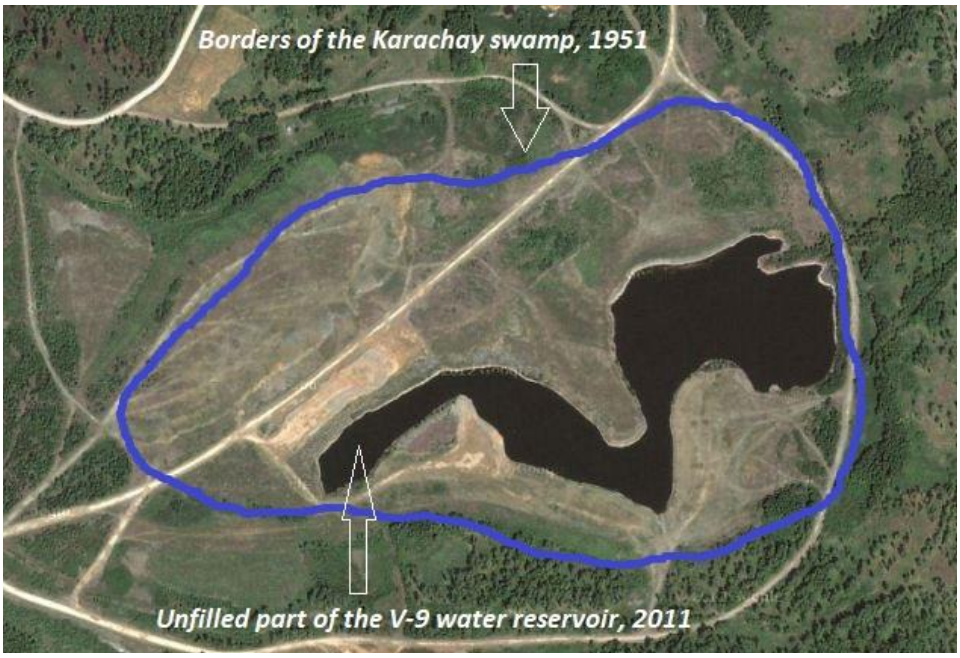


Figure 9. The original boundaries of Lake Karachay (V-9)

The reservoir was located in a natural lowering of the relief and was operated in a continuous mode with natural filtration due to a good connection with groundwater. In this case, the loam of the bed of the reservoir served as a natural protective shield, which could delay a significant number of radionuclides.

The position of Lake Karachay and the presence of a near-surface aquifer, confined to the weathering crust of the volcanic stratum having a complex geological and tectonic structure, determine both the fact of the occurrence of technogenic radioactive solutions in groundwater and the subsequent migration of radionuclide contamination in the underground hydrosphere. (Ivanov, Postovalova & Drozhko, 2005, p.23-34)

Two complexes of rocks take part in the formation of the geological structure of the Lake Karachay region: the lower one, composed of rocky Early Paleozoic volcanic rocks of andesite-basalt composition, and the upper one, which is represented by strongly eroded formations of volcanic rocks of the Late Mesozoic weathering crust, with sandy-clay sediments of Cenozoic age sporadically overlapping them.

In the undisturbed state, volcanics are practically waterproof. At the same time, the rocky base is dissected by many tectonic disturbances (schist zones, cracks, etc.), which are often grouped into fault zones. Some fault zones have a thickness of tens to hundreds of meters extending over distances of up to 10 km or more. The upper layer is composed of highly permeable and intensely fractured weathered volcanic rocks. The hydraulic permeability of tectonites exceeds the filtration characteristics of undisturbed rocks of the rock base by an order of magnitude, and it is precisely the tectonic disturbances that are the main channels of groundwater migration in the thickness of rock volcanics.

Relative groundwater abatement is the lower boundary of the weathering crust, which separates it from weakly disturbed rock volcanic rocks. The thickness of the aquifer is 50-190 m. It is replenished due to atmospheric precipitation, the amount of which determines the position of the groundwater level. In the zone of initial clayey changes, water propagates in a fissure-pore dynamic mode; in the lower zone of the weathering crust, they are filtered by a dense network of hydraulically connected closely related cracks. The groundwater flow rate, according to hydrogeological studies, is 0.2-0.7 m / day. (Velichkin, 2008, p.389-400)

5.2 The history of the operation of Lake Karachay as a waste storage facility at PA «Mayak»

On October 28, 1951, Lake Karachay became the new storage facility for liquid radioactive wastes at PA «Mayak». Only from October 1951 to 1956, liquid radioactive waste with a total activity of more than 100 million curies was dumped into the lake. The situation was aggravated by the explosion that stirred up PA «Mayak» in the fall of 1957 and the loss of radionuclides to a large territory, including to the surface of the lake. By the 1960s, an extremely unfavorable radioecological situation had developed in the Lake Karachay region. (Tolstikov & Bochkareva, 2016, p.137-141, 405)

Natural morphological regime-forming factors during the course of operation were replaced by technogenic morphological factors, which changed the hydrological regime of the lake.

Several periods can be distinguished in the history of the use and technological transformation of the reservoir V-9:

- 1951-1967 - the reservoir was used in the mode of a natural saucer-shaped cavity, and small changes in the level corresponded to significant changes in area and volume (an average of 1.3 thousand m^2 and 4 thousand m^3 / cm level); maximum spills increase the area of the most filtering sites;
- 1967-2005 – there was an embankment of the coastal strip. The surface catchment area is practically absent. Steep rocky slopes of the coast determine the insignificance of changes in the area of the aquifer, with level fluctuations;

- 1979-2007. The reservoir within the boundaries of the 1973 basin is a system of free-flowing water from an open aquifer and pore water from an increasing mass of backfill.
- 2008-November 2015 - completion of backfill and liquidation of the reservoir (Figure 10).

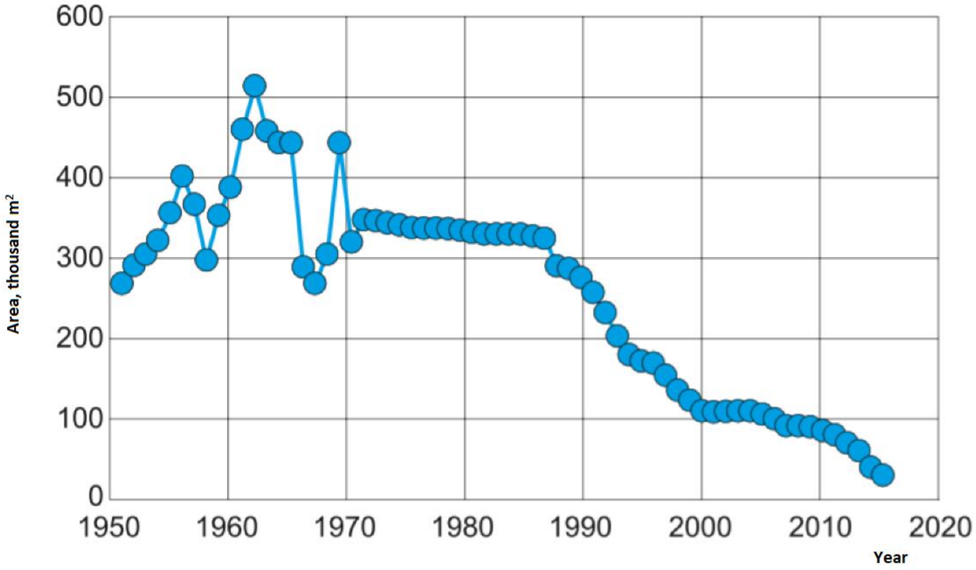


Figure 10. Change in the average annual area of Lake Karachay (1951-2014)

The volumes of technogenic input (discharges, topping up, sprinkling of the coast, backfill) are quantitatively characterized by two periods:

1951-78 - the period of maximum intake (mainly of discharges and recharge (sprinkling)) - from ~ 74 thousand m^3 (1957 g) to ~ 425 thousand m^3 (1962 g). On average, about 180 thousand m^3 / year came to Lake Karachay - at least 50% of the incoming part of the water balance

- period 1979-2005 characterized by a constant decrease in technogenic volumes from -153.5 thousand m^3 (1982) to ~ 15.5 thousand m^3 (2003); on average ~ 60 thousand m^3 / year, and in the last 10 years - 33 thousand m^3 / year. (Aleksakhin, 2007)

Due to the development and implementation of new technological processes and optimization of water consumption during the period from 2005 to 2011, the volume and activity of discharges were reduced by 1.2–1.5 times compared to the period 2000–2004 due to the development and implementation of a number of new technological processes and optimized water consumption. In 2009, due to the optimization of the internal LRW management scheme, the discharge of two types of waste into the water bodies V-9 and V-17 was stopped.

The initial stage of exploitation of Lake Karachay was characterized by a large volume of discharges, which led to an increase in the area of the water area. The gently sloping (saucer-shaped) form of the basin of the reservoir determined a significant change in area with fluctuations in water level. So, in the autumn of 1962, the mirror of the lake was 51 ha.

From 1963–1964 measures were taken to reduce the catchment area in order to reduce the migration of radionuclides together with the groundwater. In the dry period (1966-1967), the water level of Lake Karachay significantly decreased, while 2.3 hectares of the coastal strip and 2-3 hectares of the bottom of the lake were exposed, which led to the spread of about 600 Ki of activity with dust.

Not only the quantitative, but also the qualitative composition of the discharges changed. The chemical and radionuclide composition of water during the operation of the reservoir (since 1951) underwent significant changes depending on the technology used and production volumes.

The period 1951-1970 is characterized by the maximum number of discharges and the total activity of the effluent solutions (90–140 thousand m^3 and 21–34 million Ki per year, mainly short-lived radionuclides); discharges contained a large amount of salts (up to 500 g / l sodium nitrate, up to 300 g / l aluminum nitrate, up to 60 g / l acetates, elevated levels of iron, chromium, nickel);

Since 1971, a transition to extraction technology has been made. As a result, the volume and total activity of wastewater decreased (to 15–20 thousand m^3 and about 1 million Ci per year; the mineralization of solutions decreased several times; organic substances (TBP, HCBD, synthine, amines, alcohols) appeared in the effluents; 60–80% of the total activity of the effluent was due to strontium-90 and cesium-137.

Over the years of operation, natural-technogenic sludges (more than 200 thousand m^3) were formed in the V-9 reservoir, represented by a complex mixture of clays, silts, humic acids, technogenic materials (organic substances, resins, easily moving oxides of iron, aluminum, chromium).

According to official data more than 120 MCI of the total activity of beta-emitting nuclides was accumulated in the lake over the period of exploitation. Given the decay of short-lived radionuclides, which mainly determine the activity of effluent solutions, the number of radionuclides entering the V-9 reservoir was significantly higher. According to Aleksakhin (2005), up to 2004, inclusively, 556 million Ki of active waste was discharged into Lake Karachay, of which over 500 million Ki was received for the period 1951-1977. (Aleksakhin, 2005, p.42-50)

The use of the V-9 reservoir as a storage facility for liquid radioactive waste immediately changed not only the radiation situation, but also the state of the reservoir itself:

1) The radiation background on the shoreline of the reservoir immediately increased to such an extent that the current tolerances actually did not allow personnel to approach the water. In the 1950s and 1960s, the exposure dose rate on the shore of a reservoir reached 0.005-0.02 P / s, which excluded any work without special protective equipment.

2) The density of the water inside the V-9 reservoir increased significantly (due to the high salinity, mainly due to the nitrate ion), reaching maximum values at the level of 1.095 g / cm^3 with a solids content of up to 145 g / l.

3) The hydrological and hydrogeological regime of the site has changed. The pond has ceased to be drying out. The groundwater regime has become coastal in type: a correlation formed between the groundwater level and the reservoir level.

At the same time, the level regime of groundwater has changed due to the general technogenic influence of the industrial site. A general increase should be noted in the level of groundwater: in the first years of operation of the reservoir, there was a “separation” of the level of the reservoir from the surface of the groundwater, i.e. the water level mark V-9 was noticeably (1.0–2.5 m) higher than the groundwater level marks around the reservoir.

4) As a result of the discharge of a large number of pulps, a layer of mobile bottom sediments — hydroxide industrial sludge — was formed. So, in areas near the tip of the discharge line, the layer of technogenic precipitation reached 2–2.5 m with a depth of V-9 at about 3 m in the same place. Thus, partially, the V-9 reservoir was a slurry storage.

As a result, the V-9 reservoir became a permanent source of environmental pollution (the influx of radionuclides with a filtration stream into the underground aquifer, the wind dispersal of radioactive aerosols from the surface of the water area and the coastal strip). After the commissioning of treatment facilities in the 1960s, 90% of the total aerosol emissions were precisely the radioactive aerosols of the lake. (Sokhina, 2001)

Lake Karachay was become a potential source of a major radiation accident. The main radiation risks of the operation of the reservoir in the open reservoir regime of LRW were caused by:
- filtration of LRW under the bed of a reservoir and subsequent migration of contaminated groundwater with the possibility of subsequent discharge into an open hydrographic system
- the probability of wind transport of aerosols containing radioactive substances from the water body of the reservoir and the coastal zone under abnormal meteorological conditions (strong wind, tornado).
- the probability of breakthrough of dams with flooding of the territory of nearby settlements).

During the May spill of 1962, three soil dams around the reservoir were urgently constructed, which was formally justified by a reduction in the surface runoff area and a decrease in the natural inflow of surface water into the reservoir. In fact, dams were poured on the saddles: the places of their construction testify to the real purpose of building dams - to prevent overflow of V-9 water with its outlet on unpolluted (or less soiled) slopes in the direction of the Techa and Michelyak rivers and the Mayak industrial site.

After the radiation incident of 1967, preventive measures were taken. During 1967–1971 work was carried out to backfill the previously flooded areas and shallow water, as well as to reclaim the area around the reservoir.

The complicated radiation situation that formed on Lake Karachay negatively affected flora and fauna, and also people's health. At a considerable distance from the lake, the grass dried up, trees died, people who approached the lake, animals received high doses of radiation. The decision to eliminate the water area of the Karachay reservoir was made in 1967 (order of the Ministry of Environment and Transport No. 0256 of 05.16.1967).

The backfilling of the lake began in the early 1970s. In November 2015, the water area of Lake Karachay was completely eliminated (covered by rocky soil), which excluded the removal of radionuclides from the water surface of the reservoir under abnormal weather conditions and a repetition of the situation of 1967. (Bochkareva, 2018)

Currently, the Karachay reservoir remains as a source of radioactive pollution of the environment near FSUE “Mayak”. As a result of filtration, radioactive and chemical pollution of the groundwater around the reservoir occurs. (Obninsk, 2019)

5.3 Composition of water and bottom sediments of Lake Karachay

At the beginning of 1970, radionuclides were distributed in Lake Karachay as follows: 7% in water, 41% in loamy pond beds, 52% in mobile bottom sediments (hydroxide silts). The following features of the chemical and radionuclide composition of water in Lake Karachay (V-9) can be distinguished:

- V-9 waters are nitrate-sodium highly mineralized alkaline solutions of an average level of activity (up to 0.05 Ki / L), increased concentrations of calcium, magnesium, sulfate and chloride ions are noted;
- water V-9 from the beginning of its operation has always been characterized by increased density;
- the radionuclide composition of water V-9 was always very complex, but during almost the entire period of operation, the main contribution to its activity was made by cesium-137, strontium-90, and ruthenium-106, which in recent years has already played a significant role in general radionuclide balance;
- the volumetric activity of the sum of alpha-emitting nuclides in the water of the reservoir was always about four orders of magnitude lower than the specific beta activity;
- during the operation of V-9, the concentration of uranium in the water of the reservoir varied in the range from 7 to 215 mg / l, volume alpha activity - from 2.7 · 103 to 6.3 · 105 Bq / l; there is no correlation between them; only fragmentary data are available on the isotopic composition of transuranic elements;
- the concentration of uranium in V-9 water during the last forty years of operation has remained relatively stable - changes occurred within the same order, with a slightly pronounced tendency to decrease;
- the maximum concentration of uranium is confined to the period of operation of the reservoir, when the water in it had an increased mineralization / density (until the mid-70s).

A factor stabilizing the concentration of radionuclides in the water of the reservoir V-9 is the process of their equilibrium distribution between bottom sediments and water (solid and liquid phases). According to the technological regulations, discharge solutions with pH> 7 were sent to the reservoir (acidic solutions were neutralized without fail). As a result, most of the radionuclides originally represented by metal cations in acidic solutions turned into a hydroxide precipitate (together with aluminum, iron, and manganese hydroxides). The slightly alkaline medium maintained in this way in V-9 water prevented the dissolution of hydroxide precipitates, the transition of radionuclides to a dissolved state, and their migration into groundwater with a filtration stream.

Comprehensive studies of the uncovered part of Lake Karachay showed a high level of water pollution and bottom sediments of the reservoir (Table 5).

Table 5. Distribution of radionuclides in water and bottom sediments of Lake Karachay (Ivanov, Postovalova & Drozhko, 2005, p. 23-34)

Pond environment, indicator and unit of measure		**Radionuclides**				
		Uranus - 235, 238	Plutonium -239, 240	Americium -241 + Plutonium - 238	Curium - 244	Neptunium -237 + Uranus - 234
Water	Max. volumetric activity, Bq / l (mg / l)	500 (17)	$3\cdot10^4$	$4\cdot10^5$	$2\cdot10^5$	$1\cdot10^4$
	total stock, Bq (Ki) / t	$2\cdot10^{11}$ (6) / 6,8	$2{,}6\cdot10^{14}$ ($7\cdot10^3$)			
Bottom sediments	maximum specific activity, Bq / kg dry weight (mg / kg dry weight)	$6{,}3\cdot10^5$ (21400)	$1{,}2\cdot10^9$	$1{,}2\cdot10^{10}$	$2{,}3\cdot10^9$	$2\cdot10^7$
	total stock, Bq (Ki) / t	$2{,}6\cdot10^{11}$ (8) / 9	$3\cdot10^{16}$ ($8\cdot10^5$)			
The total stock in the reservoir, Bq (Ki) / t		4,6·1011 (14) / 16	$3\cdot10^{16}$ ($8\cdot10^5$)			

The values given in Table 5 show:
- the alpha activity of V-9 water, which is mainly determined by americium-241 and curium-244;
- alpha activity of V-9 bottom sediments, which is mainly determined by americium-241, curium-244 and plutonium-239,240;
- volumetric / specific alpha activity of uranium both in water and in bottom sediments is 3-5 mathematical orders lower than that of trans-uranium elements;
- more than 99% of alpha-emitting radionuclides deposited in the bottom; uranium is distributed almost equally between water and bottom sediments (respectively 7 tons and 9 tons).

Uniquely large concentrations of radionuclides were detected for natural-technogenic objects the V-9 reservoir. The distribution of radionuclides between water and bottom sediments indicates that bottom sediments create a powerful sorption barrier to the migration of transuranic elements into groundwater.

In subsequent years, the hydrological and hydro-chemical regime of the V-9 reservoir was characterized by stability with a distinct tendency to a decrease in the volumetric activity of water (Table 6).

Table 6. The chemical composition of the water of the reservoir V-9 in 2011

Metric Unit	**Quantity**
pH	8,48
Uranium, mg / dm^3	6,5
Sodium, mg / dm^3	1970
Calcium, mg / dm^3	–
Magnesium, mg / dm^3	–
Hardness, mmol / dm^3	6,60
Nitrate ion, mg / dm^3	4580
Nitrite ion, mg / dm^3	25,0
Ammonium ion, mg / dm^3	–
Chloride ion, mg / dm^3	42,9
Sulfate ion, mg / dm^3	69,4
Bicarbonate ion, mg / dm^3	394
Dry residue, mg / dm^3	7410
Hexachlorobutadiene (HCBD), mg / dm^3	<0,0003

The concentration of uranium and other pollutants is reduced due to their entry from the reservoir V-9 into groundwater.

5.4 Groundwater pollution from Lake Karachay

During the operation of the reservoir, about 5–6.6 million m^3 of technologically contaminated solutions came into groundwater from it. As a result of the infiltration of technogenic components (radionuclides and stable chemical pollutants) from the lake's waters into the underlying rocks in the underground hydrosphere under the lake and around it, a progressively expanding halo of radioactive sodium nitrate waters arose, the area of which reaches more than 20 km^2. A marker of industrial groundwater pollution in the V-9 area is nitrate ion, which, having the highest migration ability compared to radioactive components, forms the largest halos in area.

Further spreading of contaminated water poses a serious threat to the penetration of radioactive and stable toxicants into the lake-river network and drinking water intakes. (Velichkin, 2008, p.389-400)

The main components of groundwater contaminants are man-made radionuclides - strontium-90, tritium, cesium-137, uranium and other long-lived alpha emitters.

The distribution of various pollutant components with groundwater in the Lake Karachay region is affected by a number of factors, including the nature of the interaction of pollutants with the host geological environment.

Contaminated waters have a specific gravity of more than one (1.095 g / cm^3), and therefore plunge into tectonic structures formed on the rocky base of andesite-basalts. This determines the specifics of migration of polluted waters filtered from the reservoir: the initial direction of migration is with a downward flow and gravitational displacement of cleaner natural waters; later on, the main stream of contaminated water spreads over the surface of the conditional water storage. Contingent waterproofing is a practically waterproof rock base, consisting of a layer of least fractured and least permeable bedrock (porphyrites), which is located at a depth of about 60-100 m.

Then the denser contaminated solutions (compared with the pure groundwaters) from Lake Karachay spread over the water-resistant horizon. Further migration of contaminant components occurs in the groundwater flow and is determined by the properties of this flow, as well as by the processes of dispersion, dilution and radioactive decay of radionuclides.

The main channels of transport of polluted groundwater are the rocks of weathering crust. The directions of spreading and the configuration of the halo contaminated with radionuclides are determined by the fact that the boundary of rock and weathering rocks has a slope to the north-north-east and south-south-east of Lake Karachay. Groundwater also moves along linear trough-shaped depressions associated with zones of tectonic disturbances in the relief of the rock base.

Hydro-chemical studies have shown that the front of the halo of groundwater pollution of Lake Karachay is identified by the presence of abnormal concentrations of NO_3 ion (> 45 mg / l) in the water. Nitrate ion is inert with respect to mineral rocks, so it spreads unhindered. All radionuclides that have concentrations that are biohazard are recorded within the halo of nitrate distribution.

The delay in the spread of No_3 ions is caused by the processes of interaction of radioisotopes with host rocks. The intensity of these interactions is determined by the individual geochemical properties of the radionuclides, the compositions and physicochemical parameters of the transporting waters and the geological environment.

The weathered andesite-basalts contain newly formed clay and mixed-layer minerals that adsorb radionuclides and thereby slow their migration. The sorption capacity of minerals for different radionuclides is different, which determines the unequal migration mobility of pollutants. Also, the delay in the spread of radionuclides is affected by neutralization and restoration barriers that can occur in the strata of geochemically heterogeneous rocks.

Table 7 presents the distribution coefficient of uranium, cesium and strontium in the rocks of the Lake Karachay district.

Table 7. The distribution of radionuclides depending on the mineral composition of weathering rocks

Weathering Profile Zones	**The mineral composition of the rocks of the weathering profile**	**Distribution coefficient**		
		U	Cs	Sr
Clay Change Zone	Smkt*, Kaol, Smkt-Kaol, Gt, Gmt	824	376	81
Zone of initial clay changes	Gt, Cl-Smkt, Cl-Verm, Smkt, Gmt	817	520	50
Disintegration zone	Gt, Gmt, Cl-Verm, (Pl, Ab, Akt, Ser, Px, Ep	364	263	56

* Smkt - smectite; Kaol - kaolinite; Cl is chlorite; Verm - vermiculite; Gt is goeth; Gmt — hematite; Ol — olivine; Akt - actinolite; Ep is an epidote; Serp - serpentine; Cal is calcite; Ser is sericite, P1 plagioclase; Px-pyroxene; sericitis; Ab – albite

In eluvial rocks, hypergenic minerals prevail (vermiculite and mixed-layer chlorite-vermiculite). They have a large sorption capacity in relation to cesium; Therefore, they prevent the expansion of the area of its distribution. Currently, the area of groundwater pollution with cesium slightly exceeds the area of Lake Karachay.

Strontium radioisotopes are sorbed by weathered rocks, depending on the presence of alkaline-earth montmorillonite in them. However, its distribution in eluvial rocks is limited. Therefore, the amount of absorbed strontium radioisotope is relatively small. Therefore, the distribution area of $_{90}$Sr in the halo of contaminated groundwater is much larger than the halo of cesium development, but less than the halo of nitrate.

Hypergenic minerals intensively absorb dissolved uranium. However, the distribution area of waters with an anomalous uranium content is almost equal to the area of the abnormal distribution of an inert nitrate ion. This suggests that the bulk of the uranium in the halo under consideration is not in dissolved form, but in the form of colloids and / or complex compounds.

Mineralized radioactive waters have a near-neutral reaction and oxidizing properties. When contaminated waters are immersed along fracture zones in rocks consisting of basic volcanic rocks, the properties of the waters change to slightly alkaline and regenerative. This creates the conditions for the deposition of insoluble oxides of transuranic elements and carbonates containing strontium (strontianite, Sr-containing calcite).

According to many years of research, uranium and strontium-90 have the maximum distribution area in groundwater in the area of the V-9 reservoir (17 and 15 km^2, respectively) from all technogenic radionuclides (Figure 11).

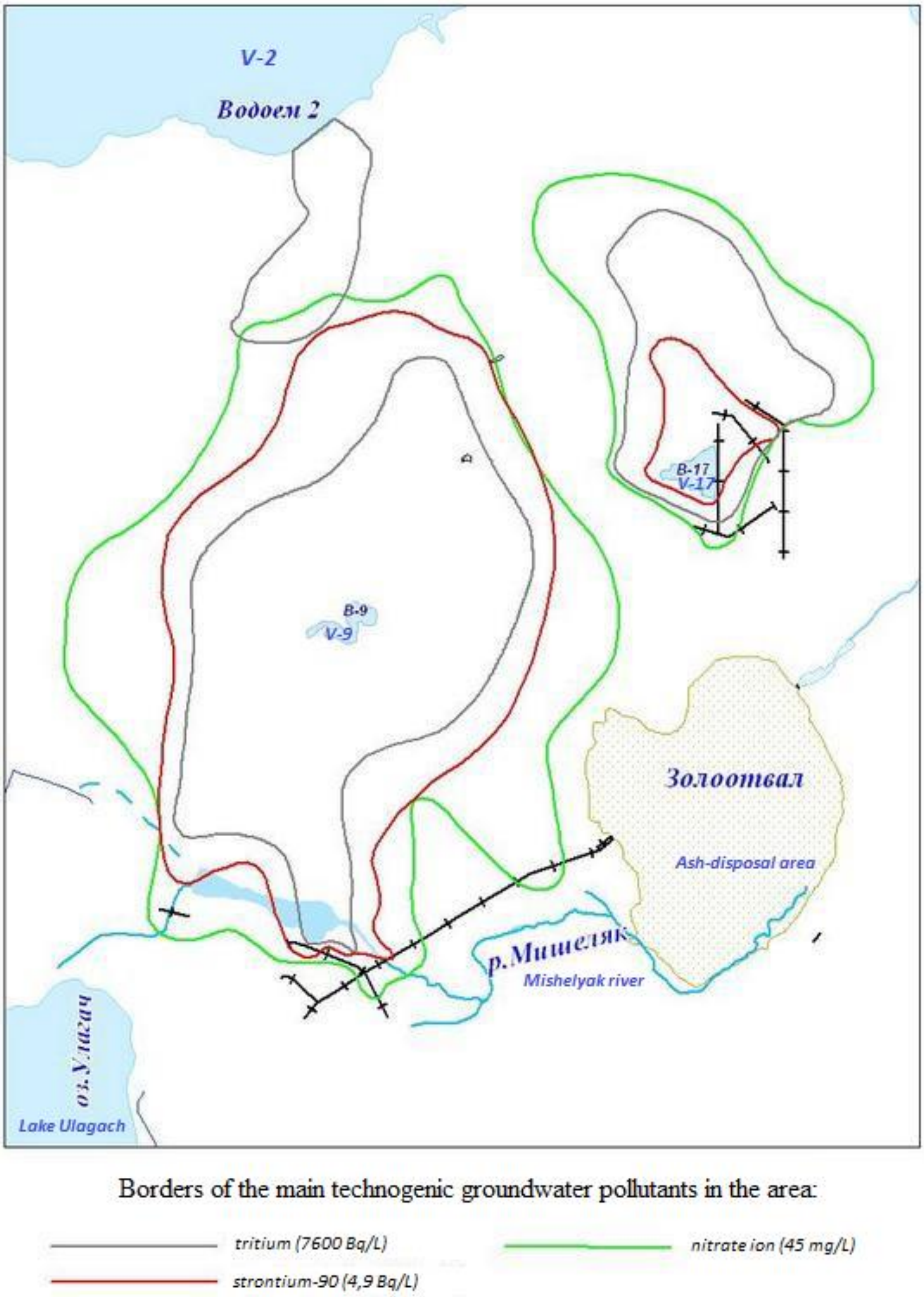


Figure 11. Distribution scheme of the main pollutants in the ground waters of the plant area and its reservoirs - V-9 and V-17 (as of 2011).

The isotopic composition of actinides in polluted groundwater according to the results of studies in 2001-2002 given in Table 8.

Table 8. Groundwater pollution by uranium and transuranic elements in comparison with surface water pollution of Lake Karachay. (Ivanov, Postovalova & Drozhko, 2005, p. 23-34)

	Characteristics of the contaminated waters, indicators and measure units	**Radionuclides**				
		Isotopes U	$^{239+240}$Pu	^{241}Am	^{244}Cm	^{237}Np
	Level of intervention values (according to NRB-99, Bq/L)	2,9-3,1	0,56	0,69	1,2	1,3
	Contribution to volumetric activity, %	97	0,06	0,2	0,002	2,7
	Volumetric activity (max), Bq/L	2300	2,1	6,4	14,0	18,2
	Intensity of groundwater pollution, **Volumetric activity (max)/Intervention level value**	766	3,7	9,3	11,7	14,0
	Contribution to volumetric activity (average), %	3,8	3,6	62,3	29,8	0,5
	Volumetric activity (max), Bq/L	$1,2\cdot10^4$	$9,0\cdot10^4$	$8,5\cdot10^5$ $(9,6\cdot10^5)$	$6,2\cdot10^5$	$3,3\cdot10^3$ (9,3·103)
	Intensity of surface water pollution, **Volumetric activity (max)/Intervention level value**	$4,1\cdot10^3$	$1,6\cdot10^5$	$1,2\cdot10^6$	$5,1\cdot10^5$	$2,5\cdot10^3$

Table 8 shows that groundwater is much less polluted compared with the activity of transuranic pollution in the source (V-9), where the values of the safe level of exposure are exceeded thousands and millions of times;

Transuranic elements (plutonium-239,240, neptunium-237, americium-241, curium-244) form around Lake Karachay are spatially combined (including with uranium, nitrate ion and strontium-90) halos (Figure 12).

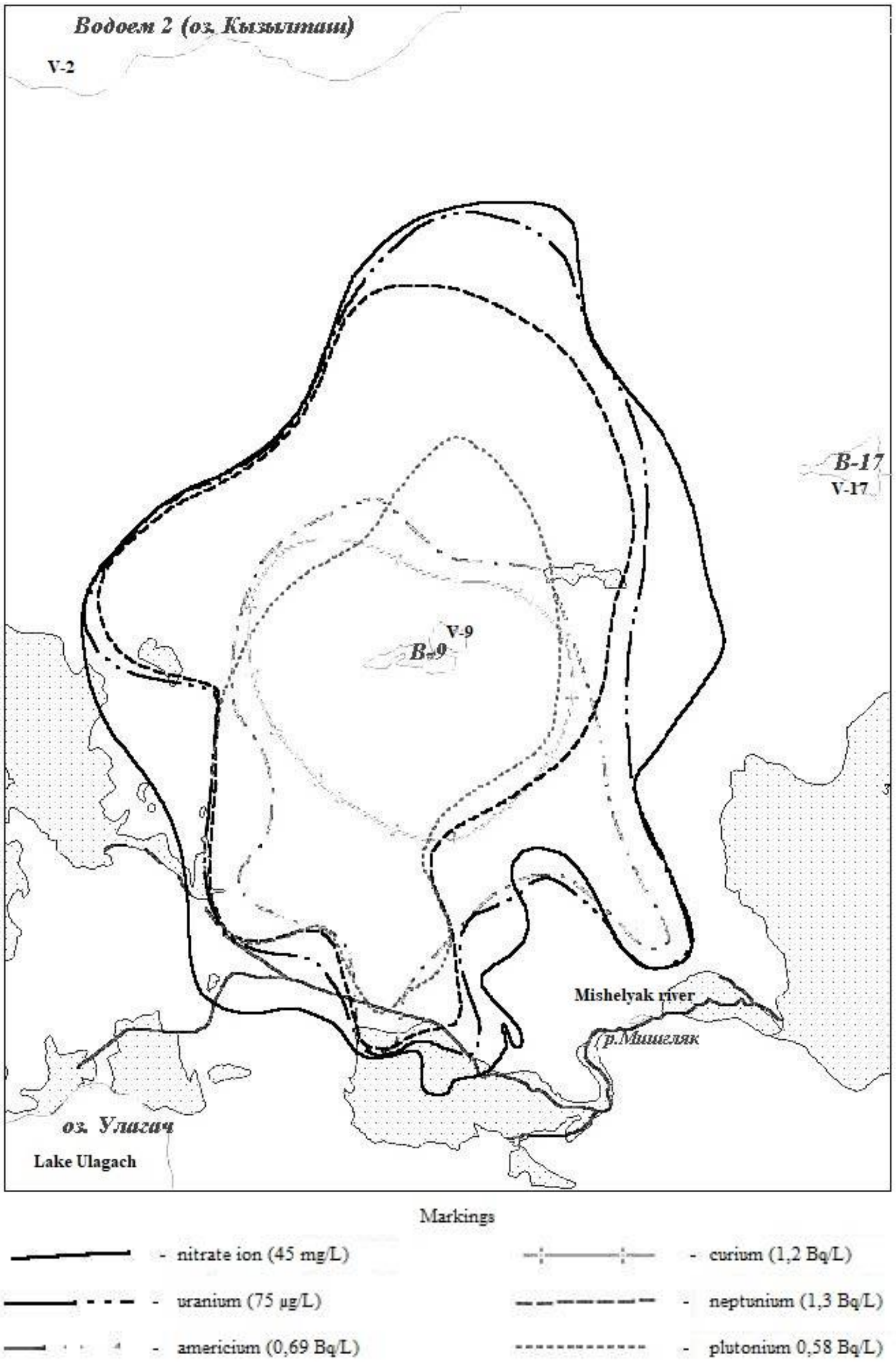


Figure 12. The distribution pattern of uranium, actinides, and nitrate ions in groundwater in the lake district.

Three zones are distinguished in the halo of uranium distribution:
- highly concentrated solutions (with a uranium content of more than 10 mg / l),
- the low-level (by uranium) liquid waste in the aquifer zone (with a uranium content of 750 μg / l, up to 10 mg / l),
- contaminated groundwater (with a uranium content of 75 to 750 μg / l).

According to the results of hydrogeochemical monitoring, the halo of the groundwater pollution in the V-9 region is characterized by a rather stable position, there is no noticeable expansion of its borders, although there is an increase in the concentrations of the main pollutant components in the frontal parts of the halo, which indicates the continuation of migration processes.

6. MEASURES TAKEN IN ORDER TO ELIMINATE THE EFFECTS OF RADIOACTIVE CONTAMINATION OF LAKE KARACHAY

After the spread of radioactive dust in 1967, the exposed sections of the coast and part of the shallow water of Lake Karachay were covered with loamy soils. As a result, surface marks of the coastal strip were raised by 1.7-3.0 m compared to the water level along the entire perimeter of the reservoir.

6.1 History of conservation of Lake Karachay

In 1969–1971 a steep rocky slope of the shore of the reservoir was backfilled. The coastal slopes formed as a result of these works and the elevated coastal strip changed the geometry of the Karachay basin: instead of a reservoir with a saucer-shaped bowl, a reservoir with steep coastal slopes similar to the walls of a glass appeared.

Water level control was established; if required, Karachay was specially fed with water. Backfilling of the water area itself was impossible; bottom sediments were forced out to the surface of the water.

In 1973, the first attempt was made to backfill the waters with rocky soil. The water surface of Lake Karachay was reduced to 36 ha.

Later, in 1980, calibrated stone with a diameter of about 30 centimeters began to be used for backfilling. However, backfilling in places with a large layer of sediments still led to the displacement of silts with radioactive deposits to the surface.

By 1986, experts had developed a unique technology for backfilling a reservoir with rocky soil using hollow concrete blocks.

Taking into account the results of the experimental work, projects were developed to eliminate the V-9 reservoir, providing for the creation of a rock-block massif at the site of the water area in the contour of the reservoir in 1973 (within the boundaries of the stone embankment of the coasts of 1970–1972).

The laying of the lake was carried out in several stages. The pond itself was divided into zones. (Figure 13)

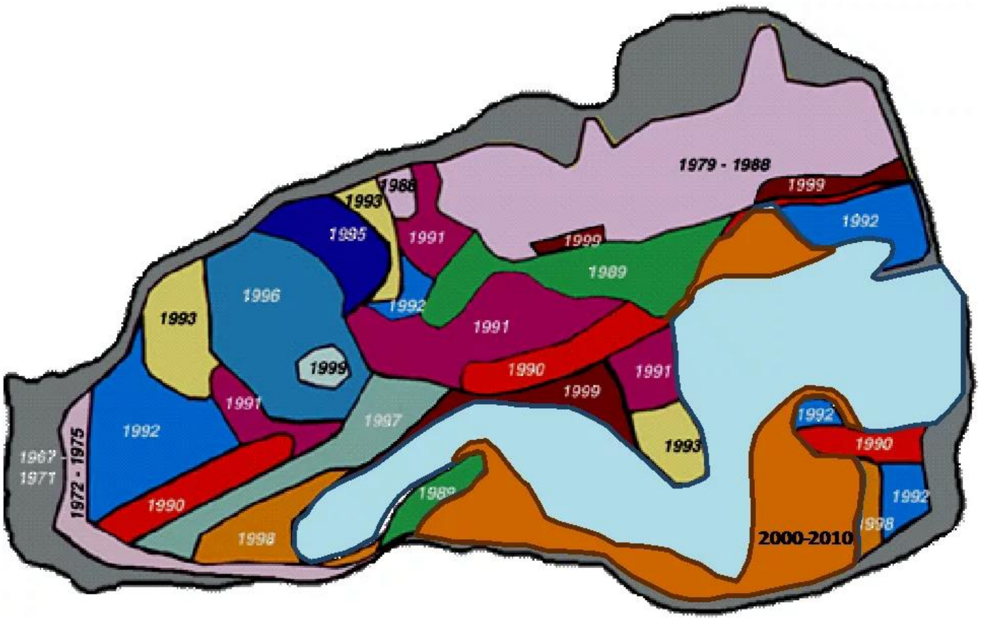


Figure 13. The scheme of filling the water area of Lake Karachay from 1972 to 1999 (Akleev, 2006)

The projects of the first and second phases envisaged the following volumes of work:

1) First of all, sections of the water area were closed near the heads of the old waste lines, where the main stocks of man-made sludge were concentrated. A new discharge line was launched in 1977.
2) The construction of dams dividing the reservoir into checks took place to reduce wave formation and reduce the removal of radionuclides with droplets of waves and surf, as well as reducing the risks of the spread of radioactivity with the possible passage of the tornado across the water area.
3) The construction of a block-rock mass of a certain porosity for reliable localization of highly active hydroxide industrial sludge.
4) Maintaining the level of the reservoir (as well as the pore water of the backfill massif) in the routine marks, while it was assumed that the lack of water supply would be compensated by the entry into the water of certain volumes of rocky soil and concrete blocks.
5) A certain order of construction of structural layers, i.e. the construction of the upper, cleaner layers after the closure of the water area by a rock-block massif. This ensures the possibility of gradual rehabilitation of the entire site of the reservoir and the clean surface of the future burial site being built on site of V-9.
6) The construction of the gravelly capillary-interrupting layer on the surface of the rock-block massif to prevent possible capillary rise of contaminated water and secondary pollution of clean structural layers and the surface of the repository.
7) The construction of a waterproofing loamy layer to exclude atmospheric nutrition of the repository, operated after the closure of V-9.
8) The construction of a shallow annular drainage ditch around the dump massif after its final formation.

The discharge of pulps into in the V-9 reservoir was stopped in the middle 1980s, which significantly reduced the accumulation of man-made hydroxide sludge. Sites with a layer of silt of low power were covered only with rocky soil without the use of concrete blocks.

The closure of the northeastern section of the water area was already completed in 1985-1987, confirming the correctness of the adopted technical solutions. In the closed part of the water area, about 60% of the total volume of hydroxide sludge was contained. As a result, 70% of all accumulated activity was localized, and the reservoir area was reduced by a third. (Mokrov & Aleksakhin, 2018, p.60-68)

The radiation situation at the site of the V-9 reservoir has improved significantly.
Since the 1980s a change in the meteorological conditions of the Southern Urals was noted, namely, an increase in precipitation and an increase in average annual precipitation over evaporation (by approximately 100 mm). In this regard, the level of water bodies and groundwater in the territory has increased.

In 2004-2005, the project of the third stage of conservation was developed and began to be implemented, involving the final closure of the water area in high water conditions. Technological measures were envisaged to reduce the levels of surface and underground waters, which made it possible to stabilize the level of water in a reservoir taking into account the existing discharge:

1) The construction of the waterproofing loamy layer on the porous rock-block massif of the closed part
2) Redevelopment of the relief in order to lower the areas of the nearest hills and to reduce runoff from them into the reservoir. Therefore, rocky material for filling was mined in the immediate vicinity of the reservoir V-9.
3) Preservation of the structure of the water balance of the reservoir. For this, the most filtering sections of the bed were supposed to be closed last. For the bookmark, BP-1 blocks were used, which provided increased porosity and permeability of the backfill array.
4) The construction of a semi-ring water interception trench around the Karachay reservoir, which in high water years is able to intercept the stream of clean underground waters unloading in V-9.
5) Filling the wetlands in the immediate vicinity of the reservoir with the construction of a waterproofing loamy layer on the surface. This ensured a reduction in groundwater infiltration supply at the site of V-9.
6) Implementation of water disposal from remote areas of the V-9 reservoir, which, in accordance with the structure of the regional groundwater flow, affect the groundwater level in the area of V-9 itself.
7) Strengthening the surface of the upper structural layer by sowing selected grass or shrub crops, which will provide additional evaporation of water due to transpiration.

The works on closing the water area of the Karachay reservoir, performed in the period 2004-2007, allowed to reduce the water area from 11.6 hectares to 7.8 hectares. On average, closing rates were in line with estimates - up to 2.2 ha / year. Table 9 below lists the work carried out to conserve the lake in the years 2011-2015.

Table 9. Work on the conservation of the lake, carried out in 2011-2015

Ongoing work	**Result**
Gravity preservation	Liquidation of the hydraulic connection between the backfill massif and the adjacent territory
Completion of the construction of a drainage upland canal	Discharge of surface runoff from B-9 in order to reduce the incoming component of the water balance
Construction of RMM, washing, engineering summary network plan	Creation of infrastructure for work
Organizational and technical preparation of the site for the preparation of the stone and the landfill	Preparation of the necessary work sites for the final conservation of the water area
Building conservation 190	Ensuring long-term safe operation of the building 190
Relief layout	Decrease in the incoming component of the water balance
Geodetic works	Ensuring the implementation of conservation work
Filling the water area with a calibrated stone	Preservation of the reservoir V-9
Development of a monitoring system (P-4 installation; transfer of a water-measuring post to P-4, creation of an automated monitoring system)	Improving the monitoring system V-9
Localization of the lens of contaminated groundwater (construction of a "guard" water intake)	Creating an emergency system

Figure 14 below schematically presents the closing area of Lake Karachay in the period 1998-2015.

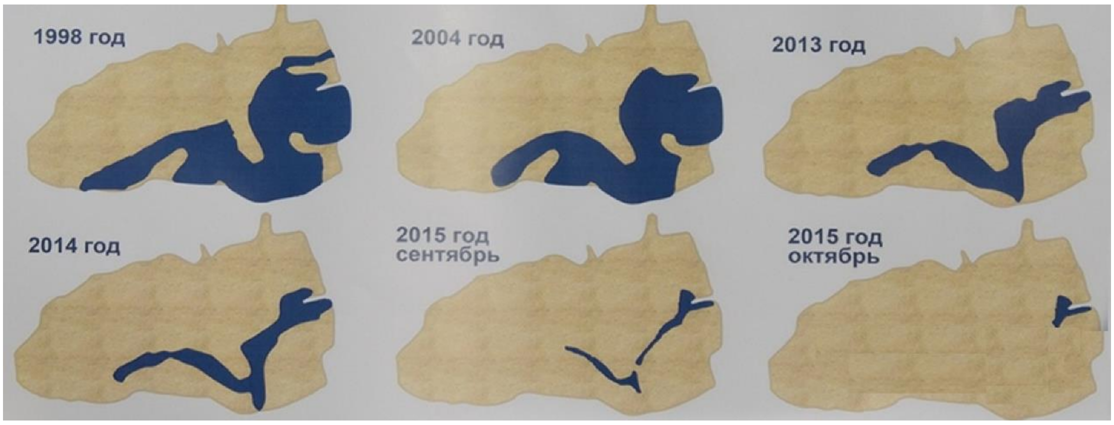


Figure 14. The water area of Lake Karachay in the period 1998-2015

Work on the elimination of the water area of the V-9 reservoir was completed on November 26, 2015. Since 2016, FSUE PA Mayak has been planning the terrain in the closed water area of the Karachay reservoir and taking measures to transfer the reservoir to the special radioactive waste storage facility.

6.2 Backfill of Lake Karachay

The liquidation process of Lake Karachay started in 1969 and took more than 40 years, primarily due to the technical complexity of the problem.

At the beginning of the work, about 15–20 thousand m^2 of shallow waters were filled up with loamy soil. However, it was not easy to fill up those parts of the reservoir where the largest amount of hydroxide sludge was accumulated. The soils pushed into the reservoir displaced light hydroxide silts, which began to protrude to the surface in front of the backfill. The exposure of bottom sediments, which are actually highly active wastes, created a pre-emergency situation similar to the wind dispersal of radioactive aerosols in 1967.

The sludge outflows that arose during the backfill operations of V-9 (both experimental and industrial) were washed away with a water jet from a hydraulic monitor.

In addition, the exposal of technogenic sludge in working area led to a severe increase in the radiation levels. Thus, according to the results of the first experimental work on liquidation of the V-9 reservoir, it turned out that the backfill array should have such an active pore structure that it would fully consume the technogenic silts.

From 1973, rocky soil was used in order to fill up the V-9 reservoir. The experimental results showed that the use of uncalibrated rocky soil allows to create an array with an effective porosity of 0.2, and a calibrated one (with fragments ≥ 0.3 m3) with an effective porosity of 0.3. However, the use of even calibrated stone in areas with a large thickness of the layer of industrial sludge led to their displacement above the water surface. The lack of effective porosity of the created bulk mass was the main disadvantage of using rocky soil as a material for backfilling.

After considering many different materials and methods for reducing the water area of the V-9 reservoir, two methods were worked out in more detail:
1) the creation of a cement mass directly in the water area of the V-9 reservoir;
2) closing (filling) the water area with rocky soil using special building structures.

The second method was recognized as the most economically feasible.

In the period between 1983-1985, the technology for backfill of the V-9 reservoir with the use of the PB-1 blocks, specially designed and manufactured at the Mayak Production Association, was developed and tested on a pilot scale.

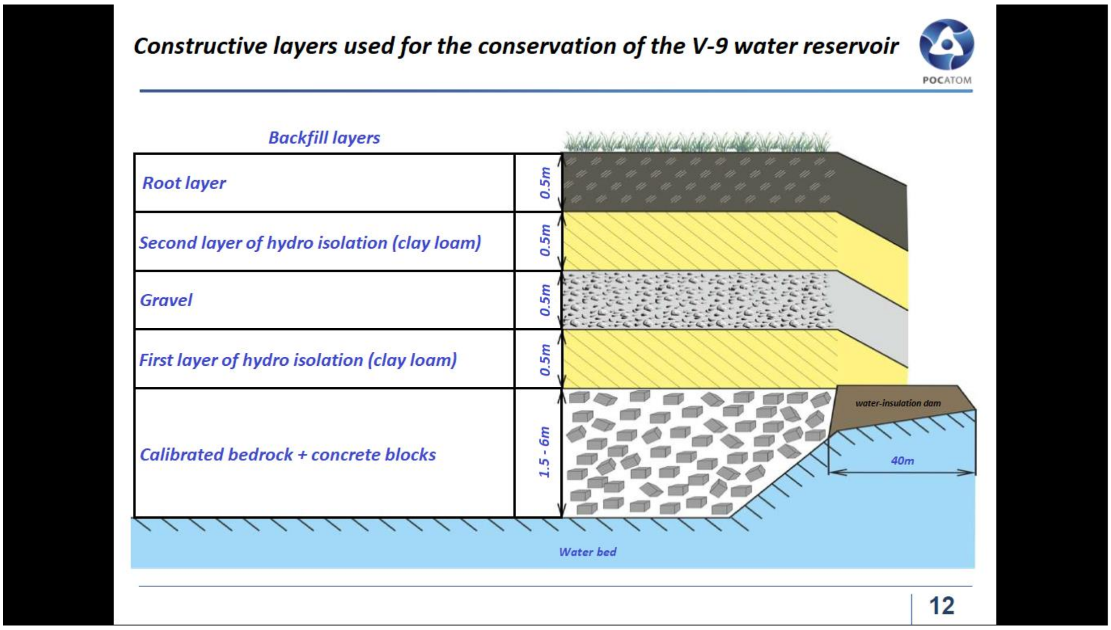
The technology consisted of installing concrete blocks in the water area from the shore and “loading” them with rocky soil.

Block PB-1 is a hollow reinforced concrete structure of a cubic shape with a wall thickness of 0.1 m and an open bottom. The blocks were supposed to be installed in one or two rows. The effective porosity of an array constructed only from PB-1 blocks is 0.605.

In areas with an increased thickness of the industrial sludge layer (> 1 m) the closure was carried out by cutting off sections of the storage facility with short dams with their subsequent closure. In the case of sludge rising to the water surface, the final closure of the site was carried out in the winter, after the ice cover was established.

To install the blocks in the V-9 reservoir, an engineering demolition machine was used. The main purpose of the machine was to disassemble the debris and create passages in the centers of nuclear destruction, which made it possible to install structural elements from the shore into the water.

The main principle of preservation of Lake Karachay was an on-site burial of the object together with an isolation of activity accumulated in the silts and soils of the bed, both above and below. The Figure 15 below shows the constructive layers used for the conservation of the V-9 water reservoir.



Constructive layers used for the conservation of the V-9 water reservoir

Backfill layers

Root layer	0.5m
Second layer of hydro isolation (clay loam)	0.5m
Gravel	0.5m
First layer of hydro isolation (clay loam)	0.5m
Calibrated bedrock + concrete blocks	1.5 - 6m

Figure 15. Conservation of the V-9 water reservoir, structural levels

The rock was delivered to the site from quarries and stored near the lake. Later, excavators poured rocky soil into KrAZ – 256B1 trucks. All the machinery was protected by lead shields, the glass thickness of the machines was 70 mm, the weight of the cabins reached 4 tons.

The blocks were laid by an engineering machine built on the base of the T – 55 tanks (Figure 16).

Figure 16. Backfill blocks PB-1

6.3 Results of the liquidation work

After the water area of the V-9 reservoir was completely closed in November 2015, the facility acquired the status of a special radioactive waste storage, which requires constant monitoring, as well as an assessment and forecast of its impact on air pollution, groundwater and surface waters. The basis of the complex of works to ensure the safe condition of the V-9 reservoir is the monitoring of the state of Lake Karachay and the environment.

The parameters of radionuclide contamination of atmospheric air, groundwater and pore water of the massif of backfill, soil, vegetation and snow are observed; groundwater and pore water levels of the backfill array are monitored.

Over the entire period of the conservation of the reservoir, the radiation situation was improving and a decrease in the volumetric activity of the atmosphere in the region of the reservoir was registered.

The emission power of radionuclides is proportional to the specific activity of the water of the reservoir and its area. In total, from 1952 to 2015, the total fallout of cesium-137 discharged from the water area of the V-9 reservoir is estimated at 30.0 kBq / m2 (0.8 Ci / km^2).

Due to the decrease in wind ablation of water aerosols from the decreasing water area of Lake Karachay, the precipitation density of the sum of β-emitting radionuclides for the period 1991—2016 decreased by more than 20 times (Figure 17).

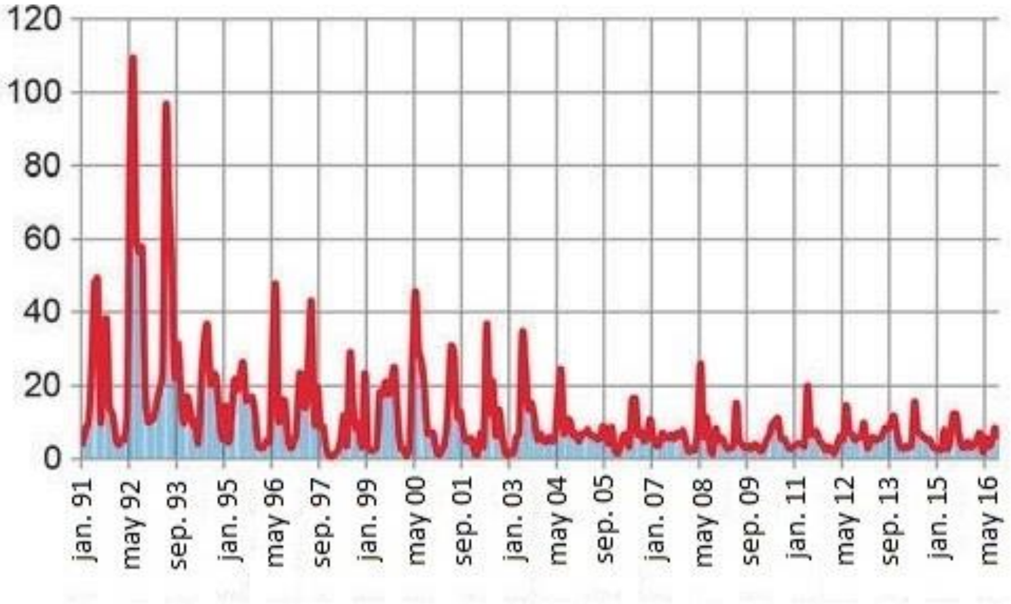


Figure 17. Dynamics deposition density of beta-emitting radionuclides (Bq / m^2 ·month) on the territory of the radiochemical plant 1991—2016.
(Mokrov & Aleksakhin, 2018, p.60-68)

After the liquidation of the water area of Lake Karachay, the probability of the occurrence of radioactive incidents due to abnormal weather conditions (similar to the situation of 1967) is excluded.

The stopping of filtration of technologically polluted waters into the underlying layers led to the stabilization of the halo of groundwater pollution in the V-9 region. According to geochemical observations of recent years, the halo of groundwater pollution is characterized by a rather stable position (Mokrov, 2018).

The monitoring results and model calculations of the development of the situation associated with the spread of radionuclide contamination in groundwater show that over the next 300 years (and even more so in the long term) the contaminated groundwater of the Karachay region will never have any noticeable or even slightly dangerous impacts on the open hydrographic network of the region for the environment and humans.

The results of ongoing monitoring and modeling indicate that even a large aureole of groundwater pollution in the V-9 area does not and will never create a significant influx of radionuclides into an open hydrographic network. According to forecasts, the parameters of groundwater pollution will only decrease in the future, and the halo of groundwater pollution by radionuclides from the Karachay reservoir will gradually degrade.

Thus, the carried-out complex of works on conservation of Lake Karachay allowed to significantly improve the radiation situation in the impact zone of the Mayak Production Association.

7. CONCLUSION

The current state of the environment in the region where FSUE PA «Mayak» is located was formed as a result of an unprecedented in terms of time and complexity tasks of the enterprise’s defense activities in the early 1950s to create nuclear deterrence weapons. The main objective of the plant was the production of weapons-grade plutonium. The major production facilities of PA «Mayak» — uranium-graphite reactors, radio-chemical and chemical-metallurgical plants — posed a serious threat of radioactive contamination to the environment. A large amount of liquid radioactive waste was generated in the process.

As a result of the activities of PA «Mayak», significant territories of the Ural region were exposed to radioactive contamination. The main sources of radioactive pollution of the environment were major radiation accidents, the discharge of large volumes of liquid radioactive waste (including highly active waste) into open water bodies and man-made emissions into the atmosphere. The largest radiation accidents included the discharge of liquid radioactive waste into the Techa river in 1949–1956, the explosion of a radioactive waste storage facility in 1957, the wind transfer of man-made radionuclides from the dried-up shoreline of Lake Karachay in 1967. The formation of a EURT (1957) and the Karachaevsky trace (1967) led to the pollution of 446.8 km^2 of the territory of the Chelyabinsk, Sverdlovsk, Kurgan and Tyumen regions. Of these, 195.96 km^2 are in the sanitary protection zone. Many ecosystems were severely disturbed, especially in the head part of the WURS. Increased radiation doses were received not only by the Mayak personnel, but also by residents of the coastal areas of the Techa river, Chelyabinsk and Kurgan Regions.

The main reasons for the large-scale radioactive contamination of the environment in the “Mayak” impact region were the lack of experience and knowledge in the field of radioactive waste management, the imperfection of technological processes and the mistakes of developers and maintenance personnel.

The long-term complex impact of radiation, thermal and chemical factors have led to a significant radiation pollution of industrial reservoirs included in the production cycle of the Mayak Production Association. Particularly severe pollution occurred in water bodies where liquid radioactive waste was discharged: the Techa river (before 1956), the Techen cascade of water bodies (V-3, V-4, V-10, V-11), Lake Karachay (V-9), Old Boloto (V-17), as well as the reservoir-cooler Lake Kyzyltash (V-2).

A progressively expanding halo of radioactive sodium nitrate waters with an area of 14-19 km^2 arose in groundwater under Lake Karachay in the period between 1956-2015. The thickness of the halo corresponds to the thickness of the aquifer and ranges from 40-60 to 100 and more meters. The halo is characterized by a multicomponent composition. The main pollutants are strontium-90, uranium, cesium-137 and other long-lived alpha emitters. The maximum concentrations of the components are confined to the lower parts of the aquifer; their migration is directed mainly to the south (towards the Michelyak river valley) and north (towards the TKV).

The decision to preserve Lake Karachay was made in May 1967; the work to eliminate the reservoir was completed on November 28, 2015. It was a multi-stage, technologically complex process. In order to prevent the displacement of radioactive mobile bottom sediments onto the surface, a special technology was developed for embedding with concrete blocks and rocky soil. Also, measures were taken to isolate the former water area from above and below, redevelop the relief, localize the lens of technologically contaminated groundwater, and organize emergency protection and monitoring. A radioactive waste repository will be operated on the site of the former Lake Karachay.

The carried-out complex of works on conservation of Lake Karachay allowed to significantly improve the radiation situation in the impact zone of the Mayak Production Association. First, the probability of the occurrence of radioactive incidents related to the spread of aerosols from the surface of the water area and the shores of the lake is excluded. Secondly, the stabilization of the groundwater pollution halo in the V-9 region was carried out, which eliminates the possibility of a significant influx of radionuclides into an open hydrographic network.

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