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RADIOACTIVE CONTAMINATION AT CHELYABINSK-65, RUSSIA

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INTRODUCTION

Fifteen kilometers east of the city of Kyshtym, on the east side of the Ural Mountains, sits the once secret complex of Chelyabinsk-65, home of the Mayak Chemical Combine. The Mayak facility housed the former Soviet Union's first industrial nuclear reactors, and produced the material for the country's first atomic bomb beginning in 1948. Over four decades of nuclear materials production and processing, the Mayak facility discharged effluents containing more than 123 million curies (MCi) of long-lived radioactivity into an open storage lake and other sites, from which some millions have leaked into the general environment. Although the facility has adopted a number of new procedures for managing the waste, serious problems remain.

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Chelyabinsk-65 did not receive foreign visitors, and was not on maps of the Soviet Union until 1989. Prior to about 1990, it was called Chelyabinsk-40. It is located in the area around Lake Kyzyltash, in the upper Techa River drainage basin among numerous other lakes with interconnecting watercourses. Chelyabinsk-65 is run by the production association Mayak (translated "Lighthouse" or "Beacon"), and the defense enterprise is referred to as the Mayak Chemical Combine. Between Lake Kyzyltash and Lake Irtyash, about 10 km from the reactor area, is Ozersk, the closed military-industrial city built to house the Chelyabinsk-65 workforce, and whose population is 83,500 (1).

Apparently fashioned after the US Hanford Reservation, Chelyabinsk-65 was the Soviet Union's first plutonium production complex. Construction was started on the first buildings of the new city in November 1945, and in June 1948 the first production reactor was brought on line (2).[1] Some 70,000 inmates of 12 labor camps were reportedly used to construct the complex (3).[2] Today the site occupies an area on the order of 200 km^2 (4). In 1989, a US delegation was told that there were some 10,000 employees and 40,000 dependents at Chelyabinsk-65.

The combine produced plutonium for nuclear weapons from 1948 until November 1, 1990. Chelyabinsk-65 now produces special isotopes, and reprocesses naval and civil power reactor fuel for plutonium and uranium recovery. The combine also produced special (read "military") instruments (5); in recent years it has begun to produce a variety of equipment for civilian use (6).

The known facilities at Chelyabinsk-65 are listed in Table 1. There are five graphite-moderated water-cooled production reactors and two light water–cooled and -moderated production reactors, one of which was a heavy water–moderated production reactor before being rebuilt in the late 1980s. The graphite reactors, which had a combined capacity of 6565 megawatts thermal (MWt), were used for plutonium production before being shut down. The two light water reactors, each with a capacity of about 1000 MWt, are used for the production of tritium and other isotopes.The Soviet nuclear weapons stockpile peaked in 1986, and has since declined by more than 20%. Consequently, tritium production may

[1]According to the posters on the wall in the A-reactor building, the development stages before startup included: from 1943—scientific research carried out; October 1945—geological prospecting began; February 1946—design completed; April 1946—government decree on beginning of construction issued. The construction area was assimilated August 4, 1946, and the first 40 specialists arrived on October 9, 1946.

[2]The city of Kyshtym is located on the railroad linking the industrial cities of Chelyabinsk and Yekaterinburg. The area has a long history of munitions production, dating back to the time of the czars.

Table 1 Facilities at the Mayak Chemical Combine (Chelyabinsk-65)

PRODUCTION REACTORS

Graphite Moderated (for plutonium production; all shut down)

- A-Reactor
- IR-Reactor
- AV-1 Reactor
- AV-2 Reactor
- AV-3 Reactor

Light Water Moderated (for tritium and special isotope production)

- Lyudmila (initially a heavy water reactor; rebuilt in late 1980s)
- Ruslan

CHEMICAL SEPARATION PLANTS

RT-1 (400 MT/y capacity; used for reprocessing naval and power reactor fuel)

Isotope separation facility ("The Vatican") used for special isotope production)

MIXED-OXIDE (MOX) FUEL FABRICATION PLANTS

Pilot Bay () MT plutonium alloys and PuO_2 fuel manufactured in the 1960s and 1970s)

"Zhemchug" operated from 1986 to 1987 with a capacity of 35 kg Pu/y (for 5 fuel assemblies/y) to produce fuel assemblies for fast reactors.

"Granat" has operated since 1988 with a capacity of 70–80 kg Pu/y (for 10 fuel assemblies/y) to produce fuel for testing in fast reactors.

"Paket" has operated since 1988 with a capacity of 70–80 kg Pu/y (for 10 fuel assemblies/y) to manufacture MOX pellets, and fabricate fuel elements for testing in fast reactors.

"Complex 300" Plant (construction suspended after 50–70% complete) has a design capacity of 5–6 MT Pu/y to manufacture fuel for BN-800 fast reactors.

TRITIUM HANDLING FACILITIES

SPENT FUEL STORAGE FACILITY (Interim pool storage for 2000 MT of VVER-440 spent fuel; construction suspended after 70% complete)

PLUTONIUM STORAGE FACILITY (contains about 25 MT of plutonium from naval and power reactors)

SOUTH URALS AES (site for three BN-800 LMFBR Reactors). Construction of all three units halted; two units abandoned; construction of the third unit, still in an early stage, may be resumed.

NUCLEAR WASTE FACILITIES

- Waste Storage Tanks (for high- and intermediate-level waste)
- Pilot Waste Vitrification Plant (500 l/h)
- Installation for "cleaning low-level waste"

FACILITIES FOR MANUFACTURING MANIPULATORS AND OTHER EQUIPMENT

FACILITIES FOR MANUFACTURING DEFENSE INDUSTRY EQUIPMENT

RADIOLOGICAL RESEARCH FACILITY

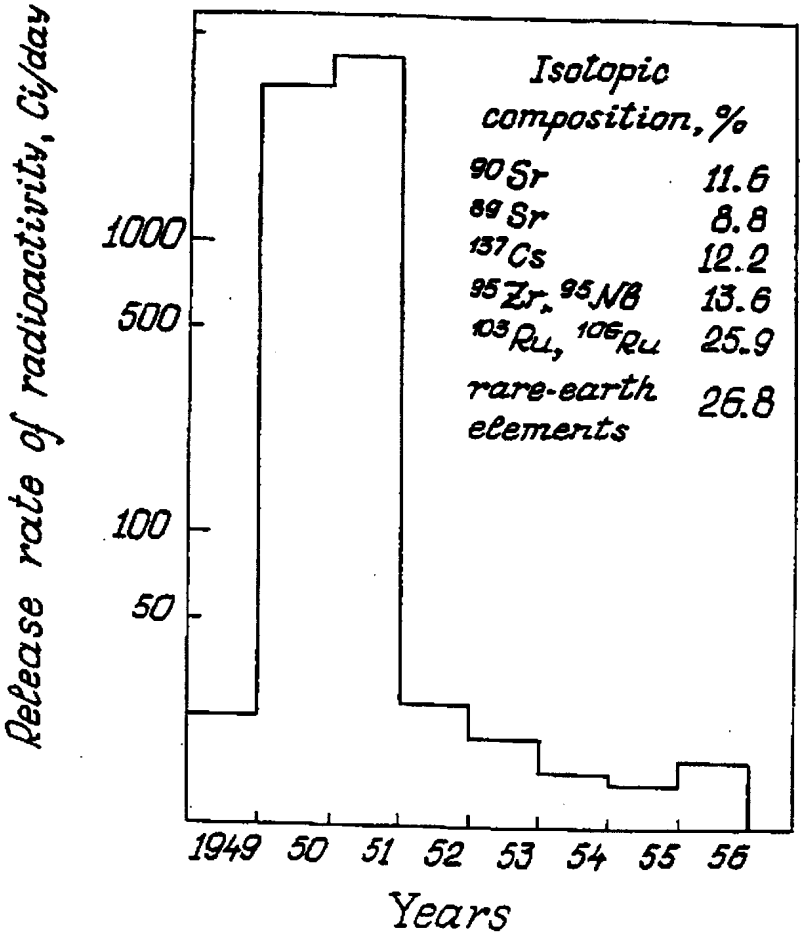

Figure 1 Radioactivity discharged into the Techa River, 1949–1956. Source: (10).

A radiation survey, taken in the summer of 1951, revealed extensive contamination of the floodplain and bed of the Techa River and excessive exposure to the inhabitants of the region. The greatest exposure was to the 1200 inhabitants of the village of Metlino, 7 km downstream from the release point. There, the gamma dose on the river bank was 5 roentgen/hour (R/h) in spots, 3.5 R/h at household patches near the river in the village, and 10–15 microroentgen/hour (μR/h) on roads and streets (11). (Many cities in the world have natural background level on the order of 10–20 μR/h.) A new solution was adopted in September 1951. Instead of dis-

charging the radioactive waste into the Techa River, the wastes were diverted into Karachay Lake (see below), and a series of artificial reservoirs was created along the Techa to retain most of the activity already discharged.

Some 124,000 people along the Techa-Iset'-Tobol River system were exposed to elevated levels of radiation, none having been warned about the danger (12). Ninety-nine percent of the radioactivity that was dumped into the Techa was deposited within the first 35 kilometers downstream (Figure 2). In 1949 there were 38 villages with 28,000 people along the Techa riverside 237 km downstream from the plant in Chelyabinsk and Kurgan oblasts (13, 14). For many of the 28,000, the river was the main source of drinking water.[7] From 1953 to 1960, 7500 people in the upper reaches of the Techa were relocated.[8] The water supply of other residents remaining along the Techa in 1956, including 4950 residents who would be resettled by 1961, was shifted to underground sources, and the radioactive floodplain was fenced off (18). The Techa River and 8000 hectares (ha)[9] of its floodlands were excluded from use for economic and drinking purposes, although this ban has not been strictly observed over the years.

An epidemiological study of the 28,100 exposed individuals who received substantial external and internal radiation doses found that a statistically significant increase in leukemia morbidity and mortality arose between 5 and 20 years after the initial exposure (19).[10] A search was made for other cancers, but the small increase in those is barely significant and unconvincing. The greatest exposure, estimated to average 140 rem effective dose equivalent, was received by the 1200 inhabitants of the town of Metlino, 7 km downstream from the release point (Table 2) (22, 23). Seventy-five hundred people from Metlino and 20 other population centers that were evacuated received average effective equivalent doses from 3.6 to 140 rem (24).

A cascade of four reservoirs (Nos. 3, 4, 10, and 11, shown in Figure 3) were created along the Techa just below Lake Kyzyltash (reservoir No.

[7]"The situation on the river Techa banks was also complicated because for the local population the river had been a major and even the only source of drinking and washing water. The wells were few, they were used by part of the population, not for all purposes since the well water here was by far of a more inferior quality in taste than the river water. Moreover, the river had been used for drinking by cattle, growing fowl, and watering vegetable gardens, fishing, bathing, washing, etc" (15).

[8]Ref. 16 says the evacuations were prior to 1960. Ref. 17 says the evacuations occurred from 1953 to 1961. Villages in the upper reaches of the Techa that were evacuated included Metlino, Tcha-Brod, Nazarovo, S. Asanovo, N. Asanovo, N. Taskino, and Gerasimovka.

[9]One hectare = 0.01 km^2 = 2.471 acres. Therefore, 8000 hectares = 80 km^2 = 30 mi^2.

[10]Thirty-seven leukemias (morbidity) were found versus 14–23 expected (19). For commentaries on Ref. 19, see (20, 21).

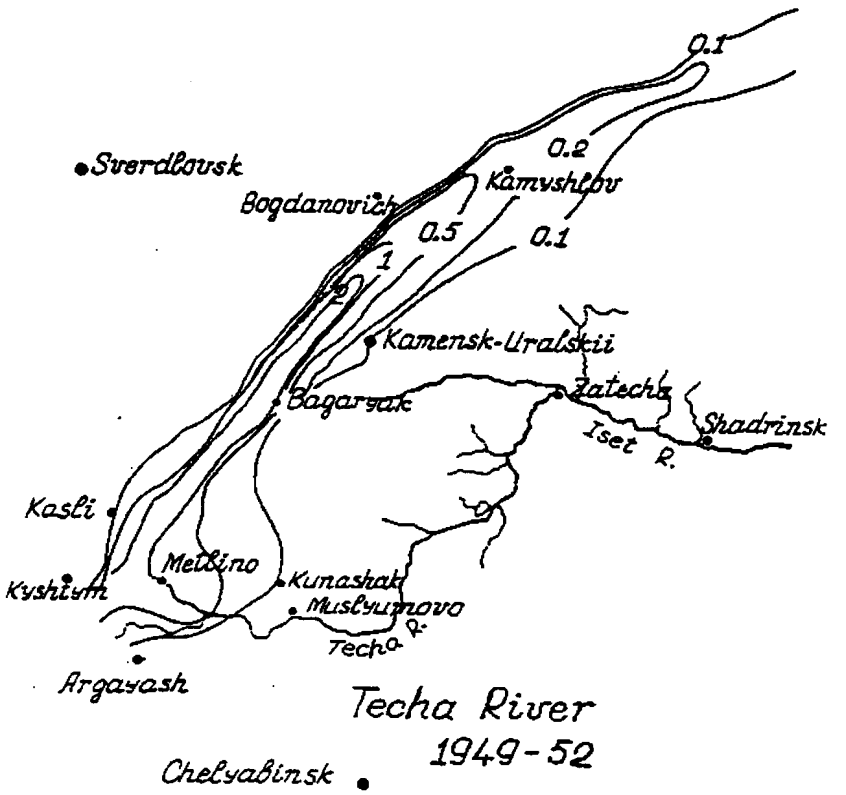

Figure 2 Radioactive fallout from the 1957 accident at Chelyabinsk-65 (contours in Ci/km^2). Sources: (13, 61)

2 in the same figure), to isolate water from the most contaminated areas. The first dam was erected in 1951, the second in 1956, the third in 1963, and the fourth in 1964. The reservoirs (including Lake Kyzyltash), with a combined area of 84 km^2 and volume of 380 million m^3, now contain about 193,000 Ci of Sr-90 and Cs-137 activity (Table 3). They reportedly "isolated about 98 percent of the radionuclides deposited in the flood-lands from the open hydrographic network," (26) but judging by the amount of Sr-90 and Cs-137 remaining, 80% would appear to be a more reasonable estimate. The decline in the concentration of radioactivity in the Techa slowed after 1952. It was hypothesized that "about 70 percent of the activity dumped in 1950–1951 had migrated into the bottom deposits of the Kohsharov and Metlinsk ponds in the upper reaches of the Techa and about 10 percent

Table 2 Organ dose estimates (external and internal) for inhabitants in some villages along the Techa River[a]

Village	Distance from point of release, km	Effective dose equivalent (rem)	Mean doses (rem)			
			Red bone marrow	Bone surfaces	Large intestine	Other tissues
Metlino	7[b]	140	164	226	140	127
	18[b]	119	127	148	119	115
	27[b]	100	127	190	104	90
	48[b]	56	95	180	62	44
Muslyumovo	78	24	61	143	29	12
	109	5.8	14	31	7	3.3
Russkaya Techa	138	8.2	22	53	10	3.7
	152	10	28	68	13	4.3
	202	3.6	8	18	2.6	2.2
Zatecha	237	6.6	17	40	8.4	3.2

[a] Source: (22)
[b] Villagers were evacuated.

into bottom deposits of the lower section of the river down to to 78 km from the discharge spot. In subsequent years the radioactively contaminated bottom deposits have become a powerful source of secondary contamination of the river water" (27).

The average annual concentrations of Sr-90 and Cs-137 in the Techa at the Muslyumovo settlement 78 km downstream from the reservoirs is shown in Table 4. The Asanovski marshes (or swamps), an area of 30 km^2 through which the Techa flows just below the last reservoir (No. 11), contain some 6000 Ci of Sr-90 and Cs-137 (29). There seems to be no data on how much radioactivity is transported from the marshes into the Techa.

Lake Karachay (Reservoir 9)

As noted above, in September 1951, the Soviets stopped discharging the diluted high-level wastes directly into the Techa, and instead diverted it into Lake Karachay—at the time, a natural 45-ha (110-acre), 2–3 m deep lake with no surface outlet (30). The intermediate waste storage facility (discussed below) apparently was not put into operation until 1953. Consequently, this practice may have continued for more than a year.

Since 1953, the Soviets have continued to discharge medium-level waste into Lake Karachay. In comparing the concentrations of cesium (Cs) and strontium (Sr) in the lake and the intermediate waste storage tanks, it appears that the precipitated sludge, which included most of the Sr, was retained

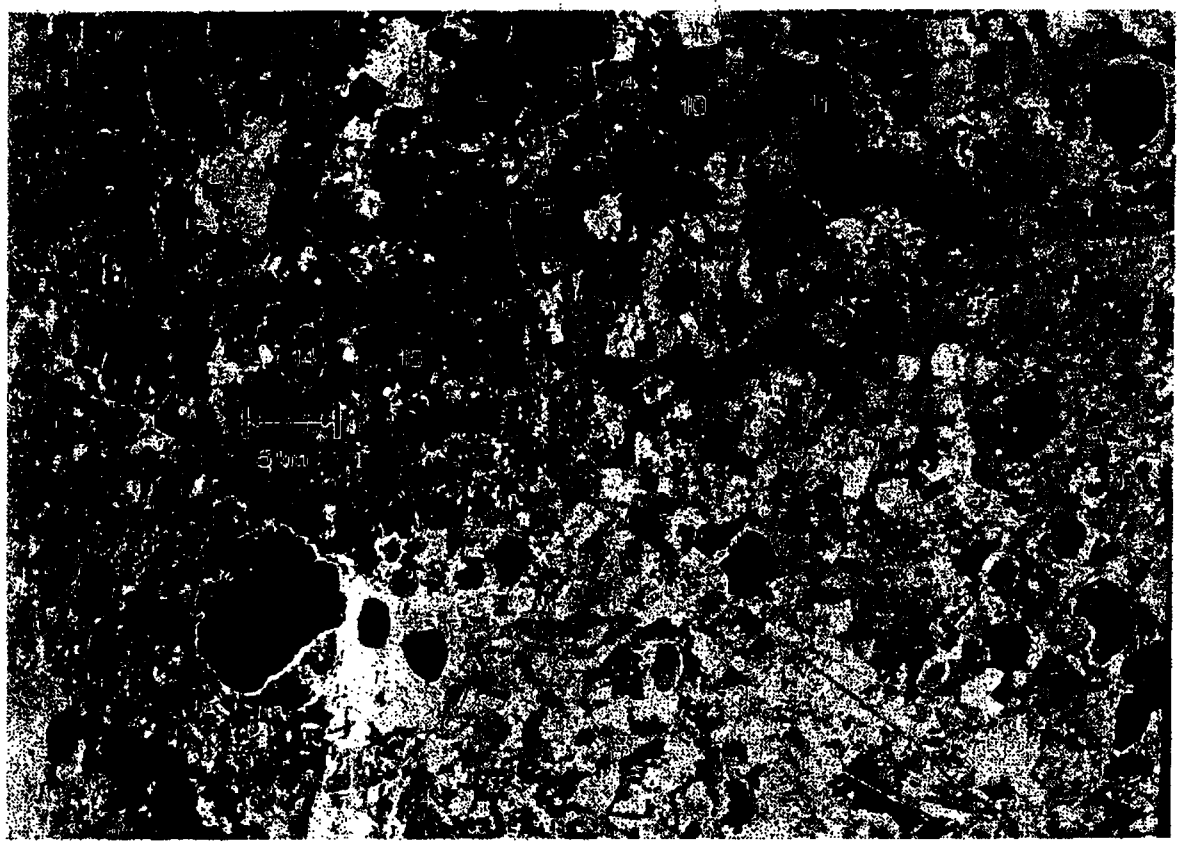

Figure 3 Reservoirs and lakes at Chelyabinsk-65. 1. Lake Irtyash (Reservoir number 1); 2. Lake Kyzyltash (Reservoir number 2); 3. Reservoir number 3; 4. Reservoir number 4; 5. South Urals Project (Construction of 3 BN-800 reactors); 6. Lake number 6; 7. Chelyabinsk-65 reactor area; 8. Ozersk (Chelyabinsk-65 residential area); 9. Lake Karachay; 10. Reservoir number 10; 11. Reservoir number 11; 12. Techa River; 13. Kyshtym; 14. Lake Bol'shaya Akulva; 15. Lake Akakul'; 16. Lake Ulagach; 17. Lake Staroe Boloto (Old Swamp). Photo copyright © Space Media Network/CNES SPOT Satellite Image.

Table 3 Radioactive contamination in the Chelyabinsk-65 reservoirs[a]

Reservoir number	Area of the reservoir (km^2)	Capacity of the reservoir (million m^3)	Composition of radionuclides: Concentration in water, Ci/l: Sr-90	Cs-137	HTO	$\Sigma\alpha$	$\Sigma\beta$	Ground deposits, Ci/kg: Sr-90	Cs-137	Accumulation, Ci: In the reservoir	In ground deposits	Overall
2	19	83	1.1×10^{-8}	4.5×10^{-8}	2.5×10^{-7}	?	—	1.3×10^{-6}	3×10^{-5}	2×10^{3}	18×10^{3}	20×10^{3}
3	0.5	0.75	1.6×10^{-6}	2.0×10^{-7}	1.4×10^{-6}	3×10^{-10}	—	1.4×10^{-4}	1×10^{-3}	2.6×10^{3}	15.4×10^{3}	18×10^{3}
4	1.3	4.1	1.7×10^{-7}	1.3×10^{-8}	5.2×10^{-7}	4.5×10^{-9}	—	4×10^{-6}	6×10^{-5}	1.7×10^{3}	4.2×10^{3}	6×10^{3}
6	3.6	17.5	3.7×10^{-10}	2×10^{-11}	1×10^{-8}	3.9×10^{-5}	—	3×10^{-7}	3.9×10^{-7}	2	300	300
9	0.25	0.4	1.7×10^{-3}	1.2×10^{-2}	5.3×10^{-5}	5.7×10^{-6}	1.9×10^{-2}	0.3	1.4	8.4×10^{6}	110×10^{6}	120×10^{6}
10	16.6	76	3.5×10^{-7}	8.6×10^{-9}	3.2×10^{-7}	1×10^{-11}	—	3.5×10^{-6}	1.5×10^{-1}	50×10^{3}	60×10^{3}	110×10^{3}
11	44	217	5.1×10^{-8}	2×10^{-11}	4.5×10^{-8}	2×10^{-12}	—	1.3×10^{-6}	1.3×10^{-7}	24×10^{3}	15×10^{3}	39×10^{3}
17	0.17	0.8	7×10^{-4}	4×10^{-6}	1×10^{-4}	1.2×10^{-3}	—	3.3×10^{-4}	3.3×10^{-2}	45×10^{3}	2×10^{6}	2×10^{6}

Sources: (25, 26) and tables given to Thomas B. Cochran by Victor N. Chukanov, USSR Academy of Sciences, Ural Department, Ecological Security Center, Sverdlosk, private communication, 13 April 1991.

Table 4 Average annual Sr-90 and Cs-137 concentration in the Techa River at the Myslyumovo settlement[a]

Observation year	Sr-90 content (pCi/l)	Cs-137 content (pCi/l)
1951	40,000	510,000
1962	10,000	4,000
1964	3,000	250
1973	2,000	40
1978	1,500	36
1983	350	24
1988	420	40

[a] Source: (28)

in the waste tanks, and the excess supernatant, which contained much of the Cs, was discharged into the lake. This is apparently still the practice, in that today medium-level waste (800,000 Ci in 1992) is still being added to maintain the water level of the lake (31).

Through 1990, the lake had accumulated 120 MCi of the long-lived radionuclides Cs-137 (98 MCi) and Sr-90 (20 MCi) (26). In comparison, 2.4 MCi of Cs-137 and 0.22 MCi of Sr-90 were released from the Chernobyl accident (32). The lake in 1990 had a surface radiation exposure level of 3–4 rad/h (30). When a visiting delegation went within a few hundred feet of the water, the radiation reading in the bus reached 80 millirems per hour (mrem/h) (30). A second delegation received 300–600 mrem/h at a point about 10–12 m from the edge of the lake (33). On the lake shore in winter the radiation dose is about 20 rems per hour (rem/h), and summer about 18 rem/h (34). In the region near where the radioactive effluent is discharged into the lake, where the specific activity of the ground deposits is up to 20 Ci/kg (dry weight; 2–3 Ci/l wet) (35), the radiation exposure rate is about 600 roentgens per hour (R/h), sufficient to provide a lethal dose within an hour (26).[11]

In 1967, a hot summer followed a dry winter. The water evaporated and dust from the lake bed was blown over a vast area, up to 75 km long, affecting 41,000 people (37). Some 600 Ci of Cs-137 and Sr-90 from the shores of Lake Karachay contaminated about 1800–2700 km^2 at a level

[11] The radiation dose at which half the population would be expected to die (LD_{50}) depends on a number of factors, including type of exposure, whether whole body or specific organ, the length of time of the exposure, the medical attention received after the exposure, etc. For whole body (or bone marrow) exposure, estimates of LD_{50} range from 250 to 650 rem; see (36ab).

greater than 0.1 Ci/km^2 (Sr-90), including the reactor site and 41,500 people in 63 villages, some of which were under the radioactive plume from the 1957 nuclear waste tank accident (discussed below).[12] The reactor site was contaminated with Cs-137 and Sr-90 in the ratio of 3:1 with Sr-90 contamination up to 10 Ci/km^2 (26).

As a result of more than 40 years of dumping into Lake Karachay, radioactivity has seeped into the groundwater and migrated 2.5–3 km from the lake. The groundwater flows toward reservoirs 2 and 3 (the Techa) in the north and northeast direction, and to the south it drains toward the Mishelyak River, a tributary of the Techa (39). Radioactive groundwater has reached the Mishelyak, flowing under the river bed at a depth of 15 m (40). The total volume of contaminated groundwater is estimated to be more than 4 million m^3, containing in excess of 5000 Ci of ~30-year half-life fission products (39).

Efforts to eliminate the reservoir began in 1967. The lake is now slowly being filled to reduce the dispersion of radioactivity. Hollow concrete blocks, one meter on a side with one side open, are first placed in the lake, then rock and soil are placed on top. The blocks keep the sediment from being pushed up to the surface. The three-point program is to: 1. fill in the lake, 2. cover the lake, and 3. pump and treat the water (30). As of mid-October 1991, about 5000 blocks had been placed into the lake. In June 1990, it was reported that the area of the lake had shrunk to 25 ha (62 acres) and its volume to 400,000 m^3.[13] In October 1991 it was reported that the lake had been reduced in size to about 20 ha, down from its original size of 45 ha (33). The plan is to completely fill the reservoir by 1995.

Lake Staroe Boloto (Old Swamp; Reservoir 17)

Built in 1949 by erecting an earthen dam, this 17-ha (42-acre) drainless lake located 5 km northeast of Lake Karachay has a volume of 35,000 m^3 and has been used as a storage reservoir for medium-level waste, including tritium condensate, since 1971 (41, 4). By 1990, it had accumulated about 2 MCi of radioactivity, mainly in bottom sediments (41, 4). Medium-level waste continues to be added to Staroe Boloto today (42). The bottom of Lake Staroe Boloto absorbs most of the radionuclides more readily than does the bottom of Karachay. Consequently, the contaminated halo is considerably smaller (43).

[12]Ref. 26 reports a contaminated area of 1800 km^2. Ref. 37 reports an area of 2700 km^2 in excess of 0.1 Ci/km^2 Sr-90 and in excess of 0.3 Ci/km^2 Cs-137. See also (38).

[13]One m^3 = 264.1721 gallons (US) and 1 acre-foot = 1233.482 m^3; therefore, 400,000 m^3 = 100 million gal. = 300 acre-feet.

Waste Explosion in 1957

The so-called "Kyshtym Disaster" was the subject of considerable analysis and speculation in the West prior to 1989, when Soviet officials revealed details of the accident.[14] During the initial period of operation of the chemical separation plant, irradiated fuel elements were treated by an "all-acetate precipitation scheme," (52)[15] resulting in high-level radioactive waste solutions containing as much as 100 grams per liter (g/l) of sodium nitrate and 80 g/l of sodium acetate (53). The solution was stored for a year in tanks (presumably at what is referred to below as the intermediate storage facility) in order to reduce the radioactivity and cool prior to further treatment for additional extraction of plutonium and uranium (53). After treatment, a portion of the solutions was returned to the storage tanks and the less active part was dumped into Lake Karachay (53).

The intermediate storage facility was put into operation in 1953 (53). It consisted of a rectangular buried stainless steel–clad concrete canyon with walls 1.5 m thick, designed for installation of 20 stainless steel tanks at a depth of 8.2 m (53).[16] Called "permanent storage containers," each tank was 300 cubic meters (m^3) (80,000 gallons US) in volume (56). The tanks, entirely immersed in water, utilized an external cooling system with water flowing through an annular gap between the tank walls and the trench (52). Some of the instruments for monitoring the tanks failed and could not be repaired due to the high radiation field in the canyon (52). As the solution in the tanks evaporated, the tanks gradually rose, breaking the seals in the waste transfer lines and contaminating the cooling water. The cooling water was treated in the same part of the plant used to process the waste. Because of insufficient production capacity, the tanks were switched to a "periodic cooling mode" (52). The cooling system in one of the unmonitored tanks failed, however, and the waste began to dry out. Nitrates and acetates in the waste precipitated, heated up to 350°C (660 °F), and on September 29, 1957 at 4:20 PM local time, exploded (57, 53) with a force equivalent to 70–100 tons of TNT (58). The meter-thick concrete lid was blown off and hurled 25 m away, and 70–80 t of waste containing some 20 MCi of

[14]The first published reports of a Soviet nuclear accident are attributable to Z. A. Medvedev (44) (see also Ref. 45) and (46). The most comprehensive Western analyses of the Kyshtym Disaster are (47) [subsequently published in condensed form in (48)], and (49–51). Additional references to the Kyshtym accident and its consequences are cited in these documents.

[15]The technology for chemically separating the plutonium from radioactive fission products changed several times over the 40-year history of the chemical separation plant.

[16]Ref. 54 says "one of 16 steel tanks" exploded, rather than one of 20. Donald Wodrich, a member of the DOE delegation that traveled to Chelyabinsk-40 in June 1990, reported 16 tanks (55) to the Advisory Committee on Nuclear Safety on October 31, 1990.

radioactivity were ejected (53).[17] By comparison, an estimated 51.4 MCi of fission products (excluding noble gases), was released in the Chernobyl accident (60).

About 90% of the radioactivity from the ejected waste fell out in the immediate vicinity of the vessel. The remaining activity, approximately 2.1 MCi, formed a kilometer-high radioactive cloud that was carried through Chelyabinsk, Sverdlovsk, and Tumensk Oblasts, reaching the neighborhood of Kamensk-Uralskiy after 4 hours, and Tyuman after 11 hours (53, 56, 60–63). Some 23,000 km^2, in a track 300 km in length and 30–50 km wide, were contaminated to a level greater than 0.1 Ci/km^2 of Sr-90. There were 217 towns and villages with a combined population of 270,000 people within this area, which was subsequently given the name, "East Ural Radioactive Trace (VURS)."[18] Guards at Chelyabinsk-65 received the largest reported dose, about 100 R. During the initial period, the external gamma dose rate was about 150 microroentgens per hour (μR/h) (equivalent to 1.3 R/year) in open areas where the Sr-90 contamination was 1 Ci/km^2 (53, 61, 62). The external gamma dose levels were two to three times higher in forests, where up to 90% of activity was initially held up in the crowns of the trees (61). Sr-90 (beta activity) accounted for only 2.7% of the total (beta and gamma) activity initially. The total activity level dropped 10-fold in the first three years, and by a factor of 44 after 36 years (in 1993). After about 3 years of radioactive decay, Sr-90 and its daughter product, Y-90, were the dominant isotopes with respect to contamination and exposure. Today, Sr-90 + Y-90 make up 99.3% of the residual radioactivity from the accident, and Cs-137 accounts for 0.7%. In a 20 km^2 area where the contamination exceeded 180 Ci/km^2, the pine needles received 3000–4000 rads in the first year, and all the pine trees died by the autumn of 1959 (65).

Water supplies along the East Ural Trace were contaminated. Calculations indicated that the cumulative dose over the first month for the three most contaminated villages, Berdyanish, Saltikovka, and Galikaeva, would range from 150 rads to about 300 rads (66, 67).[19] These three villages, in which at least 1054, and perhaps as many as 1908, people lived, were evacuated, but not until 7–10 days after the accident. Ref. 68 gives the size of population evacuated at 7–10 days as 1150 people and the average contamination density as 500 Ci/km^2. Table 4 of Ref. 62 gives the size of the population

[17]Two adjacent tanks were also damaged (59).

[18]Ref. 64 and other published figures of the fallout pattern indicate the width of the trace boundary defined by the 0.1 Ci/km^2 (Sr-90) contour is 20–30 km.

[19]The names of the villages are from (12).

evacuated in 7–10 days as 600 people and the average contamination density as 500 Ci/km^2 (Sr-90). Ref. 12 gives 1055 people in the three villages. Ref. 69 reports 1500 inhabitants in the area and 1100 inhabitants evacuated in 7–10 days. Despite the high radiation doses received, no excess late effects (e.g. cancers) were detected in a follow-up study of the residents of these three villages, due to the small size of the population (1059 persons), limited period of observation, and lack of a good control population (70).

The next wave of evacuations began about eight months after the accident, involving 6500 people. These people consumed contaminated foods for three to six months without restriction and continued to consume some contaminated food until their evacuation. In all, inhabitants of 23 villages (56), about 10,700 people, were evacuated from areas having contamination levels greater than 2 Ci/km^2 (Sr-90) (56). As of 1990, no registry had been initiated to follow the medical histories of the exposed population in all 217 towns and villages within the trace (71).

The population ate the 1957 harvest, which was contaminated with radionuclides (12). By 1959, all areas contaminated in excess of 2 Ci/km^2 were subject to special sanitary protection regulations (62, 72). In 1962, this "sanitary isolation zone" was reduced in size to 220 km^2 (62, 72). In 1958–1959, about 20,000 ha (80 mi^2) of agricultural land at the head of the cloud track were plowed under, and in 1960-1961, an additional 6200 ha (25 mi^2) (62, 72). In 1958, 106,000 ha (410 mi^2) of land were removed from agricultural use in Chelyabinsk and Sverdlovsk Oblasts (62, 72). By 1961, all the land in Sverdlovsk, 47,000 ha (180 mi^2), was returned to agriculture; and by 1978, 40,000 ha (150 mi^2) out of 59,000 ha (230 mi^2) in Chelyabinsk were returned to use (62, 72).

In experimental study areas where the ground was not plowed under, in the first two years 90% of the Sr-90 was concentrated in the upper 2 cm of soil. By 1988, 84–94% of the Sr-90 was concentrated in the upper 10 cm of soil. Transport by wind and water runoff have reduced the Sr-90 exponentially with a half-life of 4–5 years (73).

WASTE MANAGEMENT TODAY

Since 1949, Mayak has discharged in excess of 123 MCi of long-lived radionuclides (Sr-90 and Cs-135) into the environment, contaminating in excess of 26,700 km^2, and exposing more than 400,000 people, making the Chelyabinsk-65 environs arguably the most polluted spot on the planet—certainly in terms of radioactivity. Parts of the Chelyabinsk-65 site have a dose rate of up to 15 mR/h. The average value for the remainder of the site is in the range of 10 to 30 μR/h. (As noted previously, many cities in the world have natural background levels on the order of 20 μR/h.) Open

reservoirs on site contain 340 million m^3 of radioactive water. Fish in Reservoir No. 10 are reported to be "100 times more radioactive than normal" (74). The Techa River is cordoned off with a wire fence, and people are forbidden to catch fish, pick mushrooms or berries, or cut the hay, but there are many stories of farmers cutting fences so that their livestock can reach the river. The children of Muslyumovo, a village 78 km downstream that was not evacuated, were reported in 1991 to be receiving an effective dose equivalent of 0.5–1.0 rem/y (75).

The production complex, by consuming contaminated water for its needs, regulates the water level in the reservoirs along the Techa River. With all but one of the reactors shut down, a new potential danger has been identified—overfilling the reservoirs with natural water and possibly even failure of the dams, sending contaminated water into the rivers of the Ob basin. The South Urals nuclear power station, begun in 1984 and intended to consist of three liquid metal fast breeder reactors, was to avert this sort of catastrophe by using radioactive water to cool turbine condensers, thus increasing evaporation (76). But, construction of the project was halted in 1987 due to public protests following from the Chernobyl nuclear accident. Serious economic and safety concerns about the breeder program raise doubts as to whether it will ever be completed.

Storage in High-Level Waste Tanks

The current procedure for handling high-level waste involves first evaporation and then fixation in sparingly soluble compounds, i.e. hydroxide and ferrocyanide compounds. The concentrated wastes are stored in instrumented single-shell stainless steel storage tanks housed in metal-lined reinforced concrete canyons. It was reported in 1991 that at least 976 MCi of radioactive waste is kept in storage in solutions.

Waste Vitrification

In the mid-1950s, the Soviets began to develop techniques for transforming liquid radioactive wastes into solids with radionuclide fixation in stable matrixes suitable for long-term safe storage. Preference was given to vitrification (i.e. preparation of glass-like materials), and development proceeded in two directions: (*a*) two-stage vitrification with waste calcination at the first stage; and (*b*) a large development effort, the so-called single-stage method of preparing phosphate and borosilicate glass-like materials in a ceramic melter without preliminary calcination.

The Chelyabinsk-65 vitrification program began in 1967 and is still in use. In May 1992, it was reported that 60 MCi of high-level waste had been vitrified. The production capacity of the plant is now 1 t/d. Originally, the concentration of radioactivity was 100 Ci/l (50 Ci/kg); currently 400

Ci/l is achieved. The current backlog of high-level waste amounts to about 10 years work for the vitrification plant.

Solid Waste Burial[20]

There are 227 solid waste burial sites (about 10% were still receiving waste in 1990) with a total area of about 30 ha, with the burials themselves occupying 21.3 ha (Table 5) (77–79). The site contained in 1990 some 525,000 t of waste containing 12 MCi of activity (81). The burial sites for low-level and medium-level solid radioactive waste are trenches dug in the soil. After being filled, the trenches are covered with clay to reduce the intrusion of water. Burial sites usually are located where the water table is greater than four meters below the bottom of the burial. The bottom and the walls are lined with a layer of clay for further hydraulic isolation. Radionuclides can migrate from burial sites due to infiltrating atmospheric precipitation while filling the burial before the waste is covered, and can also migrate in the water-bearing horizon, and by diffusion in moist soil.

High-level solid radioactive wastes are placed in reinforced concrete structures with multiple waterproofing—with bitumen, stainless steel, concrete. The clay soil coating the bottom and the walls of the container prevent radionuclide migration. Only these high-level radioactive waste structures are equipped with instrumentation and a signalling system. The trench-like burials have no instrumentation.

Nearly all solid production wastes are dumped without being processed, due to the lack of well-developed installations for burning, compaction, deactivation, and melting. The large number of burial sites is explained by the fact that every plant had originally, and still has, its own burial sites

Table 5 Solid waste burial sites at Chelyabinsk-65[a]

Kind of waste	Number of burial sites	Volume of waste (1000 m^3)	Waste activity (Ci)	Total area (ha)
Low- and medium-level waste	203	685.1	31.6×10^3	20.2
High-level waste	24	41.3	12×10^6	1.1
Total	227	726.4	12×10^6	21.3

Source: (80)

[20]This section based on (77, 78).

for each kind of waste. The dumping was organized so as to minimize the distance between the sites of production and of burial of solid waste.

CONCLUSION

As a consequence of poor waste management practices at Chelyabinsk-65, primarily during the first two decades of operations, the site and its surroundings were extensively contaminated, and thousands of people were unknowingly exposed to excessive levels of radiation. In terms of human health consequences, most of the damage has already been inflicted. Nevertheless, containment of the residual radioactivity in high-level waste tanks, in the reservoirs along the Techa River, and in and below Lake Karachay represents expensive challenges for which the best, or even adequate solutions, have yet to be devised. Russian scientists have the knowledge to address these problems, but lack practical experience with contemporary waste management practices. Western expertise could be helpful in quantifying the extent of the problems and devising solutions. However, the real challenge will be to mobilize the economic resources for effective cleanup at Chelyabinsk-65 in light of all the other economic and environmental problems Russia faces.

APPENDIX—BASIC UNITS OF IONIZING RADIATION

We have chosen to express the quantity of radioactivity and radiation dose in terms of older units, since most of the source documents used these units. The unit for the amount of radioactivity, measured in terms of the rate of radioactive decay, is the curie (Ci), where 1 Ci = the quantity of any radionuclide, or radionuclides, that undergoes 3.7×10^{10} disintegrations per second. Historically, this unit was chosen because it was the activity of one gram of radium-226. Under the modern International System of Units (SI), the becquerel (Bq) is defined as one disintegration per second. Therefore, 1 Ci = 3.7×10^{10} Bq.

Radionuclides can be characterized, not only by the rate of disintegration, but by the types of radiation emitted—alpha-, beta-, gamma- and/or X-rays—and the energy of each quanta or particle emitted. One of the early units of radiation was the roentgen (R), which was defined in terms of the quantity of X- or gamma-radiation that produced the same number of ion pairs in one cubic centimeter of dry air that would be produced by one gram of radium at a specified distance.

Since the roentgen is limited to X- and gamma-radiation in air, another unit is needed to specify the amount of energy absorbed in matter of any type. One such unit of absorbed dose is the rad, which corresponds to the

absorption of 100 ergs of ionizing radiation in one gram of any material at the place of interest. The modern SI counterpart is the gray (Gy), and the relationship is 1 rad = 0.01 Gy = 1 cGy (centi-gray).

Since the absorption of one rad of ionizing radiation in tissue can cause different biological effects, depending on the type and energy of the radiation, another unit is needed to measure the equivalent biological damage. One such unit of dose equivalent is the rem, where one rem is the amount of ionizing radiation of any type that produces the same damage in human tissue as one rad of X-radiation at a defined energy. The modern SI unit is the sievert (Sv), and the relationship is 1 rem = 0.01 Sv = 1 cSv.

If, as often assumed for absorbed doses below a few hundred rem, the risk of a particular type of biological damage, e.g. cancer, is proportional to the dose, then it is useful to define collective dose as the sum of the individual doses, e.g. 100 person-rem = 10 rem to 10 persons = 1 rem to 100 persons, etc. The estimated number of cancers induced is then the product of collective dose and a cancer risk factor determined from epidemiological studies. We assume for the general population, one cancer fatality per 1000 person-rem. It should be recognized, however, that the cancer risk factor is a function of the type of cancer, sex and age distribution of the population, and other variables, and it has been a matter of extensive research and great debate. For the types of radiation discussed in this report, namely, the beta- and gamma-radiation from Sr-90, Cs-137, and most other fission products (everything except alpha-radiation from uranium, plutonium, and the like), 1 r $\approx$ 1 rad = 1 cGy $\approx$ 1 rem = 1 cSv. In other words, in this report these dose units are, for all practical purposes, interchangeable.

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