

Discharge of Waste into the Techa River: From the startup of the chemical separation plant in December 1948 through 1956, 78 million m³ of intermediate-level liquid nuclear waste containing 2.75 MCi of beta activity from the radiochemical plant, was discharged directly into the Techa River 6 km below its source.²⁷⁰ As shown in Figure 4, about 95 percent of the radioactivity (averaging 4300 curies/day (Ci/d)) was discharged from March 1950 to November 1951, after which it was sharply reduced to 26 Ci/d in 1952, and a somewhat lower rate during 1953-1956.²⁷¹ The composition of the beta-emitting radioactivity discharged into the Techa--655,000 Ci (23.8 percent) is due to Sr-90 and Cs-137--is also shown in the caption to Figure 2.²⁷² As best we can estimate the 630 MCi of Sr-90 and Cs-137 (95 percent of the 655 MCi) represents essentially the total inventory of these isotopes separated during this initial period, i.e., prior to November 1951--implying that all of the fission products were diluted and discharged into the Techa. The Techa River is 240 km long, flowing into the Iset' River, which flows into the Tobol River. The extent of this river system is about 1000 km.²⁷³ The Tobol flows into the Irtysh which flows into the Arctic Ocean.

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

²⁷⁰ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 11 and Vol. II, p. 50; and "Supreme Soviet Committees, Commissions Meet 5 October; Committee Views on Nuclear Pollution," *Moscow Domestic Service*, in Russian, at 1130 GMT, 5 October 1990 (translated in FBIS-SOV-90-195, 9 October 1990, pp. 35-36).

²⁷¹ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 53 and Vol. II p. 50. See also, Mira M. Kossenko, Marina O. Degteva, and Nelly A. Petrushova, "Estimate of the Risk of Leukemia to Residents Exposed to Radiation as a Result of a Nuclear Accident in the Southern Urals," *The PSR Quarterly*, Vol. 2, Number 4, December 1992, p. 189.

The total release estimated from the Figure 4 is 3.0 MCi; approximately 98.9 percent released in the period 1949-1951, and 1.1 percent of the discharge (34 thousand Ci) occurred during the period 1952-1956.

²⁷² Strontium-90 (Sr-90) and cesium-137 (Cs-137) are produced in roughly equal amounts, 3.3 Ci of Sr-90 and 3.6 Ci of Cs-137 per gram of plutonium-239 (Pu-239) produced. Had there been any effort to concentrate the insoluble fission products in tanks during this period, the discharge into the Techa would have contained a much higher concentration of Cs-137, relative to Sr-90, which is not the case. The total Sr-90 and Cs-137 discharged through 1951, about 300,000 Ci each, implies that 100 kg of plutonium were recovered during that period. This is consistent with the estimate of plutonium production at Chelyabinsk-65 during this period based on the reactor operation data (see Table 13).

²⁷³ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 53.

micro-Roentgen/hour ($\mu\text{R}/\text{h}$) on roads and streets²⁷⁴ (Many cities in the world have natural background levels on the order of 10-20 $\mu\text{R}/\text{h}$.) Radioactivity was found as far away as the Arctic Ocean. A new solution was adopted in September 1951. Instead of discharging the radioactive waste into the Techa River, the wastes were diverted into Karachay Lake (see below), and between 1951 and 1964 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 radioactivity, none having been warned about the danger.²⁷⁵ Ninety-nine percent of the radioactivity that was dumped into the Techa was deposited within the first 35 km--downstream (Figure 5). In 1949 there were 38 villages with 28,100 people identified along the Techa riverside 237 km downstream from the plant in Chelyabinsk and Kurgan oblasts.²⁷⁶ For many of the 28,100, the river was the main source of drinking water.²⁷⁷ From 1953 to 1960, 7500 people from 22 population centers in the upper reaches of the Techa were evacuated and relocated²⁷⁸ (Table 7a identifies 21 population centers). 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.²⁷⁹ The Techa River and 8000 hectares (ha)²⁸⁰ of its floodlands were excluded from use for economic and drinking purposes, although this ban has not been

²⁷⁴ *Ibid.*, Vol. I, p. 54.

²⁷⁵ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 11.

²⁷⁶ Mira M. Kossenko, Marina O. Degteva, and Nelly A. Petrushova, "Estimate of the Risk of Leukemia to Residents Exposed to Radiation as a Result of a Nuclear Accident in the Southern Urals," *The PSR Quarterly*, Vol. 2, Number 4, December 1992, p. 188. See also, "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 11.

²⁷⁷ "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.;" "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 54.

²⁷⁸ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 11 and Vol. II, p. 55 says the evacuations were prior to 1960. Mira M. Kossenko, Marina O. Degteva, and Nelly A. Petrushova, "Estimate of the Risk of Leukemia to Residents Exposed to Radiation as a Result of a Nuclear Accident in the Southern Urals," *The PSR Quarterly*, Vol. 2, Number 4, December 1992, p. 188 says the evacuations occurred from 1953 to 1961.

²⁷⁹ Mira M. Kossenko, Marina O. Degteva, and Nelly A. Petrushova, "Estimate of the Risk of Leukemia to Residents Exposed to Radiation as a Result of a Nuclear Accident in the Southern Urals," *The PSR Quarterly*, Vol. 2, Number 4, December 1992, p. 188.

²⁸⁰ One hectare = 0.01 km² = 2.471 acres. Therefore, 8000 hectares = 80 km² = 20,000 acres = 30 mi².

strictly observed over the years.

The inhabitants of the Techa riverside villages received substantial external and internal radiation exposures. The mean effective doses estimated for the 22 population centers that were evacuated (7500 people in all) ranged from 3.6 to 140 rem, with the 1200 inhabitants of Metlino receiving the highest average effective dose, 140 rem (Table 7b).²⁸¹ Individual doses were estimated to range from several times lower to several times higher than the mean values estimated for the population centers.

An epidemiological study of the 28,100 exposed individuals found a statistically significant increase in leukemia morbidity and mortality that arose between five and 20 years after the initial exposure.²⁸² A search was made for other cancers, but the small increase is barely significant and unconvincing.²⁸³

As noted above, between 1951 and 1964, a cascade of four artificial reservoirs (Numbers 3, 4, 10, and 11, shown in Figure 3) were created along the Techa, just below Lake Kyzyltash (reservoir Number 2 in the same figure), to isolate water from the most contaminated areas.²⁸⁴ As of about

²⁸¹ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 11; Mira M. Kossenko, Marina O. Degteva, and Nelly A. Petrushova, "Estimate of the Risk of Leukemia to Residents Exposed to Radiation as a Result of a Nuclear Accident in the Southern Urals," *The PSR Quarterly*, Vol. 2, Number 4, December 1992, pp. 187-197; G.I. Romanov, "Radioecological Conditions Accounted for the 1957 and 1967 Accidents and Production Activities of the Industrial Complex 'Mayak,'" paper presented at the International Radiological Conference, Chelyabinsk, Russia, 20-25 May 1992; and N. I. Dubenyok, A.Sh. Liberman, and N.I. Mironova, "The Necessity for Independent Retrospective Ecological Expertise for the Zone of Radioactive Influence of the Military Industrial complex in the Chelyabinsk Region," paper presented at the First Soviet-American Conference for Ecological Non-Governmental Organizations, 12-20 March 1991, Moscow.

²⁸² Mira M. Kossenko, Marina O. Degteva, and Nelly A. Petrushova, "Estimate of the Risk of Leukemia to Residents Exposed to Radiation as a Result of a Nuclear Accident in the Southern Urals," *The PSR Quarterly*, Vol. 2, Number 4, December 1992, pp. 187-197. Thirty-seven leukemias (morbidity) were found versus 14-23 expected. For commentaries on the paper by Kossenko, et al., see Scott Davis, "Understanding the Health Impacts of Nuclear Weapons Production in the Southern Urals: An Important Beginning," *The PSR Quarterly*, Vol. 2, Number 4, December 1992, pp. 216-220 and David Rush, "Response to the Paper of Kossenko, et al.," *The PSR Quarterly*, Vol. 2, Number 4, December 1992, pp. 221-222. "Medical examinations of the population were initiated only two years after the start of nuclide dumping into the river system and were performed on the residents of the village Metlino—a single population center in the upper reaches of the river. In other villages medical examination started only 3-6 years after the initial dumping of radionuclides into the Techa, so the early aftermath of radiation could not have been registered." "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 45.

²⁸³ Mira M. Kossenko, "Medical Effects of Population Irradiation on the River Techa," paper presented at the Harvard School of Public Health, 4 May 1992.

²⁸⁴ The first dam, creating reservoir 3, was built in 1951. Dam 4, which existed before 1917, was expanded in 1956. Dam 10 was built in 1957 at a cost of 2.7 million rubles; and dam 11 was built in 1964 at a cost of 7 million rubles. The left bank channel was built in 1963 at a cost of 7.5 million rubles; and the right bank channel was built in 1972 at a cost of 900 thousand rubles.

1990 the reservoirs (including Kyzyltash), with a combined area of 84 km² and volume of 380 million m³, contained about 193,000 Ci of Sr-90 and Cs-137 activity (Table 9). They are said to have "isolated about 98 percent of the radionuclides deposited in the flood-lands from the open hydrographic network,"²⁸⁵ but judging by the amount of Sr-90 and Cs-137 remaining, 80 percent 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--into bottom deposits of the lower section of the river down 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."²⁸⁶

The measured concentration of alpha activity (10-50 percent Pu-239) in bottom deposits (0-5 cm depth) of the Techa was 15 nano-curies/kg (nCi/kg) at Asanovo; 8 nCi/kg at Nadirovo; and 1.9 nCi/kg at Muslyumovo.²⁸⁷

The Asanovski marshes (or swamps), an area of 30 km² assessible to the public through which the Techa flows just below the last reservoir (No. 11), contains some 6000 Ci of Sr-90 and Cs-137.²⁸⁸ These marshes are said to be a major constant open source of radioactivity, flowing into the Techa²⁸⁹ (See Table 8), although there seems to be no data quantifying how much radioactivity is transported from the marshes into the Techa. Estimated deposits of Sr-90 and Cs-137 in the vicinity of Muslyumovo are at least 400 Ci. Cs-137 in river slimes at Muslyumovo reach 300-500 nCi/kg.²⁹⁰

Lake Karachay (Reservoir 9): As noted above, in November 1951, the practice of diluting and discharging the HLW directly into the Techa was curtailed, and instead the diluted HLW were diverted into Lake Karachay -

²⁸⁵ B.V. Nikipelov, A.S. Nikiforov, O.L. Kedrovsky, M.V. Strakhov, and E.G. Drozhko, "Practical Rehabilitation of Territories Contaminated as a Result of Implementation of Nuclear Material Production Defence Programmes," (undated English translation ca. 1990).

²⁸⁶ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, pp. 50-51.

²⁸⁷ *Ibid.*, Vol. II, p. 51.

²⁸⁸ *Ibid.*; see also, V.N. Chykanov, Y.G. Drozhko, A.P. Kuligin, G.A. Mesyats, A.N. Penyagin, A.V. Trapeznikov, and P.V. Bolbuev, "Ecological Conditions for the Creation of Atomic Weapons at the Atomic Industrial Complex Near the City of Kyshtym," paper presented at the Conference on the Environmental Consequences of Nuclear Weapons Development, University of California, Irvine, 11-14 April 1991.

²⁸⁹ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 52; see also, "Resonance," Chelyabinsk, 1991.

²⁹⁰ *Ibid.*, Vol. II, p. 51.

at the time, a natural 45 ha (110 acres) lake with no surface outlet.²⁹¹ The intermediate waste storage facility (discussed below) was not put into operation until 1953. Consequently, this practice must have continued for more than a year.

Comparing the concentrations of cesium and strontium in the lake and the intermediate waste storage tanks, it appears that with the advent of HLW storage tanks ca. 1953, the precipitated sludge, which included most of the strontium, was retained in the waste tanks, and the excess supernatant, which contained most of the cesium, was discharged into the lake. In order to have accumulated the reported Cs-137 inventory, 98 MCi in 1990, it appears that for several years after 1953 the Soviets must have been discharging most of the Cs-137 directly into Lake Karachay. In 1990 it was reported that recently annual additions to the lake have exceeded 1 MCi.²⁹² This represents an estimated 6 percent of the Cs-137 from chemical separation activities for that year.

In the 1960s it was discovered that radioactivity from the lake was entering the ground water. 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 over the lake, and (3) pump and treat the water.²⁹³ From 1984 through December 1991 the lake has been filled with 8088 blocks and 736,600 m³ of rock.²⁹⁴ In June 1990, it was reported that the size of the lake had shrunk to 25 ha (62 acres) and its volume to 400,000 m³.²⁹⁵ 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.²⁹⁶ The plan as of

²⁹¹ The lake originally was roughly one-half mile long by one-fourth mile wide by 8 feet deep; Frank P. Falci, "Final Trip Report, Travel to USSR for Fact Finding Discussions on Environmental Restoration and Waste Management, 15-28 June 1990," Office of Technology Development, DOE.

²⁹² "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 31; the accompanying table gives 1.15 MCi/y as the amount of incoming medium-level radioactive waste.

²⁹³ Frank P. Falci, "Final Trip Report, Travel to USSR for Fact Finding Discussions on Environmental Restoration and Waste Management, 15-28 June 1990," Office of Technology Development, DOE.

²⁹⁴ Data from a photograph of a chart on the wall at Mayak (ca. 1992). The fill material by year was: 1984: 93 blocks; 18,400 m³ rock; 1985: 559 blocks; 15,700 m³ rock; 1986: 774 blocks; 22,000 m³ rock; 1987: 1476+32 blocks; 33,500 m³ rock; 1988: 977+12 blocks; 36,000 m³ rock; 1989: 2188 blocks; 165,000 m³ rock; 1990: 614 blocks; 193,000 m³ rock; 1991: 1363 blocks; 253,000 m³ rock.

²⁹⁵ One m³ = 264.1721 gallons (U.S.) and 1 acre-foot = 1233.482 m³; therefore, 400,000 m³ = 100 million gal. = 300 acre-feet.

²⁹⁶ "Foreign Travel Report, Travel to Russia to Conduct Technology Exchange Workshops as part of the DOE U.S./U.S.S.R. Joint Coordinating Committee on Environmental Restoration and Waste Management," 16-27 October 1991, Trip Report For: Don J. Bradley, 11 November 1991.

1990 was to completely fill the reservoir by 1995.

By 1990 the lake had accumulated 120 MCi of the long-lived radionuclides Cs-137 (98 MCi) and Sr-90 (20 MCi).²⁹⁷ This compares with 2.4 MCi of Cs-137 and 0.22 MCi of Sr-90 released from Chernobyl.²⁹⁸ As shown in Table 9, under the entry Reservoir No. 9, 110 MCi (93 percent) of the accumulated activity is in ground deposits (41 percent absorbed on the clay bed and 52 percent in mobile deposits), with the remaining 8.4 MCi (7 percent) in the water.²⁹⁹ The volume of sediments is over 160,000 m³.³⁰⁰ The lake currently has a surface radiation exposure level of 3-4 rad/h.³⁰¹ When a visiting delegation approached within a few hundred feet of the water, the radiation reading in the bus reached 80 mrem/h.³⁰² A second delegation received 300-600 mrem/h at a point about 10-12 m from the edge of the lake.³⁰³ On the lake shore in winter the radiation dose is about 20 rem/h, and summer about 18 rem/h.³⁰⁴ In the region near where the waste is discharge into the lake, where the specific activity of the ground deposits is up

²⁹⁷ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," (Ordered by President M. Gorbachev, Presidential Decree # RP-1283, 3 January 1991), ca. April, 1992, [translated into English], Vol. I, p. 37 (of the English translation); B.V. Nikipelov, A.S. Nikiforov, O.L. Kedrovsky, M.V. Strakhov, and E.G. Drozhko, "Practical Rehabilitation of Territories Contaminated as a Result of Implementation of Nuclear Material Production Defence Programmes," (undated English translation ca. 1990); 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.

²⁹⁸ "Health and Environmental Consequences of the Chernobyl Nuclear Power Plant accident," U.S. Department of Energy, DOE/ER-0332, June 1987, pp. ix, 3.4, 3.18-19. The Soviet's estimated 1 MCi of Cs-137 released; State Committee for the Use of Atomic Energy of USSR, "The Accident at the Chernobyl AES and its Consequences," Prepared for the International Atomic Energy Agency Expert Conference, 25-29 August 1986, Vienna, (Translated by the U.S. Department of Energy, NE-40, 17 August 1986), Appendix 4, p. 21.

²⁹⁹ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 31. B.V. Nikipelov, A.S. Nikiforov, O.L. Kedrovsky, M.V. Strakhov, and E.G. Drozhko, "Practical Rehabilitation of Territories Contaminated as a Result of Implementation of Nuclear Material Production Defence Programmes," (undated English translation ca. 1990) report about 35 percent of the ground deposits are in the loam screen of the reservoir bed (up to 4 m) and 60 percent in mobile deposits.

³⁰⁰ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 30.

³⁰¹ Frank P. Falci, "Final Trip Report, Travel to USSR for Fact Finding Discussions on Environmental Restoration and Waste Management, 15-28 June 1990," Office of Technology Development, DOE.

³⁰² Ibid.

³⁰³ "Foreign Travel Report, Travel to Russia to Conduct Technology Exchange Workshops as part of the DOE U.S./U.S.S.R. Joint Coordinating Committee on Environmental Restoration and Waste Management," 16-27 October 1991, Trip Report For: Don J. Bradley, 11 November 1991.

³⁰⁴ Gerard Sevestre, "USSR Nuke Testing Site Legacy," 27 September 1990, *The Greenbase*, 20:51:50 GMT.

to 20 Ci/kg (dry weight; 2-3 Ci/l wet),³⁰⁵ the radiation exposure rate is about 600 R/h, sufficient to provide a lethal dose within an hour.³⁰⁶

In 1967, a hot summer followed a dry winter. The water evaporated and radioactive silt, containing some 600 Ci of Cs-137 and Sr-90, from the lake bed was blown over a tract 75 km long and 1800-2700 km² in area (contaminated in excess of 0.1 Ci/km² of Sr-90 and 0.3 Ci of Cs-137).³⁰⁷ 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/km².³⁰⁸ The contaminated area, which overlapped the trace from the 1957 accident (discussed below), contained 41,500 people in 63 towns and villages.³⁰⁹ The external radiation dose to 4800 nearby residents was 1.3 rem, while for residents in remote regions it was 0.7 rem.³¹⁰

As a result of over 40 years of dumping into Lake Karachay, radioactivity has seeped into the groundwater and migrated 2.5 to 3 km from the lake. The groundwater flows primarily toward reservoirs 2 and 3 (the Techa) in the north and northeast direction, and to the south it drains toward the Mishelyak

³⁰⁵ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 31.

³⁰⁶ B.V. Nikipelov, A.S. Nikiforov, O.L. Kedrovsky, M.V. Strakhov, and E.G. Drozhko, "Practical Rehabilitation of Territories Contaminated as a Result of Implementation of Nuclear Material Production Defence Programmes," (undated English translation ca. 1990). The radiation dose at which half the population would be expected to die (LD₅₀) depends upon 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 the LD₅₀ range from 250 rem to 650 rem; see Rosalie Bertell, *Handbook for Estimating Health Effects from Exposure to Ionizing Radiation*, 2nd Edition, Revised, October 1986, p. 2; and J.S. Evans, "Health Effects Models for Nuclear Power Plant Accident Consequence Analysis," January 1990, NUREG/CR-4214, SAND85-7185, Rev. 1, Part 1, Table 2.3, p. I-17.

³⁰⁷ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 12, and Vol. II, p. 32; and B.V. Nikipelov, A.S. Nikiforov, O.L. Kedrovsky, M.V. Strakhov, and E.G. Drozhko, "Practical Rehabilitation of Territories Contaminated as a Result of Implementation of Nuclear Material Production Defence Programmes," (undated English translation ca. 1990) report an area of 1800 km² contaminated in excess of 0.1 Ci/km² in Sr-90 and 0.3 Ci/km² Cs-137. "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 45; and "Resonance," Chelyabinsk, 1991, report an area of 2700 km² contaminated in excess of 0.1 Ci/km² Sr-90. See also, "Supreme Soviet Committees, Commissions Meet 5 Oct; Committee Views on Nuclear Pollution," Moscow Domestic Service in Russian at 1130 GMT, 5 October 1990 (English translation in FBIS-SOV-90-195, 9 October 1990, pp. 35-36).

³⁰⁸ B.V. Nikipelov, A.S. Nikiforov, O.L. Kedrovsky, M.V. Strakhov, and E.G. Drozhko, "Practical Rehabilitation of Territories Contaminated as a Result of Implementation of Nuclear Material Production Defence Programmes," (undated English translation ca. 1990).

³⁰⁹ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 12 and Vol. II, p. 32.

³¹⁰ *Ibid.*, Vol. I, p. 45.

River, a tributary of the Techa.³¹¹ Radioactive groundwater has reached the Mishelyak, flowing under the river bed at a depth of 15 m.³¹² The total volume of contaminated groundwater is estimated to be over 4 million m³, with a halo area of 10 km² and a depth to 100 m, containing in excess of 5000 Ci of long-lived fission products.³¹³ The discharge of contaminated groundwater is 65 m³/d, and the flow speed is 0.84 m/d.³¹⁴ The speed at which the contaminants move is:³¹⁵

0.23 m/d (84 m/y) for Sr-90 and NO

0.14 m/d (51 m/y) for Co-60.

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 m³ and has been used a storage reservoir for medium-level liquid waste, including tritium condensate since 1971.³¹⁶ By 1990 it had accumulated about 2 MCi of radioactivity, mainly in bottom sediments (Table 9).³¹⁷ Medium-level waste continues to be added to Staroe Boloto today.³¹⁸ The bottom of Lake Staroe Boloto absorbs radionuclides more readily than that than the bottom of Karachay. Consequently, the contaminated halo is considerably smaller.³¹⁹

Waste explosion in 1957: The so-called "Kyshtym Disaster" was the subject of considerable analysis and speculation in the West prior to 1989, when details of the accident were first revealed by the Soviet officials.³²⁰ As

³¹¹ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 34.

³¹² Ibid., Vol. I, p. 14.

³¹³ Ibid., Vol. II, p. 34.

³¹⁴ Ibid.

³¹⁵ Ibid. The speed at which the contaminants move depends on a number of factors, including the flow velocity, dispersion rate, and the physical and chemical interactions with the rock.

³¹⁶ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 30; and V.N. Chykanov, Y.G. Drozhko, A.P. Kuligin, G.A. Mesyats, A.N. Penyagin, A.V. Trapeznikov, and P.V. Bolbuev, "Ecological Conditions for the Creation of Atomic Weapons at the Atomic Industrial Complex Near the City of Kyshtym," paper presented at the Conference on the Environmental Consequences of Nuclear Weapons Development, University of California, Irvine, 11-14 April 1991.

³¹⁷ Ibid.

³¹⁸ Ibid., Vol. I, p. 13.

³¹⁹ Alexander Bolsunovsky, "Russian Nuclear Weapons Production and Environmental Pollution," paper presented at the Conference on "The Nonproliferation Predicament in the Former Soviet Union," Monterey Institute of International Studies, Monterey, California, 8 April 1992.

³²⁰ The first published reports of a Soviet nuclear accident are attributable to Zhores Aleksandrovich Medvedev, *New Scientist*, 1976, p. 264; 1977, p. 761; 1977, p. 352 (see also, *New Scientist*, 1976, p. 692; (continued...)

noted above, during the initial period of operation of the chemical separation plant, the irradiated fuel elements were treated by an "all-acetate precipitation scheme,"³²¹ resulting in HLW solutions containing as much as 100 grams per liter (g/l) of sodium nitrate and 80 g/l of sodium acetate.³²² 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.³²³ After treatment, a portion of the solutions was returned to the storage tanks and the less active part was dumped into a "storage reservoir," (presumably Lake Karachay).³²⁴

The intermediate storage facility was put into operation in 1953.³²⁵ 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.³²⁶ Called "permanent storage containers," each tank was 300 cubic meters (m³) (80,000 gal. (U.S.)) in volume.³²⁷ The tanks, entirely immersed

³²⁰(...continued)

and *Nuclear Disaster in the Urals* [New York: W.W. Norton, 1979] [paperback edition, New York: Vintage Books, 1980]). The most comprehensive Western analyses of the Kyshtym Disaster are by John R. Trabalka, L. Dean Eyman, and Stanley I. Averbach, "Analysis of the 1957-58 Soviet Nuclear Accident," Oak Ridge National Laboratory, ORNL-5613, December 1979 (subsequently published in condensed form in *Science*, 18 July 1980, pp. 345-352); Soran and Stillman, "An Analysis of the Alleged Kyshtym Disaster," W. Stratton, D. Stillman, S. Barr, and H. Agnew, "Are Portions of the Urals Really Contaminated," *Science*, 26 October 1979, pp. 423-425; and Frank L. Parker, "Search of the Russian Scientific Literature for the Descriptions of the Medical Consequences of the Kyshtym 'Accident,'" Vanderbilt University, Battelle Project Management Division, ONWI-424, March 1983. Additional references to the Kyshtym accident and its consequences are cited in these documents.

³²¹ B.V. Nikipelov and Ye.G. Drozhko, "An Explosion in the Southern Urals," *Priroda*, May 1990, pp. 48-49; the technology for chemically separating the plutonium from radioactive fission products changed several times over the 40 year history of the chemical separation plant.

³²² B.V. Nikipelov and Ye.G. Drozhko, "An Explosion in the Southern Urals," *Priroda*, May 1990, p. 48.

³²³ *Ibid.*

³²⁴ *Ibid.*

³²⁵ *Ibid.*

³²⁶ *Ibid.* In a 1957 CPSU Central Committee document the tank that exploded was identified as "storage tank No. 14 in a complex consisting of 20 such tanks;" Ye. Slavskiy, "Whose Sins Are We Paying for Today?," *Moscow Rossiyskiye Vesti*, 27 January 1993, p. 1 [translated into English in *Joint Publications Research Service-TEN-93-004*, 8 March 1993, pp. 51-52]. *Nuclear News*, January 1990, p. 74 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; "USSR 1957 Waste Tank Explosion at Kyshtym," viewgraphs from presentation by Don Wodrich, Westinghouse Hanford Company, to the Advisory Committee on Nuclear Safety, 31 October 1990.

³²⁷ "Hearing in Committee on Preparation of Law on Nuclear Safety: 1957 Accident" *Moscow Home Service*, (SU/0519i), 1200 GMT, 25 July 1989. In a 1957 CPSU Central Committee document the volume of the tank was given as 250 m³; Ye. Slavskiy, "Whose Sins Are We Paying for Today?," *Moscow* (continued...)

in water, utilized an external cooling system with water flowing through an annular gap between the tank walls and the trench.³²⁸ Some of the instruments for monitoring the tanks failed and could not be repaired due to the high radiation field in the canyon.³²⁹ 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."³³⁰ 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 29 September 1957 at 4:20 PM local time, exploded³³¹ with a force equivalent to 70 to 100 tons of TNT.³³² The meter-thick concrete lid was blown off and hurled 25 meters away, and 70-80 MT of waste containing some 20 MCi of radioactivity were ejected.³³³ By comparison, an estimated 51.4 MCi of fission products (excluding noble gases), was released into the environment from the Chernobyl accident.³³⁴

The composition of the ejected waste is given in Table 10.³³⁵ About 18 MCi (90 percent of the activity) fell out in the immediate vicinity of the vessel. The initial contamination density was in excess of 70,000 Ci/km², of which about 4000 Ci/km² was due to Sr-90. The remaining, approximately 2.1 mCi formed a kilometer-high radioactive cloud that was carried through

³²⁷(...continued)

Rossiyskiye Vesti, 27 January 1993, p. 1 [translated into English in *Joint Publications Research Service-TEN-93-004*, 8 March 1993, pp. 51-52].

³²⁸ B.V. Nikipelov and Ye.G. Drozhko, "Explosion in the Southern Urals," *Priroda*, May 1990, pp. 48-49.

³²⁹ *Ibid.*

³³⁰ *Ibid.*

³³¹ B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, N.S. Babaev, Yu.B. Kholina, and E.I. Mikerin, "Accident in the Southern Urals on 29 September 1957," International Atomic Energy Agency Information Circular, 28 May 1989, [revised and published as "Radiation Accident in the Southern Urals in 1957," *Atomnaya Energiya*, 1989, Vol. 67, No. 2, pp. 74-80]; B.V. Nikipelov and Ye.G. Drozhko, "An Explosion in the Southern Urals," *Priroda*, May 1990, p. 48.

³³² "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 29.

³³³ B.V. Nikipelov and Ye.G. Drozhko, "An Explosion in the Southern Urals," *Priroda*, May 1990, p. 48. Two adjacent tanks were also damaged; *Nuclear News*, January 1990, pp. 74-75.

³³⁴ "Health and Environmental Consequences of the Chernobyl Nuclear Power Plant accident," U.S. Department of Energy, DOE/ER-0332, June 1987, p. ix.

³³⁵ When the high-level waste is neutralized most of the fission products and actinides, except cesium, precipitate out as a sludge. The high ratio of strontium-90 to cesium-137 in the tank, equal to 75, suggests that the supernatant containing most of the cesium had been discharged, apparently discharged into Lake Karachay where the ratio of cesium-137 to strontium-90 is 5 (see Tables 9 and 10).

Chelyabinsk, Sverdlovsk, and Tyumensk Oblasts reaching the neighborhood of Kamensk-Uralskiy after 4 hours, and Tyumen after 11 hours.³³⁶ The Kaslinsky, Kunashaksky, and Argayashsky regions of the Chelyabinsk Oblast received the greatest off-site contamination. The contaminated territories were subsequently given the name, "East Ural Radioactive Trace (VURS)." Some 15,000-23,000 km², in a tract 300 km in length and 30-50 km wide, were contaminated at a level greater than 0.1 Ci/km² (Sr-90); 1000 km² in a track 105 km in length and 8-9 km wide were contaminated at a level greater than 2 Ci/km² (Sr-90); 117 km² contaminated at a level greater than 100 Ci/km² (Sr-90); and 17 km² contaminated to 1000-4000 Ci/km² (Sr-90) (see Table 11 and Figure 5).³³⁷ (The Sr-90 integrated deposition density from all atmospheric nuclear weapons testing is 0.08 Ci/km² at this latitude.³³⁸) Sr-90 (beta activity) comprised only 2.7 percent of the total beta 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). The highest contamination level, 4000 Ci/km (Sr-90) at the head of the trace immediately after the accident, corresponds to 150,000 Ci/km² (total beta activity). The initial dose rate near the epicenter was 1200 R/h.³³⁹ Radiation levels within 100 m of the crater exceeded 400 R/h. At a kilometer the levels were 20 R/h, and at 3 km the levels were 3 R/h.³⁴⁰ Guards received the largest reported dose, about 100 R. During the initial period the external gamma dose rate was about 150 μ R/h (equivalent

³³⁶ G.N. Romanov and A.S. Vorovov, "The Radiation Situation After the Explosion," *Priroda*, May 1990, p. 50; B.V. Nikipelov and Ye.G. Drozhko, "An Explosion in the Southern Urals," *Priroda*, May 1990, p. 48; B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, N.S. Babaev, Yu.B. Kholina, and E.I. Mikerin, "Accident in the Southern Urals on 29 September 1957," International Atomic Energy Agency Information Circular, 28 May 1989 [revised and published as "Radiation Accident in the Southern Urals in 1957," *Atomnaya Energiya*, 1989, Vol. 67, No. 2, pp. 74-80]; "Hearing in Committee on Preparation of Law on Nuclear Safety: 1957 Accident" *Moscow Home Service*, (SU/0519i), 1200 GMT, 25 July 1989; "A Nuclear Deadlock: Can a Nuclear Power Plant Save Us from Radioactive Contamination," *Sovietskaya Rossiya*, 21 November 1989, 2nd Edition.

³³⁷ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 41 and Vol. II, p. 58; and G.N. Romanov and A.S. Vorovov, "The Radiation Situation After the Explosion," *Priroda*, May 1990, p. 50.

³³⁸ United Nations Scientific Committee on the Effects of Atomic Radiation, "Ionizing Radiation: Sources and Biological Effects," 1982 Report to the General Assembly, with annexes, United Nations, New York, Table 6, p. 230. Strontium-90 decays by beta emission with a half-life of 28.6 years. Strontium has chemical properties similar to calcium.

³³⁹ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, p. 29.

³⁴⁰ B.V. Nikipelov, A.S. Nikiforov, O.L. Kedrovsky, M.V. Strakhov, and E.G. Drozhko, "Practical Rehabilitation of Territories Contaminated as a Result of Implementation of Nuclear Material Production Defence Programmes," (undated English translation ca. 1990).

to 1.3 R/y) in open areas where the Sr-90 contamination was 1 Ci/km².³⁴¹ The external gamma dose levels were two to three times higher in forests where up to 90 percent of activity was initially held up in the crowns of the trees.³⁴² After about 3 years of radioactive decay, Sr-90 was the dominant isotope with respect to contamination and exposure. At the end of 1992, Sr-90 comprised 99.3 percent of the residual radioactivity from the accident, and Cs-137 comprises 0.7 percent.

In a 20 km² area where the contamination exceeded 180 Ci/km² the pine needles received 3000-4000 rads in the first year, and all the pine trees perished by the autumn of 1959.³⁴³

There were 217 towns and villages with a combined population of 270,000 inside the 15,000-23,000 km² (6000-9000 mi²) area contaminated to 0.1 Ci/km² (Sr-90) or greater; 10,000 people within 1000 km² contaminated to greater than 2 Ci/km² (Sr-90); and 2100 people in within 120 km² contaminated to greater than 100 Ci/km² (Sr-90).³⁴⁴ 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.³⁴⁵

³⁴¹ G.N. Romanov and A.S. Vorovov, "The Radiation Situation After the Explosion," *Priroda*, May 1990, p. 50; B.V. Nikipelov and Ye.G. Drozhko, "An Explosion in the Southern Urals," *Priroda*, May 1990, p. 48; B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, N.S. Babaev, Yu.B. Kholina, and E.I. Mikerin, "Accident in the Southern Urals on 29 September 1957," International Atomic Energy Agency Information Circular, May 28, 1989 [revised and published as "Radiation Accident in the Southern Urals in 1957," *Atomnaya Energiya*, 1989, Vol. 67, No. 2, pp. 74-80].

³⁴² G.N. Romanov and A.S. Vorovov, "The Radiation Situation After the Explosion," *Priroda*, May 1990, p. 50.

³⁴³ D.A. Spirin, E.G. Smirnov, L.I. Suvornova, and F.A. Tikhomirov, "Radioactive Impact on Living Nature," *Priroda*, May 1990, p. 59. "Contamination of pine forests above 300 Ci/km² in Sr-90 (13,200 Ci/km² in total beta activity) resulted in complete elimination of all trees," "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 44 and Vol. II, p. 64.

³⁴⁴ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 41 and Vol. II, p. 58; G.N. Romanov and A.S. Vorovov, "The Radiation Situation After the Explosion," *Priroda*, May 1990, p. 50; B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, N.S. Babaev, Yu.B. Kholina, and E.I. Mikerin, "Accident in the Southern Urals on 29 September 1957," International Atomic Energy Agency Information Circular, 28 May 28 1989, p. 10 [revised and published as "Radiation Accident in the Southern Urals in 1957," *Atomnaya Energiya*, 1989, Vol. 67, No. 2, pp. 74-80]; A.I. Burnazyan, editor, "Results of Study and Experience in the Elimination of the Consequences of Accidental Contamination by Fission Products," *Energiya: Ekonomika, Tekhnika, Ekologiya*, No. 1, January 1990, p. 51 [translated into English by Frank C. Farnham Company, Philadelphia for Lawrence Livermore National Laboratory (LLNL), and reproduced as: A.I. Burnazyan, ed., "A Case of Accidental Regional Contamination by Uranium Fission Products: Study Results and Cleanup Experience," LLNL, UCRL-TT-106911, July 1991].

³⁴⁵ A.I. Burnazyan, editor, "Results of Study and Experience in the Elimination of the Consequences of Accidental Contamination by Fission Products," *Energiya: Ekonomika, Tekhnika, Ekologiya*, No. 1, February 1990, p. 14. A 1957 CPSU Central Committee document identified the village of Satlykovo (46 homes, (continued...))

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.³⁴⁶ The average dose received before evacuation reached 17 rem from external radiation and 52 rem of equivalent effective dose (150 rem to the gastrointestinal tract).³⁴⁷ Accounting for nonuniformity individual doses could be two times higher and lower.³⁴⁸ 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

³⁴⁶(...continued)

300 people) as the most seriously contaminated area and said a decision had been made to resettle this village by 5 October 1957; and Berdyanish (85 homes, 580 people) and Golikayevo (97 homes, 1028 people) were to be resettled prior to 1 March 1958; Ye. Slavskiy, "Whose Sins Are We Paying for Today?," *Moscow Rossiyskiye Vesti*, 27 January 1993, p. 1 [translated into English in *Joint Publications Research Service-TEN-93-004*, 8 March 1993, pp. 51-52].

³⁴⁶ M.M. Kossenko, V.A. Kostyuchenko, V.L. Shvedov, and L.A. Buldakov, "Consequences of Irradiating the Population in the Main Part of the Eastern Urals Radioactive Footprint," *Atomnaya Energiya*, November 1991, Vol. 71, No. 5, pp. 444-448 [translated into English by Plenum Publishing Corporation], reports that a later register of persons confirmed that 1059 persons lived in these three villages. A 1957 CPSU Central Committee document identified 1908 people in the three village: Satlykovo (300 people), Berdyanish (580 people), and Golikayevo (1028 people); Ye. Slavskiy, "Whose Sins Are We Paying for Today?," *Moscow Rossiyskiye Vesti*, 27 January 1993, p. 1 [translated into English in *Joint Publications Research Service-TEN-93-004*, 8 March 1993, pp. 51-52]. "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 41, and N. Chykanov, Y.G. Drozhko, A.P. Kuligin, G.A. Mesyats, A.N. Penyagin, A.V. Trapeznikov, and P.V. Bolbuev, "Ecological Conditions for the Creation of Atomic Weapons at the Atomic Industrial Complex Near the City of Kyshtym," paper presented at the Conference on the Environmental Consequences of Nuclear Weapons Development, University of California, Irvine, 11-14 April 1991, reported 1054 persons. G.N. Romanov, L.A. Buldakov and V.L. Shvedov, "Irradiation of the Population and the Medical Consequences of the Explosion," *Priroda*, May 1990, p. 64 gives the size of the population evacuated in 7-10 days as 1150 people and the average contamination density as 500 Ci/km². B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, N.S. Babaev, Yu.B. Kholina, and E.I. Mikerin, "Accident in the Southern Urals on 29 September 1957," International Atomic Energy Agency Information Circular, 28 May 1989, in Table 4, gives the size of the population evacuated in 7-10 days as 600 people and the average contamination density as 500 Ci/km² (Sr-90). N. I. Dubenyok, et al., *op. cit.*, gives 1055 people in the three villages; A.I. Burnazyan, *Energiya: Ekonomika, Tekhnika, Ekologiya*, January 1990, p. 52, reports 1500 inhabitants in the area, and in February 1990, p. 14, reports 1100 inhabitants evacuated in 7-10 days.

³⁴⁷ G.N. Romanov, L.A. Buldakov and V.L. Shvedov, "Irradiation of the Population and the Medical Consequences of the Explosion," *Priroda*, May 1990, p. 64; B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, N.S. Babaev, Yu.B. Kholina, and E.I. Mikerin, "Accident in the Southern Urals on 29 September 1957," International Atomic Energy Agency Information Circular, 28 May 1989, [revised and published as "Radiation Accident in the Southern Urals in 1957," *Atomnaya Energiya*, 1989, Vol. 67, No. 2, pp. 74-80], Table 4. See also, M.M. Kossenko, V.A. Kostyuchenko, V.L. Shvedov, and L.A. Buldakov, "Consequences of Irradiating the Population in the Main Part of the Eastern Urals Radioactive Footprint," *Atomnaya Energiya*, November 1991, Vol. 71, No. 5, pp. 444-448 [translated into English by Plenum Publishing Corporation].

³⁴⁸ B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, et al., "Radiation Accident in the Southern Urals in 1957," *Atomnaya Energiya*, 1989, Vol. 67, No. 2, pp. 74-80.

population.³⁴⁹

The next wave of evacuations began about eight months after the accident, involved 6500 people from areas where the Sr-90 contamination exceeded 4 Ci/km².³⁵⁰ These people consumed contaminated foods for three to six months without restriction and continued to consume some contaminated food until their evacuation. Some 280 people in areas with average contamination of 65 Ci/km² (Sr-90) received (before evacuation was completed 250 days after the accident) 14 rem from external radiation and 44 rem of equivalent effective dose; an additional 2000 people where the average contamination density was 18 Ci (Sr-90)/km² received 3.9 rem external dose, and 12 rem effective dose equivalent, before evacuation was completed 250 days after the accident; 4200 people where the average contamination density was 8.9 Ci (Sr-90)/km² received 1.9 rem external dose, and 5.6 rem effective dose equivalent, before evacuation was completed 330 days after the accident.³⁵¹ Finally, 3100 people where the contamination density was 2-4 Ci/km² (Sr-90) and averaged 3.3 Ci (Sr-90)/km² received 0.68 rem external dose, and 2.3 rem effective dose equivalent, before evacuation was completed 670 days after the accident.³⁵² In all, inhabitants of 23 villages, about 10,700 people, were evacuated from areas having contamination levels greater than 2 Ci/km² (Sr-90).³⁵³

The 1957 harvest, contaminated with radionuclides, was eaten by the population.³⁵⁴ By 1959 all areas contaminated in excess of 4 Ci/km² (ca. 700

³⁴⁹ M.M. Kossenko, V.A. Kostyuchenko, V.L. Shvedov, and L.A. Buldakov, "Consequences of Irradiating the Population in the Main Part of the Eastern Urals Radioactive Footprint," *Atomnaya Energiya*, November 1991, Vol. 71, No. 5, pp. 444-448 [translated into English by Plenum Publishing Corporation].

³⁵⁰ G.N. Romanov, L.A. Buldakov and V.L. Shvedov, "Irradiation of the Population and the Medical Consequences of the Explosion," *Priroda*, May 1990, p. 64.

³⁵¹ Ibid. "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 75, claims, "There was a massive relocation which was implemented in two stages. The population centers located on areas having a contamination density 80 Ci/km² [sic, probably 8.9 Ci/km²] in Sr-90 were relocated 330 days following the accident (3860 persons). A subsequent relocation was implemented 700 days following the accident, 3030 residents of population centers averaging contamination density of 6 Ci/km² in Sr-90."

³⁵² Ibid.

³⁵³ "Hearing in Committee on Preparation of Law on Nuclear Safety: 1957 Accident" *Moscow Home Service*, (SU/05191), 1200 GMT, 25 July 1989; and "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 75.

³⁵⁴ N. I. Dubenyok, A.Sh. Liberman, and N.I. Mironova, "The Necessity for Independent Retrospective Ecological Expertise for the Zone of Radioactive Influence of the Military Industrial complex in the Chelyabinsk Region," paper presented at the First Soviet-American Conference for Ecological Non-Governmental Organizations, 12-20 March 1991, Moscow.

km² = 270 mi²) were subject to special sanitary protection regulations.³⁵⁵ In 1962, this "Sanitary Protection Zone" was reduced in size to 220 km².³⁵⁶ In 1958-1959, about 20,000 ha (80 mi²) of agricultural land at the head of the cloud track were ploughed under, and in 1960-1961 an additional 6200 ha (25 mi²).³⁵⁷ In 1958, 106,000 ha (410 mi²) of land were removed from agricultural use in Chelyabinsk and Sverdlovsk Oblasts.³⁵⁸ By 1961, all the land in Sverdlovsk, 47,000 ha (180 mi²) were returned to agriculture; and by 1978, 40,000 ha (150 mi²) out of 59,000 ha (230 mi²) in Chelyabinsk were returned to use.³⁵⁹

In experimental study areas where the ground was not ploughed under, in the first two years 90 percent of the Sr-90 was concentrated in the upper 2 cm of soil. By 1988, 84-94 percent 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.³⁶⁰

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,³⁶¹ and therefore no careful epidemiological study has been performed on the exposed population. In 2-5 years after the accident 2767 people were examined in outpatient clinics and compared against a control group of 964 people.³⁶² None of the patients showed the clinical pattern of radiation

³⁵⁵ G.N. Romanov, L.A. Buldakov and V.L. Shvedov, "Irradiation of the Population and the Medical Consequences of the Explosion," *Priroda*, May 1990, pp. 64-67; "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, pp. 75-76. B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, N.S. Babaev, Yu.B. Kholina, and E.I. Mikerin, "Accident in the Southern Urals on 29 September 1957," International Atomic Energy Agency Information Circular, 28 May 1989 [revised and published as "Radiation Accident in the Southern Urals in 1957," *Atomnaya Energiya*, 1989, Vol. 67, No. 2, pp. 74-80] suggest that the Sanitary Protection Zone was defined by the 2 Ci/km² isoline, but this is the area from which people were evacuated.

³⁵⁶ *Ibid.*

³⁵⁷ *Ibid.*

³⁵⁸ *Ibid.*

³⁵⁹ *Ibid.*

³⁶⁰ G.N. Romanov, D.A. Spirin, and R.M. Alexahin, "Sr-90 Migration Peculiarities in the Environment," 1991. Paper presented to the US DOE Delegation, 21 October 1991.

³⁶¹ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 27.

³⁶² A.I. Burnazyan, editor, "Results of Study and Experience in the Elimination of the Consequences of Accidental Contamination by Fission Products," *Energiya: Ekonomika, Tekhnika, Ekologiya*, No. 1, January 1990, p. 51 [translated into English by Frank C. Farnham Company, Philadelphia for Lawrence Livermore National Laboratory (LLNL), and reproduced as: A.I. Burnazyan, ed., "A Case of Accidental Regional Contamination by Uranium Fission Products: Study Results and Cleanup Experience," LLNL, UCRL-TT-106911, July 1991], p. IX-10 (in the English translation).

sickness.³⁶³ One-fifth of 5000 people living in the areas with a contamination greater than 2 Ci/km² showed reduced leukocytes in the blood, and, in rare cases, thrombocyte levels also were reduced.³⁶⁴ No deviations in the incidence of diseases of the blood and in the incidence of malignant tumors have been registered,³⁶⁵ but this is attributable to the lack of a careful epidemiological study. The combined collective effective dose commitment of the evacuated population prior to evacuation was approximately 130,000 person-rem; and the collective effective dose commitment of those persons that were not evacuated was 450,000 person-rem.³⁶⁶ Over their lifetimes the collective radiation exposure from this accidental release could result in as many as 1000 additional cancers in the population.³⁶⁷

High-Level Waste Tanks: In the early years the practice of managing HLW involved the production of nitrate acetate solutions, which upon drying yielded an explosive similar to gun powder; and, as noted above, one of the waste tanks in fact exploded in 1957. The current procedure for handling HLW involves first evaporation and then fixation in sparingly soluble compounds, i.e. hydroxide and ferrocyanide compounds. The concentrated waste are stored in instrumented single shell stainless steel storage tanks housed in metal-lined reinforced concrete canyons. A 1990 inventory indicated that there are 546 MCi of radioactive solutions and sediments, including (note sum is 528 MCi):³⁶⁸

374 MCi	sodium nitrate solution
149 MCi	hydroxide and ferrocyanide pulps
4.9 MCi	sediments (purlite pulp).

At the time of this survey a small portion of the wastes (4 MCi) has been vitrified. These data are consistent with other sources that indicate that there are some 150 MCi (a volume of 20,000 m³) of HLW sediments stored in

³⁶³ Ibid.

³⁶⁴ B.V. Nikipelov, G.N. Romanov, L.A. Buldakov, N.S. Babaeov, Yu.B. Kholina, and E.I. Mikerin, "Accident in the Southern Urals on 29 September 1957," International Atomic Energy Agency Information Circular, 28 May 1989, p.5. [revised and published as "Radiation Accident in the Southern Urals in 1957," *Atomnaya Energiya*, 1989, Vol. 67, No. 2, pp. 74-80].

³⁶⁵ Ibid.

³⁶⁶ V.N. Chykanov, Y.G. Drozhko, A.P. Kuligin, G.A. Mesyats, A.N. Penyagin, A.V. Trapeznikov, and Bolbuev, "Ecological Conditions for the Creation of Atomic Weapons at the Atomic Industrial Complex Near the City of Kyshtym," paper presented at the Conference on the Environmental Consequences of Nuclear Weapons Development, University of California, Irvine, 11-14 April 1991.

³⁶⁷ This assumes one cancer fatality per 1000 person-rem, and two cancers incurred per cancer fatality.

³⁶⁸ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, pp. 28-29; also cited in Alexander Bolsunovsky, "Russian Nuclear Weapons Production and Environmental Pollution," paper presented at the Conference on "The Nonproliferation Predicament in the Former Soviet Union," Monterey Institute of International Studies, Monterey, California, 8 April 1992.

approximately 60 single-walled steel tanks.³⁶⁹ Alexander Penyagin is reported to have said there are a total of 99 waste tanks at Mayak. There are two buildings containing the tanks used for long-term storage of HLW sediments, one with 14 tanks and the other with six tanks.³⁷⁰ The steel-lined (3 mm thick) concrete tanks are 19.5m x 9.5 m x 7 m (capacity = 1300 m³ each; working volume = 1170 m³).³⁷¹ Eight tanks in the first building are non-cooled; the others are internally cooled with a 186 m² radiator surface.³⁷²

Waste Vitrification: In the mid-1950s the Soviets began to develop techniques for transforming liquid radioactive wastes into a 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. In the latter case dehydration, calcination of wastes, and their melting with fluxing additions are conducted in one apparatus, where (the zone of glass-like melt) liquid HLWs and fluxing agents are added directly. For obtaining phosphate glass the orthophosphoric acid is added as a fluxing agent and for borosilicate glass the boron-containing mineral-datolite is added. The heating of glass-like melt is carried out by conducting alternating current through the glass melt. Despite the bulky technological flowsheet, the technique of single-stage vitrification is characterized by high capacity and allows the high alkali metal salt-containing wastes to be processed.³⁷³

The Soviets developed a process for extracting Sr-90 from acidic HLW using a crown-ether based extractant, and 1.5 million curies have been

³⁶⁹ V.N. Chykanov, Y.G. Drozhko, A.P. Kuligin, G.A. Mesyats, A.N. Penyagin, A.V. Trapeznikov, and P.V. Bolbuev, "Ecological Conditions for the Creation of Atomic Weapons at the Atomic Industrial Complex Near the City of Kyshtym," paper presented at the Conference on the Environmental Consequences of Nuclear Weapons Development, University of California, Irvine, 11-14 April 1991; and Falci, Frank P., "Final Trip Report, Travel to USSR for Fact Finding Discussions on Environmental Restoration and Waste Management, 15-28 June 1990," Office of Technology Development, DOE.

³⁷⁰ Paper provided by Russian representatives at Chelyabinsk-65 to U.S. Department of Energy representatives, 22 October 1992 (translated by Lydia Papova).

³⁷¹ Ibid.

³⁷² Ibid.

³⁷³ E.G. Drozhko, B.V. Nikipelov, A.S. Nikiforov, A.P. Suslov, and A.F. Tsarenko, "Experience in Radioactive Waste Management at the Soviet Radiochemical Plant and the Main Approaches to Waste Reliable Confinement Development," Ministry of Nuclear Power Engineering and Industry, (undated English translation ca. 1990).

extracted.³⁷⁴

The Chelyabinsk-65 vitrification program began in 1967. After almost 10 years of testings carried out in a 100 l/h facility using model solutions, in 1986 a 500 liter/hour (l/h) vitrification facility for liquid high-active solutions was put into operation at Chelyabinsk-65. The process, still in use, is based on radionuclide introduction into phosphate glass, prepared in a ceramic melter made of high-alumina zirconium refractory material with molybdenum electrodes. Orthophosphoric acid is used as a fluxing addition. Vitrified wastes are poured through special drains into 0.2 m³ vessels. After cooling three such vessels are placed into metal containers (0.63 m diameter, 3.4 m height).³⁷⁵ The first liquid-fed, ceramic melter, which was placed in operation in 1986, ran for 13 months before the electrode failed due to a very high current load (2000 amperes). Contents of the melter were spilled onto the building floor. The furnace was decommissioned in February 1987. Maximum output was 90 kg/hr of glass. About 162 MT of phosphate glass (998 m³) containing 3.97 million Ci was poured into 366 canisters.³⁷⁶ The aluminum-carrying waste were from reprocessing highly enriched fuel elements,³⁷⁷ presumably naval reactor fuel. The furnace was too large (30' long x 13' wide x 10' high) to be removed. A second similar furnace was constructed in the same building. Testing began in December of 1990, and after six months vitrification was resumed on 25 June 1991. As of 1 October 1991, 440 m³ of HLW solution was processed, producing 88 MT of glass containing 13 MCi of activity. Initially, the waste solution was from reprocessing high-enriched BN type fuel, and then a mixture of waste from processing BN and VVER fuel.

In May 1992 it was reported that 60 MCi had been vitrified. The production capacity of the plant is now 1 MT/d. Originally, the concentration

³⁷⁴ Frank P. Falci, "Final Trip Report, Travel to USSR for Fact Finding Discussions on Environmental Restoration and Waste Management, 15-28 June 1990," Office of Technology Development, DOE.

³⁷⁵ E.G. Drozhko, B.V. Nikipelov, A.S. Nikiforov, A.P. Suslov, and A.F. Tsarenko, "Experience in Radioactive Waste Management at the Soviet Radiochemical Plant and the Main Approaches to Waste Reliable Confinement Development," Ministry of Nuclear Power Engineering and Industry, (undated English translation ca. 1990).

³⁷⁶ Frank P. Falci, "Final Trip Report, Travel to USSR for Fact Finding Discussions on Environmental Restoration and Waste Management, 15-28 June 1990," Office of Technology Development, DOE. According to E.G. Drozhko, B.V. Nikipelov, A.S. Nikiforov, A.P. Suslov, and A.F. Tsarenko, "Experience in Radioactive Waste Management at the Soviet Radiochemical Plant and the Main Approaches to Waste Reliable Confinement Development," Ministry of Nuclear Power Engineering and Industry, (undated English translation ca. 1990), "About 1000 m³ high active solutions, containing 3.9x10⁶ Ci of total activity, was vitrified during 1987-1988. The total weight of the obtained glass blocks has constituted 160 metric tons."

³⁷⁷ "Foreign Travel Report, Travel to Russia to Conduct Technology Exchange Workshops as part of the DOE U.S./U.S.S.R. Joint Coordinating Committee on Environmental Restoration and Waste Management," 16-27 October 1991, Trip Report For: Don J. Bradley, 11 November 1991.

of radioactivity was 100 Ci/l (50 Ci/kg); currently 400 Ci/l is achieved.³⁷⁸ Evgeniy Dzekun, chief engineer of the RT-1 reprocessing plant in late-1992 said the current backlog of liquid HLW would amount to about 10 years work for the vitrification plant.³⁷⁹

The glass blocks, after being placed into metal containers, are put into surface storage, equipped with a forced system of air cooling and with a powerful gas-purification system. Permanent temperature and gas control of the containers will be carried out by air cooling the canisters for 20-30 years, after which the Soviet plan is to bury the waste in a granite or salt formation. The government has been looking in the region of the Urals for a possible granite site, and are experiencing public opposition.

*Solid Waste Burial:*³⁸⁰ There are 227 solid waste burial sites (about 10 percent of which were still receiving waste in 1990) comprising total area of about 30 ha, with the burials themselves occupying 21.3 ha (Table 12).³⁸¹ The site contained in 1990 some 525,000 MT of solid radioactive wastes containing 12 MCi of activity: 150,000 MT of low-level waste (LLW); 350 MT of intermediate-level waste; and 25 MT of HLW.³⁸² The burial sites for low-level and medium-level solid radioactive waste are trenches dug in the ground. 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. Radionuclide migration is also prevented by the clay soil coating the bottom and the walls of the container. Only these HLW structures are equipped with instrumentation and a signalling system. The trench-like burials have no

³⁷⁸ Oleg Bukharin, notes taken at meeting with Evgeny Mikerin, Frank von Hippel, and others, Moscow, 28 May 1992.

³⁷⁹ Frank von Hippel, Thomas B. Cochran, and Christopher E. Paine, "Report on an International Workshop on the Future of Reprocessing, and Arrangements for the Storage and Disposition of Already-Separated Plutonium (Moscow, 14-16 December 1992), and an International Workshop on Nuclear Security Problems (Kiev, 17 December 1992)," 10 January 1993.

³⁸⁰ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. II, pp. 26-28; see also, Alexander Bolsunovsky, "Russian Nuclear Weapons Production and Environmental Pollution," paper presented at the Conference on "The Nonproliferation Predicament in the Former Soviet Union," Monterey Institute of International Studies, Monterey, California, 8 April 1992.

³⁸¹ *Ibid.*, see also, "Resonance," Chelyabinsk, 1991.

³⁸² *Ibid.*, Vol II, p. 26.

instrumentation.

Nearly all of solid production wastes are dumped without being processed due to the lack of well-developed installations for burning, compaction, deactivation, melting. The large number of burial sites is explained by the fact that originally every plant had, and still has, its own burial sites for each kind of waste. The dumping was organized according to the following principle -- the distance between the production site and the burial site for solid waste must be reduced to the minimum.

Contamination Today: Since 1949 Mayak has discharged in excess of 123 MCi of long-lived radionuclides (Sr-90 and Cs-137) into the environment, about 15 percent of that produced over its 45 year history, contaminating in excess of 26,700 km², and exposing more than 437,000 people, making the Chelyabinsk-65 environs arguably the most polluted spot on the planet -- certainly in terms of radioactivity. The industrial site grounds have been contaminated by 24,000 Ci of Cs-137 (maximum density 1000 Ci/km²) and 50,000 Ci of Sr-90 (maximum density 1000 Ci/km²) (see Figure 6).³⁸³ Parts of the Chelyabinsk-65 site have a dose rate of up to 15 milli-Roentgen/hour (mR/h). The average value for the remainder of the site is in the range of 10 to 30 μ R/h. (As noted previously, many cities in the world have natural background levels on the order of 10-20 μ R/h.) There are 340 million m³ of radioactive water in open reservoirs on site. In 1991 it was reported that 90 million Ci of high-level, 1 million Ci of medium-level, and 6000 Ci of liquid LLW were being produced annually from continued chemical separation activities.³⁸⁴ The medium- and low-level wastes continue to be dumped into Lake Karachay, Staroe Boloto, and the Techa reservoirs (Numbers 2, 3 and 4).³⁸⁵ In 1991 it was reported that Lake Kyzyltash was receiving 4000 Ci/y of long-lived radionuclides, and Reservoir 3 more than 2000 Ci/y.³⁸⁶ Fish in Reservoir No. 10 are reported to be "100 times more radioactive than normal."³⁸⁷ 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 animals can reach the river. The children of Muslyumovo, a village 78 km down stream that was not evacuated, were reported in 1991 to be receiving an effective

³⁸³ "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," Vol. I, p. 13.

³⁸⁴ Ibid.

³⁸⁵ Ibid.

³⁸⁶ Ibid., Vol. II, p. 36.

³⁸⁷ *Nucleonics Week*, 26 July 1990, p. 11.

dose equivalent of 0.5-1.0 rem/y.³⁸⁸

The production complex, by consuming contaminated water for its needs, regulated the water level in the lakes. With five of seven production reactors shut down, a new 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.³⁸⁹ The South Urals nuclear power station is now being proposed, in part, to avert this sort of catastrophe by using radioactive water to cool turbine condensers, thus increasing evaporation.³⁹⁰ But, as noted above, the South Urals project may never be completed.

The Siberian Chemical Combine (Tomsk-7, Seversk)

In 1949 *The Voice of America* revealed “in the environs of Tomsk near the village of Belaya Boroda an atomic factory is being built.”³⁹¹ The Siberian Chemical Combine (Sibkhimkombinat), known also by its code name Tomsk-7, was thus founded on the Tom River in Tomsk Oblast, 15 km northwest of the city of Tomsk. At Belaya Boroda the closed city of Seversk (population 107,700) was built to house the Tomsk-7 work force, and is now a satellite town of Tomsk.³⁹² Tomsk, itself has about 500,000 inhabitants.

Tomsk-7 is said to occupy an area greater than 20,000 ha (200 km²).³⁹³ This undoubtedly refers to the sanitary protection zone, established

³⁸⁸ “Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast,” Vol. I, p. 11.

³⁸⁹ *Ibid.*, Vol. I, p. 39.

³⁹⁰ *Ibid.*; and “Chain Reaction of Wastefulness - Do We Need the South Urals AES?,” *Sovietskaya Rossiya*, 24 December 1989.

³⁹¹ Tomsk Ecological Initiative, “Information about the Siberian Chemical Facility (Tomsk-7).”

³⁹² Akira Furumoto, *Tokyo Yomiuri Shimbun*, in Japanese, 17 November 1991, Morning Edition, p. 1 (translated in *Foreign Broadcast Information Service-SOV-91-225-A*, 21 November 1991, p.3.); *Izvestiya*, 4 May 1990, morning edition, p. 6 (Translated in *FBIS*, London UK, Serial: PM0405112290); Moscow Central Television First Program Network in Russian, in its *Vremya* Newscast at 1530 GMT, 2 January 1991 (Translated in *FBIS*, London UK, Serial: LD0201170891); and “Open Deal in a Closed City,” *Izvestiya*, 25 January 1991, Union Edition, p. 2 (Translated in *FBIS*, London UK, R 251109Z Jan 1991).

³⁹³ V. Kostyukovskiy, et al., “Secrets of a Closed City,” *Moscow Izvestiya*, Union Edition, 2 August 1991 (in Russian), (translated in *JPRS-TEN-91-018*, 11 October 1991, pp. 71-72).

in 1970, which elsewhere is reported to cover 192 km².³⁹⁴ Tomsk-7 is the site of the Siberian Atomic Power Station, a chemical separation plant, facilities for plutonium processing and blending and pit fabrication, an enrichment plant, and nuclear waste management facilities.³⁹⁵ The Siberian Atomic Power Station houses five graphite-moderated reactors, four of which are dual-purpose. Three of the reactors have been shut down as of mid-1992, and the remaining two dual-purpose reactors are to be shut down by 2000. Additional power is also provided by a fossil fueled plant.³⁹⁶ The Ministry of Atomic Energy with U.S. funding assistance proposes to construct at Tomsk-7, a large facility for storage of fissile material recovered from retired warheads.

Gennadiy Khandorin has been identified as the director of the Siberian Chemical Combine, at least since 1991.³⁹⁷ Leonid Khasanov is (in 1993) chief of "Sibkhim" Production and Technology Association.³⁹⁸

Siberian Atomic Power Station: The first of the five plutonium production reactors, identified as "I-1," operated from 20 November 1955 to 21 August 1990.³⁹⁹ The second reactor, the first of four dual-purpose reactors, operated from about September 1958 to 31 December 1990.⁴⁰⁰ The third reactor to be shut down operated from 14 July 1961 to 14 August 1992.⁴⁰¹ The startup dates of the remaining two dual-purpose reactors, which

³⁹⁴ Alexander Bolsunovsky, "Russian Nuclear Weapons Production and Environmental Pollution," paper presented at the Conference on "The Nonproliferation Predicament in the Former Soviet Union," Monterey Institute of International Studies, Monterey, California, 8 April 1992. Bolsunovsky claims, "it is not a rare occasion that within this area [the sanitary protection zone] vegetables are planted, berries and mushrooms are collected, [and] fish caught." According to Tomsk Ecological Initiative, "Information about the Siberian Chemical Facility (Tomsk-7)," "The borders of the sanitary protection zone (SPZ), which was established only in 1970, run from the point of sewage release along the right flood plain and the left bank of the Chernil'shchikov canal to Vetpyanii Lake (6-7 km). The village of Chernil'shchikov, which is located 4 km downstream from the sewage release point, is not included in the SPZ. The border of the SPZ runs along the right bank of the canal and is marked with special signs."

³⁹⁵ The reactor site near Tomsk is located at 56° 37'N/84° 47'E.

³⁹⁶ The smoke plume from this plant can be seen in LANDSAT images.

³⁹⁷ Viktor, Kostyukovskiy, "Tomsk-7: Nuclear Ordinarity after the Explosion," *Moscow Izvestiya*, in Russian, 12 May 1993, p. 7. The head of the station in 1990 was named Meshcheryakov.

³⁹⁸ Moscow Ostankino Television First Channel Network, in Russian, 27 February 1993, 0955 GMT.

³⁹⁹ *Ibid.*; and "Siberian Atomic Reactor Closes," *Moscow Tass*, International Service in Russian, 21 August 1990, 1449 GMT.

⁴⁰⁰ In September 1958, a brief announcement in *Pravda* revealed that the first stage of a second atomic power station (following the 5 megawatt-electric (MW_e) experimental installation at Obninsk) had entered service, and that its eventual capacity would reach 600 MW_e.

⁴⁰¹ *Moscow Komsomolskaya*, in Russian 6 August 1992, morning edition, p. 2 (Translated JPRS-TND-92-029, 20 August 1992, p. 20.). The Collegium of Gosatomnadzor (GAN), Russia's atomic energy inspector-

(continued...)

are still operating, are presumed to be spaced a year or two apart.⁴⁰²

In 1958, at the Second International Conference on Peaceful Uses of Atomic Energy, the Soviets described the nuclear reactors at this station as being solely for electric power generation.⁴⁰³ In 1981, A.M. Petrosyants, then Chairman of the State Committee for Utilization of Atomic Energy, admitted that the reactors served a dual-purpose plutonium production for warheads and power generation.⁴⁰⁴ Not until 4 May 1990 did the Soviets reveal that the reactors were at Tomsk, supplying energy to the Siberian Chemical Combine and heat to agricultural complexes and housing.⁴⁰⁵

The reactors are graphite-moderated, water-cooled, and most have 2101 channels. Thus, they are slightly larger than the 2001 channel AV-1, AV-2, and AV-3 reactors at the Chelyabinsk-65 complex. The thermal power output of all units were probably increased significantly over time.⁴⁰⁶ For purposes of estimating plutonium production, we assume their thermal power levels were increased to about 2000 MW_t each. The four dual-purpose reactors—two still operating—produce 200 MW_e each.⁴⁰⁷ In addition to

⁴⁰¹(...continued)

ate, earlier in the year had directed that a third reactor at Tomsk-7 be shut down in 1992; Khots, Yuriy, "Plutonium-Producing Reactors in Krasnoyarsk to be Shut Down," *Moscow ITAR-Tass World Service*, in Russian, 19 May 1992, 1352 GMT.

⁴⁰² *Nuclear News* has been reporting for several years that the first reactor began operating September 1958; the second December 1959; and the remaining reactors spaced a year apart (See *Nuclear News*, August 1993, p. 73). This estimate is wrong with respect to the location of the reactors. Consequently, the accuracy of the startup dates is questionable.

⁴⁰³ A film of the new station was shown to delegates at the conference, then in session, and it was disclosed that its location was in Siberia.

⁴⁰⁴ A.M. Petrosyants, *Nuclear Energy*, (Moscow: 1981), p. 13.

⁴⁰⁵ *Izvestiya*, 4 May 1990, morning edition, p. 6 (Translated in *FBIS*, London UK, Serial: PM0405112290).

⁴⁰⁶ By comparison, in the U.S. program at Hanford the first four graphite reactors, B, D, F, and DR, which began operating between 1944 and 1950, had a design power level of 250 MW_t; the next two, H and C, which came on line in 1948 and 1951, had design power levels of 400 and 600 MW_t, respectively; and the last two, KE and KW, were initially rated at 1850 MW_t at startup in 1952 and 1953. By 1964 the rating of these eight reactors had been increased to between 2090 and 4400 MW_t; see Thomas B. Cochran, et al., *Nuclear Weapons Databook*, Vol. II, p. 61.

⁴⁰⁷ In 1964, it was reported that the station had exceeded its design capacity of 600 megawatts-electric (MW_e), and in 1979 it was reported that "the capacity of this nuclear power station considerably exceeds 600,000 kw [kilowatts];" A. M. Petrosyants, *Problems of Nuclear Science and Technology*, 4th ed., translated from the Russian by W. E. Jones (Oxford: Pergamon Press, 1981), p. 103. Western sources always describe it as now consisting of six 100 MW_e units, and this appears to have been the original intention; *Nuclear News*, August 1993, p. 73. However, there are only four dual-purpose units. Aleksandrov mentions five units—presumably counting the first unit that did not produce electricity—with the second unit producing 200 MW_e; *Kommunist*, No. 1, 1976, p. 65. In 1993, *Moscow Rossiyskiye Vesti* reported that each of the three remaining dual-purpose reactors (the two at Tomsk-2 and one at Krasnoyarsk-26) produces 200 MW_e; Sergei Ovsienko, "Weapons-Grade Plutonium Stocks Dwindling," *Moscow Rossiyskiye Vesti*, in Russian, 19 May 1993, p. 7.

serving Tomsk-7 and the closed city, in 1992 it was reported that the reactors were supplying 40 percent of the heat and electricity for Tomsk. This may be true with respect to electricity, but it is unlikely the four reactors supplied 40 percent of Tomsk's heating needs. Minatom proposes to construct two 500 MW, AST reactors at Tomsk, bring them on line between 2001-2005.⁴⁰⁸

The four dual-purpose reactors (two still operating) have closed cycle cooling systems, with heat transferred from the closed primary loop to the secondary loop via an intermediate heat exchanger. Presumably the first reactor--not dual-purpose and now shut down--utilized once through cooling. In announcing its shut down, *Tass* reported ". . . soon another reactor [the second] will be shut down. As a result it is said that the amount of harmful effluent going into the Tom River will be halved."⁴⁰⁹

Chemical Separation Plant: The chemical separation and fuel storage facilities probably date from 1956 shortly after the first reactor went on line. As noted above under the discussion of chemical separation at Chelyabinsk-65, in 1976 the Soviets initiated an extensive program of civilian fuel reprocessing and shifted the RT-1 separation plant operations at Chelyabinsk-65 from military to civilian operations. As a result, the Tomsk began receiving by rail the plutonium production reactor fuel from Chelyabinsk-65 for processing.⁴¹⁰ These shipments would have ceased shortly after the last of the plutonium production reactors at Chelyabinsk-65 was shut down at the end of 1990.⁴¹¹ The spent fuel from the two remaining operating production reactors at Tomsk-7 was being processed at the only operating chemical separating plant (Building 15) when an accident (described below) crippled the plant on 6 April 1993. Minatom is currently working to bring the plant back on line. The director of the chemical separation plant at the time was V. Korotkevich.⁴¹²

Tomsk-7 Chemical Separation Plant Accident: On 6 April 1993, at 2:00 pm (0600 GMT) a tank used in the PUREX process exploded causing extensive damage to the plant and extensive off-site contamination. To understand where in the process the explosion occurred, it is useful to review some of the basic elements of the PUREX process. In the first extraction

⁴⁰⁸ The Concept of Development of Nuclear Power in Russian Federation. 14 July 1992, The Council (Kollegia) of the Minatom RF.

⁴⁰⁹ "Siberian Atomic Reactor Closes," *Moscow Tass*, International Service in Russian, 21 August 1990, 1449 GMT.

⁴¹⁰ Christopher Paine, "Military Reactors Go on Show to American Visitors," *New Scientist*, 22 July 1989, p. 22.

⁴¹¹ We assume the fuel elements from the light water production reactors at Chelyabinsk-65 are processed at RT-1. If not, they may have been, and perhaps continue to be, shipped to Tomsk-7.

⁴¹² Viktor Kostyukovskiy, "Tomsk-7: Nuclear Ordinarity after the Explosion," *Moscow Izvestiya*, in Russian, 12 May 1993, p. 7.

stage, irradiated uranium fuel is dissolved in nitric acid forming an aqueous solution of uranium nitrate, tetravalent plutonium nitrate, and fission product nitrates. The aqueous solution is then fed to the center of a counter current solvent extraction contactor. The contactor is fed from the bottom with organic solvent tributyl-phosphate (TBP) in solution with a carrier such as kerosene. It is fed from the top with a dilute nitric acid. The uranyl and plutonium nitrates concentrate in the organic solvents along with some fission products. The nitric acid scrub cleans the solvent of fission products, which leave the bottom in an aqueous stream while the plutonium and uranium leave the top in an organic stream. The uranium and plutonium are separated from each other in further extraction steps involving valence changes of plutonium. The organic stream containing tetravalent plutonium nitrate and uranyl nitrate is fed to a second contactor. This second contactor is also fed from the bottom by TPB, and from the top with a dilute nitric acid solution of ferrous sulfamate that reduces the plutonium to the trivalent state, leaving the uranium in its hexavalent state. As a result the plutonium is transferred to the aqueous phase and leaves the bottom of the contactor. The uranium and neptunium and some plutonium and fission product impurities remain in the organic stream, which is fed to a third contactor for further purification of the uranium.

The 35 m³ tank that exploded appears to be a holding tank between the second and third contactor. It contained 25 m³ of a uranium-plutonium solution with some residual fission products. Nitric acid was being added to the tank to increase the acidity of the solution.⁴¹³ To avoid the formation of a thin layer of "red oil"--the name given to a nitrite produced in mixtures of TBP and HNO₃ that can explode when heated above 130 °C--compressed air is used to mix the solution and stop the layer from forming. In violation of operating procedures this was not done. Exactly what happened next is uncertain. Russian experts believe gases from the reaction increased the pressure in the tank until it ruptured. The gases mixed with air outside the tank; and a short circuit ignited the gases causing a violent explosion. An alternative hypothesis is that failing to monitoring the temperature in the tank, the thin layer of "red oil" that formed on the surface overheated and exploded violently.⁴¹⁴ Three explosions involving "red oil" have occurred at U.S. chemical separation plants: in 1975 in the A-line at at the Savannah River Site's H-Canyon, at Savannah River in 1953, and at Hanford in 1953.⁴¹⁵ In any case the explosion is attributed to human error.

⁴¹³ "Tomsk-7 Caused Minimal Radiation Hazards, IAEA Team Reports," *Nuclear Waste News*, Vol. 13, No. 16, 22 April 1993, p. 157.

⁴¹⁴ *Ibid.*

⁴¹⁵ George Lobsenz, "DOE Studies Tomsk-7 for U.S. Ramifications," *The Energy Daily*, 7 June 1993, p. 1.

The violent explosion blew a hole in the roof; and blew out the upper wall of the galley for a distance of 100 m, or so. The pressure wave passed down the galley of about 100 m in length, bursting the lateral brick wall and causing extensive damage to other areas of the plant.⁴¹⁶ A fire broke out on the roof, but was put out within five minutes.⁴¹⁷ The building in which the blast occurred is said to have been destroyed over several hundred square meters.⁴¹⁸

At the actual site of the explosion, the dose rate was 10-15 R/h, "after 20 days of washing."⁴¹⁹ The highest recorded external dose received by a worker was 0.7 rem, while a fireman received about 0.2 rem.⁴²⁰ No internal dose estimated have been reported. Within one hour of the explosion, the dose rate was several mrem/h within the plant site and 0.4 to 0.5 mrem/h at the perimeter fence. At the same time, fission product contamination was reported as 20 Ci/km², and plutonium 20 mCi/km².⁴²¹ Light winds limited the spread of the contamination. A sketch of the radioactive plume published in the Russian press is reproduced in Figure 7. Radioactive material spread 20 km beyond the perimeter fence in the northeast direction; and the total area of the trace was about 250 km², defined by the 20 μ rem/h external dose rate isoline⁴²²; 50 km² outside the plant boundary above 30 μ rem/h;⁴²³ and 30-35 km² above 60 μ rem/h.⁴²⁴ Outside the contaminated area the background dose rate ranges from 5 to 17 μ rem/h.⁴²⁵ The accident contaminated mostly forest, 100 ha of stock producing fields, and two villages, Georgievka and

⁴¹⁶ Viktor Kostyukovskiy, "Tomsk-7: Nuclear Ordinarity after the Explosion," *Moscow Izvestiya*, in Russian, 12 May 1993, p. 7.

⁴¹⁷ AFP Wire Service, Moscow, 7 April 1993, 05:40.

⁴¹⁸ AFP Wire Service, Vienna, 7 April 1993, 06:21.

⁴¹⁹ Viktor Kostyukovskiy, "Tomsk-7: Nuclear Ordinarity after the Explosion," *Moscow Izvestiya*, in Russian, 12 May 1993, p. 7.

⁴²⁰ Ibid. UPI Wire Service, Moscow, April 7, 01:16, reported that firefighters who fought the flames received 0.6 R of exposure.

⁴²¹ Viktor Kostyukovskiy, "Tomsk-7: Nuclear Ordinarity after the Explosion," *Moscow Izvestiya*, in Russian, 12 May 1993, p. 7.

⁴²² Veronika Romanenkova, "Independent Experts on Tomsk-7 Accident Aftermath," *Moscow ITAR-TASS*, in English, 20 April 1993, 1321 GMT.

⁴²³ *Moscow Izvestiya*, in Russian, 17 April 1993, First Edition, p. 2.

⁴²⁴ Tomsk Ecological Initiative, "Information about the Siberian Chemical Facility (Tomsk-7);" this source claims the extent of the fallout above 15 μ rem/h was 28 km with a maximum width of 6 km and an area of 123 km².

⁴²⁵ *Moscow INTERFAX*, in English, 9 April 1993, 1655 GMT (reproduced in *Foreign Broadcast Information Service*, FBIS-SOV-93-068, 12 April 1993, p. 39).

Chyornaya Rechka.⁴²⁶ Sixteen km from the accident center, Georgievka, with a population of 200, was exposed to an initial external dose rate of 18-45 $\mu\text{rem/h}$ from external beta/gamma contamination reported at 150 Ci/km^2 , and plutonium at 0.4-0.5 mCi/km^2 .⁴²⁷ The radiation levels in Chyornaya Rechka ranged from 12-15 $\mu\text{rem/h}$,⁴²⁸ essentially background levels. The width of the radioactive trace where it crossed the northern road of the Tomsk region was 3 km (28 to 31 km from Tomsk).⁴²⁹ There was no timely notification of the population about the accident, and they were not provided with regular official bulletins.

The chemical separation plant was put back into operation sometime prior to 18 August 1993.⁴³⁰

Plutonium Processing: In the 1960s blending of plutonium of different isotopic concentrations took place at Plant 5 and was transferred to Plant 25, as evidenced by more recent criticisms of plant activities at these plants.⁴³¹ A former employee of Plant 25 has alleged that in 1967, management officials at Plant 25 falsified plutonium blending ratios, apparently creating a "fictitious" inventory of plutonium. "[I]n a ten-month period, about 90 kg of 'fictitious' plutonium oxalate 'piled up' at the Shop 1 warehouse." According to the same source, management officials at Plants 25 and 15 decided cover up the problem by transferring the "fictitious" plutonium to Plant 15 for "purification." "In this operation only 50-60 kg of pure plutonium were manipulated, and several hundred kilograms of plutonium plus several tons of HEU were dumped by Plant 25 into its reservoir."⁴³²

Waste Management Activities: Large quantities of radioactive waste have been dumped into open reservoirs on site. According to Ecological Initiative, a grass roots environmental movement in the Tomsk area, "Until 1963 wastes [presumably the HLW, perhaps after dilution to medium level] were simply poured into an open lake, which is still found on the site of the

⁴²⁶ Ibid and *Moscow Izvestiya*, in Russian, 17 April 1993, First Edition, p. 2.

⁴²⁷ "Tomsk-7 Caused Minimal Radiation Hazards, IAEA Team Reports," *Nuclear Waste News*, Vol. 13, No. 16, 22 April 1993, p. 157.

⁴²⁸ Tomsk Ecological Initiative, "Information about the Siberian Chemical Facility (Tomsk-7)."

⁴²⁹ Ibid.

⁴³⁰ Interview with Viktor Mikhailov by Andrei Vaganov, *Moscow Nezavisimaya Gazeta*, in Russian, 18 August 1993, pp. 1,3 (Translated into English in *Foreign Broadcast Information Service*, FBI-SOV-93-159, 19 August 1993, pp. 34-37).

⁴³¹ L.V. Stryapshin, "We Need Independent Assessments," *Tomsk-37*, 8 July 1991.

⁴³² Ibid.

SCC [Siberian Chemical Combine].⁴³³ The Combine is apparently in the process of filling in this reservoir, similar to what is taking place at Lake Karachay. As described in a Russian television report, "As soon as the snow melts, these lead-plated machines and mechanisms will again be moving earth to the radioactive reservoir. Several years will be needed to fill in the reservoir and thus prevent lethal evaporation. The question is, however, what will happen to the water. ... We were allowed to run to the edge of the reservoir, on condition that we would shoot for no more than a minute and then run back again. ... This is no place for gawkers."⁴³⁴ *Izvestiya* reported that the radioactive waste burial site is poorly fenced and contaminated water areas are not fenced at all. Elk, hare, duck, and fish are contaminated, and 38 people were found to have higher than permissible levels of radioactive substances in their body. Of these 38, four adults and three children have been hospitalized.⁴³⁵

During the 30-year operation of the plant, about 127,000 tons of solid and about 33 million m³ of liquid radioactive wastes have been collected in underground storage facilities.⁴³⁶ "The Sibkhimkombinat (Siberian Chemical Combine) burial sites are located 10-20 km from the river Tom. At these sites radioactive wastes of unknown quantity and concentration have been pumped into sandy beds at a depth of 320-460 meters. In the immediate area of the burial sites the beds are covered with uniform, water-resistant clay strata; however, throughout the region as a whole these strata can thin out."⁴³⁷

Another source describes the wastes as, "...buried underground, in sand strata of chalk deposits at a depth of 320-460 m and 12-15 km from the water supply. The quantity of buried RAW is around 36 million cubic meters containing 1.06 billion curies of radioactivity."⁴³⁸ According to this source,

"Beginning in 1989-1990, there was a threat of contamination to the underground water supply by the radioactive material due

⁴³³ Tomsk Ecological Initiative, "Information about the Siberian Chemical Facility (Tomsk-7)." There is reason to question the accuracy of this reference. The report goes on to say, "The radioactivity on the shore is 600 megacuries. A person standing on the lake shore receives in 10 seconds his annual norm of radiation (5 rem) [i.e., 1800 rem/h]." But by our calculations only about 356 MCi of Sr-90 + Cs-137 would have accumulated from all production reactor operations at Tomsk-7 through 1992; and only about 20 MCi would have accumulated prior to 1963, half of which would have decayed by 1993.

⁴³⁴ Moscow Ostankino Television First Channel Network, in Russian, 27 February 1993, 0955 GMT.

⁴³⁵ "Urgent Warning: Radioactive Waste Available to All," *Izvestiya*, 4 May 1990, morning edition, p. 6 (Translated in *FBIS*, London UK, Serial: PM0405112290).

⁴³⁶ V. Kostyukovskiy, et al., "Secrets of a Closed City," *Moscow Izvestiya*, Union Edition, 2 August 1991 (in Russian), (translated in *JPRS-TEN-91-018*, 11 October 1991, pp. 71-72).

⁴³⁷ *Ibid*; quoting from an article appearing "not long ago" in *Rossiyskaya Gazeta*, which in turn was quoting from an official document compiled by specialists from Tomskneftegasgeologiya.

⁴³⁸ Tomsk Ecological Initiative, "Information about the Siberian Chemical Facility (Tomsk-7)."

to the fact that wells in the northern part of the aquifer hit water that was in contact with the buried liquid RAW. The results of the investigations carried out by the PGO 'Birch Geology' clearly show major tectonic faults in the earth's crust in the Tomsk region: these faults create the conditions for the mixing of subterranean waters from different strata. It is specifically in the region between two deep breaks that the operational wells of the 3 lines of the water supply are found. This break follows the right bank of the Tom and encloses the zone where the liquid RAW is buried. This creates a corridor within which there exists the possibility of the mixing of underground waters of the strata with another. This intensive pumping out of water from the wells of the 3 lines of the water supply (the Ob'-Tomsk water shed is the only source of drinking water for 2/3 of the oblast population, which is concentrated in this region) forms favorable conditions for the contamination of underground water in a strata due to the unloading of the lower water carrying strata of chalk deposits. The active movement of underground waters in the chalk deposits causes the pulling up of a front of underground water which is in contact with the buried RAW. This can lead to a speeding up of the contamination of operational water in the northern part of the water supply. In this case, the population would lose 50-60% of the volume of water now used in Tomsk.⁴³⁹

Problems with defense waste at Tomsk date back to the 1970s. At that time, a senior engineer responsible for "monitoring stocktaking and storage of special output" discovered a "vast quantity of radioactive output" at the plant. *Izvestiya* claims that his letter to the Central Committee and L.I. Brezhnev only resulted in his reprimand and threatened expulsion from the party.⁴⁴⁰ Not until 18 April 1990, when Tomsk-7 radio warned that people had been contaminated, did the public learn of this problem.⁴⁴¹

At Tomsk-7 there are several facilities, both underground and surface, for radioactive waste storage. At one solid waste burial site surrounded by several fences, "Containers of toxic waste are deposited in special burial vaults and underground bunkers. There is also a surface bunker. What protection the walls of the containers offer can be judged from this radiation reading on

⁴³⁹ *Ibid.*

⁴⁴⁰ "Urgent Warning: Radioactive Waste Available to All," *Izvestiya*, 4 May 1990, morning edition, p. 6 (Translated in *FBIS*, London UK, Serial: PM0405112290).

⁴⁴¹ *Ibid.*

opening the bunker, which has not yet been bricked up. ... Fifty-six millisieverts/hour [5.6 rem/h]"⁴⁴²

A series of dams along Romashka Creek, a tributary of the Tom River, form temporary holding ponds for reactor coolant water, prior to discharge into the Tom. The hold up affords some cooling of the discharged water and partial decay of radionuclides. With the only reactor that utilized once-through cooling now shut down, cooling the discharged water no longer seems necessary. However, other sources of radioactivity also may be discharged into the Romashka, and the holding ponds may still serve to retain radioactivity. In July 1990, French scientists took radiation measurements just outside the Tomsk-7 site.⁴⁴³ At the bank of the cooling water discharge canal, where it flows into the Tom about 2.5 km downstream from the reactors, the gamma radiation levels were 300 microrad/hour ($\mu\text{rad/h}$) in air and 400 $\mu\text{rad/h}$ in the water in the canal.⁴⁴⁴ On the bank of the Tom, 2 km downstream from the creek or canal, the gamma radiation level was 150 $\mu\text{rad/h}$ in air. A sample of sediment, taken at 5 cm depth in the canal where it flows into the Tom, was found to contain 121 Becquerels/kilogram (Bq/kg) of Cs-137, 4036 Bq/kg of cobalt-58, 18,564 Bq/kg of chromium-51, and 2441 Bq/kg of zinc-65.⁴⁴⁵ The high levels of activation products (Co-58, Ch-51, and Zn-65) are indicators of corrosion in one or more of the reactors.

Uranium Enrichment Plant: On January 25, 1991, *Izvestiya* reported a commercial deal whereby the Siberian Chemical Combine would enrich up to four percent uranium recovered from reprocessed French power reactor fuel.⁴⁴⁶ A contract (No. 54-02/60006) was signed in March 1991 by Techsnabexport and Cogema providing for shipment to Tomsk-7 "in 1992-93 of recovered uranium in the form of mixed uranium oxides (U_3O_8) in quantities up to 150 tonnes annually, and in 1994 and subsequent years in the form of uranium hexafluoride (UF_6) in quantities up to 500 tonnes annually. This contract shall remain in effect until the year 2000."⁴⁴⁷ The Russians

⁴⁴² Ibid.

⁴⁴³ Max Lariviere and Jaqueline Denis-Lampereur, *Science & Vie*, February 1991, pp. 102-103.

⁴⁴⁴ Normal background levels in the region are 10-20 microrad/h.

⁴⁴⁵ Max Lariviere and Jaqueline Denis-Lampereur, *Science & Vie*, February 1991, p. 103. Subsequent gamma spectroscopy of the sample identified Mn-54, Co-60, Zn-65, Eu-152, and Pu-239,240 in concentrations above background levels.

⁴⁴⁶ "Open Deal in a Closed City," *Izvestiya*, 25 January 1991, Union Edition, p. 2 (Translated in *FBIS*, London UK, R 251109Z Jan 1991); and Moscow Russian Television Network, 3 January 1991, 1700 GMT (translated from Russian).

⁴⁴⁷ Kirill Belyanov, "Version: French Nuclear Wastes Exploded at Tomsk-7," *Moscow Novaya Yezhednevnyaya Gazeta*, in Russian, 21-27, 1993 [signed to press 20 May 1993], pp. 1,5 (translated into English in *Foreign Broadcast Information Service-USR-93-071*, 9 June 1993, p. 39).

would be paid around \$50 million a year under the cooperative arrangement.⁴⁴⁸ Later that year it was reported that these were precontract negotiations.⁴⁴⁹ Apparently, the French want to avoid contaminating their own enrichment plants with uranium-232 and uranium-236 impurities in the uranium recovered from spent fuel, by enriching the recovered uranium in Russian enrichment plants.

Long-Term Storage Facility for Fissile Material from Weapons: Minatom's decision to start designing a centralized long-term storage of fissile materials from weapons at the Siberian Chemical Combine was taken after evaluating other options and was based on favorable hydro-geological environment in the Tomsk area and availability of relevant equipment and expertise allowing handling fissile materials should such operations be required. Public opposition to siting the storage facility at Tomsk-7, as a consequence of the 6 April 1993 accident at the Tomsk-7 chemical separation plant, may force Minatom to shift the facility location, e.g., to Sverdlovsk-45 or Chelyabinsk-65.

The design of the facility has been developed by the Institute of Industrial and Energy Technologies (VNIPIET, St.Petersburg) with the U.S. technical and financial assistance.⁴⁵⁰ The facility is designed to provide storage of 40,000 fissile-material containers over the period of 80-100 years.⁴⁵¹ The materials will be stored in the form of weapons components in criticality-safe, airtight, shock- and fire-proof containers AT-400R, developed by the Arzamas-16 laboratory.

The complex of the storage facility will be located in a high-security area within the protected area of the Siberian Chemical Combine. The underground bunker will accommodate hermetically isolated storage compartments and premises for vital support equipment including a diesel-generator, air-conditioning, cooling-, and accumulator stations. The design does not foresee operations involving opening the containers inside the facility. A railway terminal, administrative building, electricity generator, compressor, heater, fire-and security force stations will be built on the surface.

The facility is to be built with the assistance of U.S. (Nunn-Lugar) funds. The United States and Russia have agreed on "General Safety Criteria

⁴⁴⁸ Ibid.

⁴⁴⁹ V. Kostyukovskiy, et al., "Secrets of a Closed City," *Moscow Izvestiya*, Union Edition, 2 August 1991 (in Russian), (translated in JPRS-TEN-91-018, 11 October 1991, pp. 71-72).

⁴⁵⁰ Russia and the United States have signed the agreement providing for U.S. assistance in designing a storage facility. Some \$15 million of the Nunn-Lugar funds was allocated for this purpose.

⁴⁵¹ V. Golozubov, "Basic Principles of the Design of the Storage for Fissile Materials in Russia," presented at the International Workshop "Reprocessing of Nuclear Fuel, Storage and Disposition of Civilian and Weapons Plutonium," 14-16 December 1992, Moscow. The facility is being designed to permit the construction, if needed, of a "second stage" with the additional storage capacity of up to 60,000 containers.

for the Russian Fissile Material Storage Facility.” According to these criteria, the facility is designed to withstand the following events: a tornado, earthquake, fire, flood, increase in temperature due to plutonium phase transformations, container leak, mistake by the personnel, electricity black-out, airplane crash, bombing, and terrorist attack. The safety criteria will be met by the robust design of containers capable of withstanding a 9-meter fall, an 800°C fire for 30 minutes and immersion in water at up to 12 atmospheres pressure (corresponding to a depth over 100 meters), as well as by careful geological siting of the facility, and by special engineering and institutional measures. According to designers, integrity of the storage may be violated only in the event of an attack with nuclear or conventional high-power concrete-penetrating weapons.

The design specifications require the occupational radiation exposure to be five times less than that currently used across the nuclear industry in Russia. Special efforts to localize and contain any accident within the facility are undertaken to reduce radiation exposure due to an accident. Even for worst basic design accidents, the additional cancer risk would not exceed 0.1 of that associated with the occupational radiation exposure. The population dose would not exceed occupational exposure limit under any circumstances.⁴⁵²

Mining and Chemical Combine (Krasnoyarsk-26, “Devyatka,” Zheleznogorsk, “Atomgrad,” Dodonovo)

In 1950, Stalin authorized the building of a “radiochemical enterprise” for producing plutonium on the mountainous east bank of the Yenisey River in the Siberian taiga not far from the Stolby National Preserve,⁴⁵³ 50 km (64 km by road) northeast of Krasnoyarsk.⁴⁵⁴ Thus, in the same year was born, “Sibkhimstroy” (Siberian Chemical Complex), now known as the Mining and Chemical Combine [Gorno-Khimicheskiy Kombinat (GKhK)]⁴⁵⁵ (local inhabitants call it “Devyatka”), code-named Krasnoyarsk-26. The Krasnoyarsk-

⁴⁵² S.Petrin “Safety of the Fissile Materials Storage,” presented at the International Workshop “Reprocessing of Nuclear Fuel, Storage and Disposition of Civilian and Weapons Plutonium,” 14-16 December 1992, Moscow.

⁴⁵³ The Mining and Chemical Combine was built by the USSR Council of Ministers Order No. 13523 RS/OP, dated 26 August 1950; V.I. Korogodin, V.F. Idimechev, S.V. Lopatko, A.I. Maslyuk, G.P. Matrosov, A.G. Pakulo, A.A. Samarkin, V.G. Khizhnyak, and O.I. Shamov, “Report of the Interdepartmental Commission for Assessment of the Radiation Situation in the Vicinity of the City of Krasnoyarsk,” *Krasnoyarsk DOKLAD*, in Russian, 1990, pp. 1-12, appendices. See also, “The Nuclear City: A Trip to a Populated Area Which is Not on the Map,” *Pravda*, 26 June 1989; Aleksey Tarasov and Dmitriy Khrupov, “Spy Satellites are Made Here: Report from a Closed Military City,” *Moscow Izvestia*, in Russian, 11 January 1992, Union Edition, pp. 1,8 (translated into English); and Steven Erlanger, “A Siberian Town: Not a Secret and Ready to Deal,” *New York Times*, 29 March 1992, pp. 1,6.

⁴⁵⁴ Krasnoyarsk-26 is located at 56° 20’N/93° 36’E.

⁴⁵⁵ Postal address: 660033, Krasnoyarsk-33, ul. Lenia 53.

26 site, which is fenced off, covers more than 17 km².⁴⁵⁶ A larger sanitary protection zone covering 13,100 ha (131 km²) was established in 1971.⁴⁵⁷ About 10 km to the south of the Krasnoyarsk-26 is the closed city Zheleznogorsk (population 90,000 living on 35 km²)⁴⁵⁸, often called "Atomgrad." by *Gorod i Gorozhanye*, the local newspaper. There use to be a small village called Dodonovo at or near the closed city.

The Combine comprises five "plants"—the "reactor plant," with three plutonium production reactors, of which only one is still operating; a radiochemical plant used to recover the plutonium from the reactor spent fuel; the reactor coolant water preparation plant; the partially completed RT-2 radiochemical plant; and the engineering and repairs plant—and 22 individual workshops and sections.⁴⁵⁹

Unlike Chelyabinsk-65 and Tomsk-7, the plutonium production and separation at Krasnoyarsk-26 takes place entirely underground. The three plutonium production reactors, the reactor coolant water preparation plant, the chemical separation plant, which has operated since 1965, the waste treatment and storage facilities, and "innumerable laboratories," are all located within a huge cavern some 200-250 m underground. There are three tunnels into the underground complex, one for transportation, one for ventilation, and a third for supply lines.⁴⁶⁰ "A concrete road that stretches along the shore of the Yenisey leads to a tunnel situated at the base of an enormous mountain."⁴⁶¹ The 11,000 employees⁴⁶² of the combine go to work by train along the five km long tunnel.

Digging the multilevel system of underground tunnels and 3,500 rooms took three years and more than 65,000 prisoners. Some 100,000 military construction workers replaced the prison labor in 1953, after the death of Beria. The first reactor began operating five years later in 1958. In 1992, it

⁴⁵⁶ T.N. Zhabina, From the "This is How We Live" Series, subtitled "Closed City," Moscow Russian Television Network, in Russian, 15 October 1992, 1500 GMT.

⁴⁵⁷ It was established by resolution 886, dated 15 January 1971, of the executive committee of the closed city, Krasnoyarsk-26; V.I. Korogodin, et al., "Report of the Interdepartmental Commission for Assessment of the Radiation Situation in the Vicinity of the City of Krasnoyarsk," *Krasnoyarsk DOKLAD*, in Russian, 1990, pp. 1-12, appendices.

⁴⁵⁸ Akira Furumoto, *Tokyo Yomiuri Shimbun*, in Japanese, 17 November 1991, Morning Edition, p. 1 (translated in *Foreign Broadcast Information Service-SOV-91-225-A*, 21 November 1991, p.3.). "Sibkhimstroy" (Siberian Chemical Complex) should not be confused with "Sibkhimkombinat" (Siberian Chemical Combine), which is Tomsk-7 at Tomsk.

⁴⁵⁹ *Ibid.*

⁴⁶⁰ Moscow Ostankino Television First Channel Network, in Russian, 27 February 1993, 0955 GMT.

⁴⁶¹ Yu. Khots, "Underground AES [Nuclear Power Station] Will No Longer Produce Plutonium," *Moscow Izvestiya*, Union Edition (in Russian), 14 November 1991, p. 6.

⁴⁶² *Izvestiya*, 1 July 1992.

was reported that some 7 million m³ had been excavated, more than three times the 2 million m³ volume of the Pyramid of Cheops.⁴⁶³ In the 1970s, the volume of excavation was compared to that of the Moscow metro.⁴⁶⁴ Its dimensions may be judged by the fact that every hour 5.5 million m³ of air are pumped underground into the combines shops and living premises.⁴⁶⁵ The underground ventilation system reportedly changes the air volume every ten hours. The production facilities were placed underground to provide protection against potential enemy air raids; and, in fact, the tunnels have several widened areas designed to suppress the shock wave from a nuclear attack.⁴⁶⁶

Nearby, aboveground, there is a fossil fueled plant that can be used to provide backup power. Also aboveground, construction of RT-2, a second chemical separation plant, was halted in 1989. A spent fuel storage facility was completed at the RT-2 site. Across the river, some 10 km away, is Site 27, where radioactive waste from RT-2 was to have been injected into the ground. Some 500-600 wells were drilled for this purpose.

The director of the Mining and Chemical Combine is Valeriy Lebedev.⁴⁶⁷

A second nuclear weapons related facility at Krasnoyarsk-26 is the Scientific Production Association of Applied Mechanics, established in 1959, employing 11,000 workers, and headed by Academician Mikhail F. Reshetnev, a colleague of S. Korolev.⁴⁶⁸ This facility is part Krasmach, a larger defense industry enterprise with facilities in and around Krasnoyarsk. The START Treaty data exchange identifies the Krasnoyarsk Machine Building Plant (Krasmach) at Krasnoyarsk as a production facility for Submarine-Launched Ballistic Missiles (SLBMs).⁴⁶⁹ Krasmach also designs, manufactures, and tests spy satellites, space vehicles, special communications, and satellites for the Academy of Sciences.⁴⁷⁰ More than one-third of the Cosmos space vehicles

⁴⁶³ *Pravda*, 30 June 1992, p. 1, translated in FBIS-SOV-92-130, 17 July 1992, p. 47.

⁴⁶⁴ Aleksey Tarasov and Dmitriy Khrupov, "Spy Satellites are Made Here: Report from a Closed Military City," *Moscow Izvestiya*, Union Edition, in Russian, 11 January 1992, p. 1,8 (translated into English).

⁴⁶⁵ V. Nelyubin, "Mountains Cause Excess Misfortune from Excess Cleverness," *Moscow Komsomolskaya Pravda*, in Russian, 20 October 1992, p. 2 (translated in *Foreign Broadcast Information Service*, FBIS-USR-92-137, 24 October 1992, p. 25).

⁴⁶⁶ Tarasov and Khrupov, "Spy Satellites are Made Here."

⁴⁶⁷ Tarasov and Khrupov, "Spy Satellites are Made Here."

⁴⁶⁸ *Ibid*; and Erlanger, *New York Times*, 29 March 1992, pp. 1,6.

⁴⁶⁹ United States Arms Control and Disarmament Agency, *Arms Control and Disarmament Agreements: START, Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Reduction and Limitation of Strategic Offensive Arms*, 1991, p. 186.

⁴⁷⁰ Tarasov and Khrupov, "Spy Satellites are Made Here."

were worked on here.⁴⁷¹ The firms output is represented by the Molniya, Raduga, Gorizont, Ekran, Luch, and radio satellites, navigation (including the Tsikada and Glonass satellites), and Geodesy (Geoik and Etalon).⁴⁷²

Also about 90 km east of Krasnoyarsk is the Electrochemistry Plant, one of four uranium enrichment plants in Russia. It is also identified as Krasnoyarsk-45, with its closed city Zelenogorsk (population 63,300).⁴⁷³

Graphite Reactors: The three graphite-moderated production reactors are hidden 200-250 m underground.⁴⁷⁴ The first reactor, "AD," was started up in 1958,⁴⁷⁵ and was shut down on 30 June 1992;⁴⁷⁶ the second, "ADE-1," began operating in 1961, and was shut down on 29 September 1992; and the third was started up in 1964, began supplying the underground facility and closed city with electricity and steam heat in 1965, and is still operating as a dual-purpose reactor.⁴⁷⁷ Judging by photograph of the reactor fuel loading deck, one or two of the reactors (probably the first two) are estimated to be comparable in size to the AV-1, AV-2, and AV-3 reactors at Chelyabinsk 65, each of which has 2001 channels.⁴⁷⁸ Prior to being shut down their operating capacity is assumed to have been about 2000 MW. In March 1990 the thermal capacity of AD and ADE-1, the two once-through cooling reactors, was reduced by 20 percent.⁴⁷⁹ One or two of the reactors--probably only one--has

⁴⁷¹ Ibid.

⁴⁷² Ibid.

⁴⁷³ Akira Furumoto, *Tokyo Yomiuri Shimbun*, in Japanese, 17 November 1991, Morning Edition, p. 1 (translated in *Foreign Broadcast Information Service-SOV-91-225-A*, 21 November 1991, p. 3.).

⁴⁷⁴ "Out from Under the Earth," *Pravda*, 21 December 1991.

⁴⁷⁵ The start-up dates for all three reactors is given by V.I. Korogodin, et al., "Report of the Interdepartmental Commission for Assessment of the Radiation Situation in the Vicinity of the City of Krasnoyarsk," *Krasnoyarsk DOKLAD*, in Russian, 1990, pp. 1-12, appendices.

⁴⁷⁶ Aleksey Tarasov, "In Secret Caverns of Krasnoyarsk-26 Reactor Which Produced Weapons-Grade Plutonium Has Been Shut Down," *Moscow Izvestiya*, in Russian, 1 July 1992, Morning Edition, p. 2 (translated in *Joint Publications Research Service*, JPRS-TEN-92-015, 30 July 1992, p. 67).

⁴⁷⁷ *Moscow Reuters*, 30 June 1992; Yuriy Khots, "Plutonium-Producing Reactors in Krasnoyarsk to be Shut Down," *Moscow ITAR-Tass World Service*, in Russian, 19 May 1992, 1352 GMT; Yuriy Khots, "Plutonium-Producing Krasnoyarsk Reactor Shut Down," *Moscow ITAR-Tass World Service*, in Russian, 29 September 1992, 0518 GMT (Translated into English in *Foreign Broadcast Information Service*, FBIS-SOV-92-194, 6 October 1992, pp. 38-39); Yuriy Khots, "Underground AES [Nuclear Power Station] Will No Longer Produce Plutonium," *Moscow Izvestiya*, Union Edition (in Russian), 14 November 1991, p. 6; V. Yaroslavtsev, "The Yenisey's X-Rays" from "What Troubles our Conscience: A Polar Chernobyl Syndrome," *Vozdushnyy Transport*, 4 October 1990, p. 3; and *The Washington Post*, 21 April 1992, P. A15.

⁴⁷⁸ "Out from Under the Earth," *Pravda*, 21 December 1991. Photographs of the control room and the floor of one of the reactors accompany the article.

⁴⁷⁹ V.I. Korogodin, et al., "Report of the Interdepartmental Commission for Assessment of the Radiation Situation in the Vicinity of the City of Krasnoyarsk," *Krasnoyarsk DOKLAD*, in Russian, 1990, pp. 1-12, appendices. See also, V. Yaroslavtsev, "The Yenisey's X-Rays" from "What Troubles our Conscience: A Polar Chernobyl Syndrome," *Vozdushnyy Transport*, 4 October 1990, p. 3.

2832 channels, including 120 containing control rods. Probably only the third reactor has the larger number of channels, since it is dual-purpose--producing plutonium, electricity, and providing steam for district heating.⁴⁸⁰ For estimating plutonium production it is assumed to operate at about 2000 MW_e. In 1993, *Moscow Rossiyskiye Vesti* reported that each of the three remaining dual-purpose reactors (the two at Tomsk-7 and one at Krasnoyarsk-26) produces 200 MW_e.⁴⁸¹

The third reactor is scheduled to be shut down by 2000,⁴⁸² but must await the availability of replacement power (electricity and steam). The Sosnovoborsk power and heating plant, under construction near Krasnoyarsk, has been cited as the source of replacement power.⁴⁸³ But this plant is too far removed to supply steam to the closed city at Krasnoyarsk-26, and in any case, there is public opposition to completing the plant.

As noted above, the first two reactors utilized once-through cooling.⁴⁸⁴ Since water from the Yenisey was pumped through these reactors and returned directly to the river, the river is contaminated with fission product leakage and neutron induced radioactivity. In 1991 it was reported that radioactive contamination of the discharged cooling water "results in an increase in the radioactivity level of the dumped water to 3000 micro-roentgen per hour."⁴⁸⁵ These two reactors were ordered closed in 1992 by due to pollution of the Yenisey River. The dual-purpose reactor (the third reactor) has a closed cooling cycle and is therefore less polluting. Two streams of thermal effluents into the Yenisey River are visible in a composite of LANDSAT images, a day image from December 17, 1989 combined with a night image from 5 September 1989. The southern most, or upstream, discharge is the combined flow of water from the two reactors with open cycle cooling, which were still operating at the time. The northern most, or

⁴⁸⁰ The heat and electricity serve the underground facility and the closed city.

⁴⁸¹ Sergei Ovsienko, "Weapons-Grade Plutonium Stocks Dwindling," *Moscow Rossiyskiye Vesti*, in Russian, 19 May 1993, p. 7.

⁴⁸² Ibid.

⁴⁸³ Alexander Bolsunovsky, "Russian Nuclear Weapons Production and Environmental Pollution," paper presented at the Conference on "The Nonproliferation Predicament in the Former Soviet Union," Monterey Institute of International Studies, Monterey, California, 8 April 1992.

⁴⁸⁴ Called single-flow [pyamotchnyy] reactors.

⁴⁸⁵ "Nuclear Storage and Weapon Plutonium Facilities at Krasnoyarsk," 1991 *The British Broadcasting Corporation; Summary of World Broadcasts*, 20 December 1991, Postfactum in English 2147 GMT 9 December 1991.

downstream, discharge is from the secondary loop of the dual-purpose reactor.

Tritium has not been produced at Krasnoyarsk-26. The three reactors have produced only plutonium.⁴⁸⁶ Assuming the one remaining reactor is operating at 2000 MW_e with a capacity factor of 0.8, and a fuel burnup of 500 MWd/MT, it is producing about 0.5 MT of weapon-grade plutonium annually.

Chemical Separation Facilities: In 1964 a radiochemical plant, housed in the underground facility, was put into operation to process irradiated fuel from the three production reactors.⁴⁸⁷ Presumably the plant is still in operation to process fuel from the one remaining production reactor. From 1958 to 1965, spent fuel from the production reactors presumably was shipped to Tomsk-7 or Chelyabinsk-65 for processing.

RT-2 Spent Fuel Storage and Chemical Separation Plant: In 1975, it was resolved to build an irradiated fuel-storage facility and a fuel reprocessing (i.e., chemical separation) plant to be used for recycling civil reactor spent fuel, namely, fuel from the new 1000 MW_e pressurized water reactors (VVER-1000) and "other" reactors. Construction of the facilities, called RT-2, was begun in 1976 or 1978, at a 140 ha hill-top site overlooking the Yenisey River just north of the underground reactors.⁴⁸⁸

The spent fuel storage facility with auxiliary and service buildings was put into service in December 1985. The storage pool has a design capacity of 6000 MTHM. It comprises 1328 cylinders (6 m in length and 2 m in diameter), with the fuel stored eight meters below ground under three meters of water.⁴⁸⁹ In early 1992, it was reported to contain some 750 MTHM of spent fuel from VVER-1000 power reactors, including spent fuel shipped from Ukraine prior to 1991 (See Table 21). This represents about 12.5 percent of its capacity. The seven Russian VVER-1000s discharge about 130 MTHM/y, and the ten Ukrainian VVER-1000s discharge about 185 MTHM/y, giving a total of about 315 MTHM/y (41 percent from Russia) exclusive of five or more new reactors that could come on line (See Tables 23 and 24). In 1992 the Russian parliament passed an environmental law that prohibited the import of radioactive waste into Russia. No spent fuel was returned to Russia during the following year pending resolution of whether spent fuel constitutes

⁴⁸⁶ "Out from Under the Earth," *Pravda*, 21 December 1991. Photographs of the control room and the floor of one of the reactors accompany the article.

⁴⁸⁷ V.I. Korogodin, et al., "Report of the Interdepartmental Commission for Assessment of the Radiation Situation in the Vicinity of the City of Krasnoyarsk." *Krasnoyarsk DOKLAD*, in Russian, 1990, pp. 1-12, appendices.

⁴⁸⁸ RT-2 is situated on the right bank of the Yenisey River at a distance of 5 km from the river and 6 km from the village of Atamanovo, down stream on the opposite bank.

⁴⁸⁹ "Nuclear Storage and Weapon Plutonium Facilities at Krasnoyarsk," 1991 *The British Broadcasting Corporation; Summary of World Broadcasts*, 20 December 1991, Postfactum in English 2147 GMT 9 December 1991.

radioactive waste. A total of 150 MTHM delivered in 1992, all from Russia.⁴⁹⁰ The law was overridden by Yeltsin's Presidential Decree of 21 April 1993, which provides for the return of spent fuel from abroad for reprocessing.⁴⁹¹ If shipments are resumed from Ukraine and five new VVER-1000 reactors are brought on line by 1995, RT-2 has sufficient storage capacity until about 2005. If only Russian fuel is shipped the capacity is adequate until well into the next century.

The second section of RT-2, the 1500 MTHM/y fuel reprocessing plant,⁴⁹² which is adjacent to and surrounds the spent fuel facility, was scheduled to be completed by 1997-98. It was to employ 5000 people. There was a sharp reduction in funding for the project in 1985.⁴⁹³ It was only about 30 percent complete when construction was interrupted and then halted in 1989, as a result of public controversy.⁴⁹⁴ In June 1989, *Komsomolskaya Pravda* reported that some 60,000 people in Krasnoyarsk signed a protest, in part, because they were angered by the revelation that the scientific study justifying the selection of the site was actually produced nine years after construction started.⁴⁹⁵ In 1989 or 1990, by order of the Ministry of Atomic Power and Industry, the construction of RT-2 stopped for a five year period due to lack of funding.⁴⁹⁶ Two hundred million rubles were spent on the project. Just preserving the construction would require 30 million rubles, but in 1991 only 1.5 million rubles was allocated.⁴⁹⁷

⁴⁹⁰ *Nuclear Fuel*, 4 January 1993, p. 6.

⁴⁹¹ Boris Yeltsin, "Decree of the President of the Russian Federation on the fulfillment of the Russian Federation of intergovernmental agreements on cooperation in the construction of nuclear power stations abroad," Decree No. 472, 21 April 1993.

⁴⁹² RT-1, the first reprocessing plant for civil reactor fuel, is located at Chelyabinsk-65.

⁴⁹³ Aleksey Tarasov and Dmitriy Khrupov, "Spy Satellites are Made Here: Report from a Closed Military City," *Moscow Izvestiya*, Union Edition, in Russian, 11 January 1992, p. 1,8 (translated into English).

⁴⁹⁴ "The Mystery of Site 27," *Sotsialisticheskaya Industriya*, 29 July 1989; and V. Yaroslavtsev, "The Yenisey's X-Rays," from an article "What Troubles Our Conscience: A Polar Chernobyl Syndrome," *Vozdushnyy Transport*, 4 October 1990, p. 3; and "Soviet Union Postpones Completion of Siberian Reprocessing Plant," *Nuclear Fuel*, 16 October 1989, pp. 1-2.

⁴⁹⁵ "Regular Daily Spot: Commission is Here for 1 Hour But We...," *Komsomolskaya Pravda*, 15 June 1989.

⁴⁹⁶ V.I. Korogodin, et al., "Report of the Interdepartmental Commission for Assessment of the Radiation Situation in the Vicinity of the City of Krasnoyarsk." *Krasnoyarsk DOKLAD*, in Russian, 1990, pp. 1-12, appendices reports construction was halted in 1989 by order of the ministry. Valeriy Lebedev, director of Krasnoyarsk-26 is reported to have said that the Minister of Atomic Power and Industry in 1990 ordered the construction of RT-2 stopped for a five year period due to lack of funding; "Nuclear Storage and Weapon Plutonium Facilities at Krasnoyarsk," 1991 *The British Broadcasting Corporation; Summary of World Broadcasts*, 20 December 1991, Postfactum in English 2147 GMT 9 December 1991.

⁴⁹⁷ Aleksey Tarasov and Dmitriy Khrupov, "Spy Satellites are Made Here: Report from a Closed Military City," *Moscow Izvestiya*, Union Edition, in Russian, 11 January 1992, p. 1,8 (translated into English).

Technical plans for the RT-2 plant include:

- storage of spent fuel rods, dissolution of chopped fuel and clarification of solutions received;
- separation and purification of uranium and plutonium in the first extraction cycle with parallel extraction of neptunium, technetium and zirconium from the starting solution;
- extraction of plutonium and production of oxides of plutonium and uranium for preparation of MOX fuel;
- preparation of MOX fuel rods for VVER-1000 reactors;
- separation of long-lived fission products and trans-plutonium elements and subsequent solidification for long-term geologic storage.

Under the plans finished products would include:

- uranyl-nitrate for subsequent U-235 enrichment for reactor fuel.

In discussing the proposed RT-2 reprocessing plant, L.N. Lazarev of the St. Petersburg Radium Institute promised 99.98 percent recovery of plutonium; 95 percent capture of the volatile fission products Kr-85 and I-129; partitioning (99%) for separate treatment of the long-lived radionuclides, neptunium-237 and technetium-99; zero discharge of contaminated water into the surface environment and deep injection of tritium contaminated water into an aquifer where water has an "age" (before contact with surface water) of 40,000 years.⁴⁹⁸

A key feature of the RT-2 reprocessing plant was the method of handling radioactive waste. According to Lazarev, the final extraction of actinides, neptunium, and transuranic isotopes from the high-level waste of RT-2 would be carried out in the underground chemical separation facility used for weapons plutonium production. Here also, the high-level waste was to be partitioned into its liquid and solid components. The solid waste precipitate would be stored in tanks at the underground facility. According to *Moscow Trud*, the liquid waste was to be injected between layers of clay at a depth of 700 meters.⁴⁹⁹ The waste was to be piped to the injection location, called Site 27, some 16 km from the site of the reprocessing plant on the opposite side of the Yenisey River.⁵⁰⁰ Before construction of Site 27 was

⁴⁹⁸ L.N. Lazarev, "Reprocessing and the Environment in Russia." See also, Frank von Hippel, Thomas B. Cochran, and Christopher E. Paine, "Report on an International Workshop on the Future of Reprocessing, and Arrangements for the Storage and Disposition of Already-Separated Plutonium (Moscow, 14-16 December 1992), and an International Workshop on Nuclear Security Problems (Kiev, 17 December 1992)," 10 January 1993.

⁴⁹⁹ "Secret Site," *Moscow Trud*, 11 July 1989. During a trip to Krasnoyarsk-26 in June 1992, Greenpeace representatives were told that the shafts were 975 m deep and about 15 m in diameter.

⁵⁰⁰ "Checking for Stability," *Sotsialisticheskaya Industriya*, 23 July 1989; and T.N. Zhabina, From the "This is How We Live" Series, subtitled "Closed City," Moscow Russian Television Network, in Russian, 15 October 1992, 1500 GMT. The distance to the injection location has been variously reported as 10, 16 and 20 km.

halted completely in 1989 or 1990, a 2,150 m long tunnel had been dug some 50 meters under the river. Shaped like the mathematical sign for an integral, it was conceived as a two-story tunnel. The lower part was to house a pipeline, and the upper part was to be a corridor for the transportation of service personnel. The tunnel and the decision to inject liquid waste into the ground generated substantial controversy and undoubtedly was partially responsible for the controversy leading to cancellation of construction. Work on the tunnel was also halted. No piping and no pumping stations were built.⁵⁰¹ It has been damaged and water is spraying into the tunnel from the concrete arch.⁵⁰² The tunnel is now serving as an ordinary transport route linking the two sides of the river.⁵⁰³

Waste Management Activities: Little is known about the management of radioactive effluents and wastes at Krasnoyarsk-26. As described in a Russian television report about, "This white field is a snow-under reservoir, a radioactive waste sedimentation tank. Behind it, the Yenisey is winding its way. In order to minimize the risk of the reservoir overflowing, a drain has been installed. Via the pipe water is siphoned off into the Yenisey. However, during major floods, the drain is not sufficient."⁵⁰⁴

Liquid radioactive waste is injected into the ground at the depth of 270 m at the "Severny" (Northern) testing ground, which is to be closed down in 2000, which is also when the last reactor is scheduled to halt operations. As described in the television report, "It is into these reservoirs that highly toxic waste is pumped. ... And here is the water with the high radioactive content [video shows closeup of a leaking pump]. Its progress to the underground lake is strickly monitored [video shows pressure equipment]. Special boreholes determine where on a vertical scale this water intermingles with pure water."⁵⁰⁵

With respect to atmospheric releases of radioactivity from the reactors, Combine officials claim that the gas purification efficiency is 99.9 percent, but

⁵⁰¹ T.N. Zhabina, From the "This is How We Live" Series, subtitled "Closed City," Moscow Russian Television Network, in Russian, 15 October 1992, 1500 GMT.

⁵⁰² Aleksey Tarasov and Dmitriy Khrupov, "Spy Satellites are Made Here: Report from a Closed Military City," *Moscow Izvestiya*, Union Edition, in Russian, 11 January 1992, p. 1,8 (translated into English).

⁵⁰³ T.N. Zhabina, From the "This is How We Live" Series, subtitled "Closed City," Moscow Russian Television Network, in Russian, 15 October 1992, 1500 GMT.

⁵⁰⁴ Moscow Ostankino Television First Channel Network, in Russian, 27 February 1993, 0955 GMT.

⁵⁰⁵ Ibid.

this must apply to iodine and other particulates, and not to noble gases. The average accumulation of Cs-137 in the top 5 cm of soil over a distance of 12 km from the plant chimney-stack is reported to be 38 mCi/km², of which 40 percent (15 mCi/km²) represents discharges from the plant and the remaining 60 percent from nuclear weapons fallout.⁵⁰⁶

Due to the discharge of coolant water from the production reactors (and presumably from laboratory operations and the chemical separation plant within the same underground tunnel complex), radioactivity is discharged into the Yenisey River. In July-August 1990 (and again the following year), prior to the shutdown of the two reactors using once-through cooling, an investigation of the radioactive contamination in the Yenisey showed that:⁵⁰⁷

- The discharge from the Mining and Chemical Combine occurs in the sanitary protection zone 50 to 100 m from the right shore of the Yenisey River, one meter below the surface. The gamma dose in the water along the axis of a radioactive jet at the discharge site was 600 to 3000 μ R/h. In some places on shore at a distance of 5-7 m from the water line the radiation dose exceeds 60 μ R/h (0.5 R/y). By 20 km downstream the dose rate has dropped by a factor of 150 due primarily to dilution.
- The contamination of the river could be traced for a distance of more than 800 km (due primarily to the presence of 27.7 d half-life chromium-51), and the contamination of the floodland for a distance of 1500 km, down the river from the discharge site.

⁵⁰⁶ L.N. Lazarev, "Reprocessing and the Environment in Russia," paper presented at the International Workshop on the Future of Reprocessing, and Arrangements for the Storage and Disposition of Already-Separated Plutonium," Moscow, 14-16 December 1992.

⁵⁰⁷ In August-September, 1990 specialists of the Applied Geophysics Institute of the State Committee for Hydrometeorology and Environmental Monitoring (Roskomgidromet), together with scientists of the Krasnoyarsk Research Centre of the Siberian Branch of the Russia Academy of Sciences, investigated into the current state of the radiation situation of the Yenisey River from Krasnoyarsk to Igarka. Some chapters of the report made by the expedition were published in *Ekologicheskyy Vestnik*, a newspaper of Krasnoyarsk ecologists, No 3, 1991, pp.2-4, and detailed in a 4April 1992 letter from Yu.F. Zubov, chairman of Roskomgidromet, to A.V. Yablokov, Russian Federation advisor on Environmental and Health Protection Policy. A summary of these results were reported by Alexander Bolsunovsky, "Russian Nuclear Weapons Production and Environmental Pollution," paper presented at the Conference on "The Nonproliferation Predicament in the Former Soviet Union," Monterey Institute of International Studies, Monterey, California, 8 April 1992. Bolsunovsky also reported that the results of the investigation carried out by the scientists of the Institute of Applied Geophysics, as well as by the North Yenisey geophysical expedition, and by the Krasnoyarsk complex geophysical expedition in 1991, confirmed the fact the Yenisey has been contaminated by the chemical combine. The results of the Roskomgidromet survey are summarized in a letter from Yu.F. Zubov, Chairman of Roskomgidromet, to Alexei V. Yablokov, Russian Federation Advisor on Policies of Ecology and health Protection, 4 April 1992; reproduced in "Proceedings of the Commission on Studying the Ecological Situation in Chelyabinsk Oblast," (Ordered by President M. Gorbachev, Presidential Decree # RP-1283, 3 January 1991), ca. April, 1992 [translated into English], Vol. I, pp. 29-34 (the page numbers cited here and subsequently are for the English translation).

- The trail of contaminated water to the Kan River valley (25 km below the discharge) passes against the right bank, while the left channel remains relatively clean. The higher rate of contamination along the right side of the river persists for a distance of 250 km (virtually to the settlement of Strelko), and along the right bank for a distance of 50 km from the discharge site. Sodium-24 (half-life = 15 h) is the main contributor to the exposure dose of the river water used for drinking in the segment of the river to Strelko. In the discharge zone concentrations of sodium-24 and manganese-56 (half-life = 2.6 h) exceeded the permissible standard by factors of 10 and 2. The river also contained the following medium- and long-lived radionuclides below permissible limits: phosphorus-32, chromium-51, zinc-65, manganese-54, cobalt-60, europium-152 and -154, and cesium-137.
- The village of Atamanovo (2,200 inhabitants),⁵⁰⁸ the first population center below the point of discharge, is 5 to 6 km downstream on the left bank. It gets its water from artesian wells, rather than the river. The density of bottom deposits contamination along the right bank at Atamanovo was: 35 Ci/km² of chromium-51, 3.3 Ci/km² of cobalt-60, 2.5 Ci/km² of zinc-65, 2.2 Ci/km² of cesium-136. An uniform distribution of cobalt-60 and cesium-137 was observed to the depth of 15 cm.
- Contaminated algae can be a secondary source of radioactive contamination of bottom deposits in the Yenisey River and the river-side. The coefficient of accumulation of long-lived nuclides by the algae was $(1-6) \cdot 10^3$. The body of the fish caught at 700 km from the discharge site downstream contained $(3-9) \cdot 10^{-10}$ Ci/kg of cesium-137 and $(5-6) \cdot 10^{-9}$ Ci/kg of zinc-65. Migrating fish can carry radioactivity for long distances, both downstream and upstream as far as the city of Krasnoyarsk, from the source of contamination.
- Radioactive contamination of the floodland of the Yenisey River is extremely uneven. The maximum soil contamination found was 41 Ci/km² (dose rate = 136 μ R/h) at Atamanovo island 6 km below the discharge. Measured contamination concentrations ranged from 0.03 to 41 Ci/km² at Atamanovo; from 0.74 to 17 Ci/km² at Bolshoy Balchug (300 inhabitants) 16 km downstream, and from 0.07 to 11 Ci/km² at Kononovo 25 km downstream. After that, for a distance of 500 km the contamination density does not depend on the distance from the source, but fluctuates within the range of 3-10 Ci/km², due to hydrological peculiarities of the river. For a distance

⁵⁰⁸ The Norilsk Mining and Metallurgy Combine, a 5,000-bed prisoner camp which was built before 1940, is located below Atamanovo.

from 500 to 1500 km from the source the contamination density of the floodland is up to 0.1 Ci/km² of cesium-137 and cobalt-60. The zone of radioactive contamination of the floodland of the Yenisey River is a narrow, 5-50 m wide, strip of land along the river.

- Of the nuclides contained in the soil the most important in terms of potential health effects are: plutonium-238, -239, -240; cobalt-60; cesium-137, -134; manganese-54; zinc-65; europium-152, -154, -155; cerium-144; and strontium-90.
- At Atamanovo island the soil contamination density reached 47 $\mu\text{Ci}/\text{km}^2$ (0.23 $\mu\text{Ci}/\text{kg}$) of plutonium-239/240 and 23 $\mu\text{Ci}/\text{km}^2$ (0.11 $\mu\text{Ci}/\text{kg}$) of plutonium-238.

Others report that the level of gamma activity in the river exceeds background by a factor of five or six.⁵⁰⁹ More than 400 km down the Yenisey, radiation levels up to 100 $\mu\text{R}/\text{h}$ have been observed (the natural background level is 10 to 15 $\mu\text{R}/\text{h}$).⁵¹⁰ In the region of Lesosibirsk and Yeniseisk, the radiation level exceeds background by a factor of 10 to 14. In these same regions, and lower down the river, crumbly silty radioactive deposits are being discovered in many locations.⁵¹¹

Military Conversion Activities: With the shutdown of the two production reactors in 1992, the combine plans to build a plant for the production of polycrystalline silicon for semiconductor technology, producing 200 tons within two or three years.⁵¹² "We have set up the production of printed circuit boards, transformer units, and scans [razvertki] for the 'Rassvet' monochrome television sets produced in Krasnoyarsk. We have concluded a contract with the Samsung firm..."⁵¹³ The combine is also examining the production of especially pure materials such as gallium arsenide, germanium and tellurium.⁵¹⁴

⁵⁰⁹ V. Yaroslavtsev, "The Yenisey's X-Rays" from "What Troubles our Conscience: A Polar Chernobyl Syndrome," *Vozdushnyy Transport*, 4 October 1990, p. 3. The article stated that the activity levels were established by two research expeditions by specialists from the Krasnoyarsk Scientific Center and the State Committee for the Protection of Nature.

⁵¹⁰ *Ibid.*

⁵¹¹ *Ibid.*

⁵¹² "Russian Plutonium Reactors Closed for Conversion," *Moscow Rissiysskaya Gazeta*, in Russian, (translated in *Joint Publications Research Service*, JPRS-TND-92-026, 31 July 1992, p. 25).

⁵¹³ V. Nelyubin, "Mountains Cause Excess Misfortune from Excess Cleverness," *Moscow Komsomolskaya Pravda*, in Russian, 20 October 1992, p. 2 (translated in *Foreign Broadcast Information Service*, FBIS-USR-92-137, 24 October 1992, p. 25).

⁵¹⁴ Yuriy Khots, "Plutonium-Producing Reactors in Krasnoyarsk to be Shut Down," *Moscow ITAR-Tass World Service*, in Russian, 19 May 1992, 1352 GMT.

Plutonium and Tritium Production Estimates

The sizes and startup dates of some of the Soviet production reactors are unknown; and none of the operating power levels and capacity factors are known. Consequently, there are large uncertainties associated with estimates of the total plutonium-equivalent production⁵¹⁵ based on the reactor operating histories alone. However, plutonium and tritium inventory data from several independent sources are consistent with what we know about the sizes and operating periods of the reactors, and permit us to derive reasonable estimates of the missing parameters. First, the sizes of most of the graphite reactors were estimated by comparing the respective number of channels to the number of channels in the original eight U.S. graphite production reactors at Hanford. As a rough rule of thumb, each channel of an upgraded graphite production reactor can supply about one MW of thermal power. The capacity factors (i.e., the average power level divided by the full power level) were chosen to be reasonably consistent with the capacity factors achieved by the Hanford production reactors in the United States. We assumed the capacity factors of each reactor were 0.4 during the first year of operation, 0.6 during the second year, and 0.8 thereafter.

At Chelyabinsk-65 we know the A-Reactor was upgraded from 100 to 500 MW_e and the IR-Reactor was 65 MW_r. The last three reactors had 2001 channels and are assumed, therefore, to be comparable in size to the C-Reactor at Hanford. We have assumed that the AV-1 and AV-2 Reactors began operating on 1 January 1952 and 15 April 1951, respectively. The AV-3 Reactor startup was on 15 September 1952. We assume each of these three reactors began operation at a power level of 650 MW_e and each was upgraded over a six year period to 2000 MW_r.⁵¹⁶ Under these assumptions, as seen in Table 13, the total production by the five graphite production reactors at Chelyabinsk-65 between 1948 and 1990 inclusive is estimated to be approximately 58 MT of weapon-grade plutonium-equivalent (4.6 percent Pu-240).

The first of the five plutonium production reactors at Tomsk-7 operated from 20 November 1955 to 21 August 1990; the second reactor operated from about September 1958 to 31 December 1990; and the third reactor operated from 14 July 1961 to 14 August 1992. The startup dates of the remaining two dual-purpose reactors, which are still operating, are

⁵¹⁵ Plutonium-equivalent production is a measure of the total production of plutonium and other isotopes (usually tritium), where the unit of measure is the amount of plutonium alone that could have been produced. The production of one kg of tritium is equivalent to the production of 72 kg of weapon-grade plutonium.

⁵¹⁶ We use the Hanford C-Reactor as a model. C-Reactor had an original design power of 650 MW_e and was upgraded to 1740 MW_e after 7.5 years, and to 2310 MW_e over the next three years; see Thomas B. Cochran, et al., *Nuclear Weapons Databook*, Vol. II, p. 61.

presumed to be spaced a year or two apart. We assume the each of the reactors were upgraded from 650 MW_e to about 2000 MW_e (about the size of the C-Reactor at Hanford, which has about the same number of channels, after it was upgraded) over four years. Under these assumptions Tomsk-7 would have produced some 74 MT of plutonium-equivalent (See Table 15).

The first reactor at Krasnoyarsk-26 operated from 1958 to 30 June 1992; the second reactor operated from 1961 until 29 September 1992; and the third started up in 1964 and is still operating. The first two reactors are assumed to be comparable in size to the AV-1, AV-2, and AV-3 reactors at Chelyabinsk-65. We assume each operated at about 2000 MW_e. The third reactor, while larger than the first two, is dual-purpose, and therefore we assume it also operated at about 2000 MW_e. Together these three reactors are estimated to have produced about 45 MT of plutonium-equivalent (See Table 16).

The combined production at Chelyabinsk-65, Tomsk-7, and Krasnoyarsk-26 is estimated to be about 177 MT plutonium-equivalent.

We have virtually no knowledge regarding tritium production or inventories in the former Soviet Union. We assume the two water-moderated reactors--one initially a heavy water and the other a light water type--at Chelyabinsk-65 were dedicated primarily to tritium production. The heavy water reactor came on line in 1951. Assuming that it was upgraded from 250 to 1000 MW_e, and that the light water reactor came on line about 1970 at 1000 MW_e, we estimate that these two reactors could have produced 15 MT plutonium-equivalent (Table 14), sufficient to build up an inventory of 90 kg of tritium by the mid-1980s (Table 17).

An independent upper-bound estimate of plutonium-equivalent production can be made from the contribution to the buildup of krypton-85 (Kr-85) in the earth's atmosphere. Kr-85 is a gaseous fission product produced when U-235 or Pu-239 is fissioned. It is ordinarily released to the atmosphere when spent nuclear fuel is chemically processed. Chemically inert and with a radioactive half-life of 10.76 years, Kr-85 accumulates in the atmosphere. The Soviet contribution to the atmosphere's Kr-85 is estimated by subtracting the contributions from known sources outside the Soviet Union from the estimated total releases. The U.S. intelligence community monitors the atmospheric concentrations of Kr-85 and uses these data to estimate the cumulative plutonium-equivalent production over time and from that, the annual production rate. Using a similar approach, and the data on atmospheric concentrations of Kr-85 published in the open literature, von Hippel, et al. have estimated that the Soviets had released some 44-66 MCi of Kr-85 as of

the end of 1983.⁵¹⁷ By our estimates some 10 MCi would have come from processing VVER spent fuel at Chelyabinsk-65, leaving 34-56 MCi Kr-85 from chemical separation of production reactor fuel—producing 75-122 MT of weapon-grade plutonium-equivalent. In Tables 13-16 we estimate 140 MT of plutonium-equivalent production through 1983, a value 15 percent higher than the estimate by von Hippel, et al. Since we also estimate that 42 MT of weapon-grade plutonium-equivalent was produced during the period 1984-1992, von Hippel, et al.'s upper limit estimate should now be increased to about 164 MT.

Russia is currently producing 1.5 MT of weapon-grade plutonium per year and separating an additional 1.0 MT of reactor-grade plutonium per year (see Table 4), and production and separation is planned to continue for several more years.

Nuclear Fuel Cycle Activities in Russia
by Oleg Bukharin

The fuel cycle of a nuclear reactor can be divided into three main stages. The first stage, the so-called front-end, involves mining and milling of uranium ore, conversion of uranium into U_3O_8 (called yellow cake), conversion of U_3O_8 into a chemical and physical form suitable as a reactor fuel (e.g., uranium metal or uranium oxide (UO_2), fabrication of the reactor fuel, and its delivery to the reactor. If the reactor operates with uranium enriched in the isotope U-235, the U_3O_8 is first converted into UF_6 and enriched at an enrichment plant, before the enriched product is converted into appropriate chemical and physical form for the reactor fuel. The second stage of the fuel cycle is the use of the fuel—its irradiation—in the reactor. And the third stage, the so-called back-end of the fuel cycle, involves management and disposition of irradiated reactor fuel. In Russia, the fuel cycles of the production reactors are thoroughly integrated with fuel cycles of the research, naval and civil power reactors. Moreover, the front-end fuel cycle activities were integrated with the production of enriched uranium for weapons. This section addresses various aspects of the fuel cycle infrastructure—developed over the period of more than 40 years—focusing on production capabilities and potential developments of the facilities associated with the front-end, research, naval and civil power reactors, and civil use and disposition of plutonium at the back-end of the fuel cycle.

⁵¹⁷ Frank von Hippel, David H. Albright and Barbara G. Levi, "Quantities of Fissile Materials in the U.S. and Soviet Nuclear Weapons Arsenals," Princeton University, 27 March 1986. See also, Frank von Hippel and Barbara Levi, "Controlling Nuclear Weapons at the Source: Verification of a Cutoff in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons," Hearing Before the House Committee on Foreign Affairs, 20 June 1989, pp. 302-303.

Front-End of the Fuel Cycle

Uranium Resources: Industrial-scale exploration of uranium started in the USSR in the late 1940s as a part of the nuclear weapons program. The Ministry of Geology (P.Y. Antropov, also Deputy-Chairman of the PGU) was assigned responsibility for geological survey and mining.⁵¹⁸ The first effort led to discoveries of the Krivorozh, Stavropol and Karamazar uranium districts.⁵¹⁹ In the 1950s, application of new geological survey methods, including airborne radiometry, resulted in discovery of the Zacaspiysk, Pribalkhash, Kyzylkum and Kokchetavsk districts, which became the basis for the uranium-production industry in the USSR. In the 1960s, systematic theoretical research in the area of geology of uranium deposits and ore formation models permitted discovery of deposits which are inaccessible for study by airborne radiometry. In particular, the Strelitsa district and new deposits in the Krivorozh and Kyzylkum districts were found. The Strelitsa and Kyzylkum district became the most important uranium mining areas in Russia and the Soviet Union respectively. Discoveries of sandstone type deposits in the Zauralsk and Vitimsk districts and black-shale deposits in the Kyzylkum and Onezhsk districts in the 1970s and 1980s completed the Soviet period of exploration of uranium resources. Future significant discoveries are expected in the Far Eastern district, the speculative resources of each are estimated to be 300,000 MTU.

Known uranium resources are located in nine districts with developed uranium deposits called "uranium ore areas," and five undeveloped districts called "uranium bearing areas" (Table 21). As of 1991, the known uranium resources in the categories Reasonably Assured Resources (RAR) and Estimated Assured Resources, Category I (EAR-1), amount to 685,600 MTU, some 26 percent of the world known resources in these categories.⁵²⁰ Of them, 465,000 MTU are recoverable at costs up to \$80/kgU.⁵²¹

⁵¹⁸ N. Sinev, "Enriched Uranium for Nuclear Weapons and Power," CNIIAtominform, 1991.

⁵¹⁹ "Uranium Raw Material Base," *Science and Technology/Central Eurasia Engineering and Equipment*, JPRS-UEQ-93-002, 5 February 1993.

⁵²⁰ Additional 501,200 MTU and 500,000 MTU belongs to the categories EAR-II and SR (speculative resources), respectively. Reasonably assured resources (RAR) are defined as resources that occur in known deposits and recoverable within the given production cost range (up to \$130/kgU). Estimated assured resources, category I (EAR-I) correspond to resources that are expected to occur, the expectations are based on direct geological evidence or geological continuity; the data, however, are not sufficient to classify the resources as RAR. EAR-II corresponds to resources that are less certain than EAR-I; speculative resources (SR) are thought to exist on the basis of geological exploration or indirect evidences. ("Uranium: Resources, Production and Demand," OECD, 1986.)

⁵²¹ "Uranium In The New World Market: Supply And Demand 1990," Uranium Institute, 1991. B.V. Nikipelov, "Informatsionnyy Byulleten, in Russian, 1991, pp.14-17, says total uranium reserves amount to 2 million tons, broken down as follows: 735,000 tons at less than \$60/kgU; 465,000 tons from \$60 to \$90/kgU; and 800,000 tons at more than \$90/kgU.

Uranium Production: Exploration of the resources has been paralleled by advances in technologies of uranium mining and extraction. By the early 1960s, the industry gained substantial practical experience in application of the in-situ leaching mining techniques (ISL) allowing more effective and economic development of sandstone and fish-bone type deposits. Uranium is recovered by leaching with sulfuric acid or alkali carbonate solution and subsequent concentration by selective precipitation, solvent extraction, or ion exchange. The principal technology for production of uranium product from conventionally-mined ore is based on the "sorption non-filter continuous process" developed in the Institute of Chemical Technologies (Moscow).⁵²² The process is based on grinding uranium ore into fine powder and intensive pneumatic mixing of powder's slurry with ion-exchange resins. Subsequently, the ion-exchange resins are washed with neutral or alkali solutions to produce uranium-bearing solution called the eluate. Uranium is precipitated from the eluate by ammonium, alkali or magnesium oxide. Precipitated uranium is processed through the purification process, called "affinazh." The process is based on solvent extraction of uranium from the solution by TBP and designed to remove neutron absorbing hafnium, boron, and rare-earth metals. Purified uranium is subsequently calcined to produce uranium concentrate (yellowcake) U₃O₈. The principal uranium production centers are presented in Table 22.

The Soviet Union began selling uranium enrichment services on the world market in 1973, and natural uranium in 1973. The break-up of the Soviet Union resulted in major restructuring of the tightly integrated Soviet uranium-production industry. Since 1991, the republics have been developing independent policies with regard to production and marketing of uranium. Kazakhstan has terminated shipments of uranium ore produced in the Pribalkhash district to Tadzhikistan and scaled-down the ore supply to Kyrgyzstan.⁵²³ As a result, production of uranium was canceled in Tajikistan, and significantly reduced in Kyrgyzstan. The milling facilities in these countries were converted to produce precious metals. The Pribalkhash ore is sent to Stepnogorsk milling facilities to compensate for mothballing 6 out of 8 mines of the Kokchetavsk district.⁵²⁴ Uzbekistan is also reducing uranium mining by phasing-out some of its conventional (both underground and open-pit) mining operations.⁵²⁵ Reduction in uranium production in the Central Asian republics is caused by disruption of inter-republican relations, social and

⁵²² N.M. Sinev and B.B. Baturov, *Economics of Atomic Energy: Basics of Technology and Economics of Nuclear Fuel*, M:Atomizdat, 1980.

⁵²³ Interview of O. Bukharin with Vice-President of the Kazakh State Atomic Power Engineering and Industry Corporation (Katep), 6 May 1993.

⁵²⁴ The closure of Stepnogorsk mines was reported by *Moscow News*, 18 April 1993.

⁵²⁵ D. Garrow (Nuexco), "Uranium Supply Potential. Central Asian Republics." The paper is presented at the International Uranium Seminar 92, USCEA, 20-23 September 1992.

economic crisis, depression of the world uranium market, and protective measures by the U.S. Department of Commerce and Euratom.⁵²⁶ There is also a concern about potential disruption of the market due to release of uranium from dismantled weapons and national strategic stocks. Estimated uranium inventories in the former Soviet countries amount to 150,000 MTU.⁵²⁷ In addition, equivalent of 131,300 MTU will become available as a result of the U.S.-Russia HEU deal, according to which the United States will purchase 500 MT Russian HEU recovered from nuclear weapons for its subsequent conversion into low-enriched uranium for nuclear power applications.⁵²⁸ Lack of infrastructure to transport uranium and problems with maintaining uranium mining and milling facilities create additional obstacles for uranium exports from Central Asia. Kazakhstan has probably adjusted to new conditions better than other Asian republics. The republic has substantial machine-building and chemical industries capable of supporting its uranium production industry. Some chemicals and ion-exchange resins are imported from Russia and Ukraine respectively. For its uranium exports Kazakhstan uses the transportation system of Russia: uranium is shipped by rail to St.Petersburg and from there by sea to customers in North America and Europe.⁵²⁹

Ukraine, with its high domestic requirements, has intensified production of uranium by re-opening previously closed mines and by mining higher-cost uranium ores. Starting 1993, Ukraine sends to Russia 1000 MTU a year. The material is enriched and fabricated into fuel for Ukrainian power reactors. The deficit of uranium (about 700 MT) is covered by Russia.⁵³⁰

⁵²⁶ Natural uranium imports from the former Soviet Union to the United States increased from less than 1 million lb in 1988 to nearly 7 million lb in 1991. U.S. producers filed anti-dumping petitions claiming that the sudden increase in imports caused them material injury. The "uranium dumping investigation," brought in November 1991 against 6 uranium-producing former Soviet republics, was consummated in October 1992 by signing the suspension agreements between the U.S. Department of Commerce and the CIS republics. The agreements are based on price-based quotas. At the price level of \$13-14 per lb U3O8, the individual quotas for uranium-mining republics are as follows (in million lb U3O8 and MTU): 0.5 (230) for Russia, 0.4 (180) for Ukraine, 1.0 (460) for Kazakhstan, and 1.0 (460) for Uzbekistan. The agreement provides increase in the quotas with increase in uranium prices. (*Nuclear Fuel*, 21 October 1992). Recently, Ukraine has indicated that it may terminate the agreement. The Euratom Supply Agency is in favor of more flexible limitation of CIS exports and reviews contracts on a case-by-case basis (with the assumption that a single producer's share of the West European supply should not exceed 25 percent).

⁵²⁷ "Nuclear Fuel Supply & Demand in Western Europe 1991-2004. Joint Open/Unipede 1991 Survey," *Nuclear Europe Worldscan*, 1-2 1991 pp. 33-39. Some republics agreed not to sell their national stocks.

⁵²⁸ The agreement was signed on 18 February 1993. According to the agreement, at least 10 MT HEU will be blended down each year for the first five years; at least 30 MT HEU per year will be converted into LEU during the next 15 years.

⁵²⁹ Interview with Vice-President of the Katep, 6 May 1993.

⁵³⁰ The Program of Development of Nuclear Power in the Russian Federation for the Period until 2010. Minatom RF.

The domestic Russian uranium requirements for the program of nuclear power can be estimated to be slightly above 4000 MTU/y⁵³¹ (Table 23). In addition, Russia fabricates fuel for Lithuania and Kazakhstan, and, in part, covers uranium requirements of Ukraine and Eastern Europe (Russia provides 300 MTU/y in addition to 1300/y MTU coming from Eastern Europe⁵³²). Significant amounts of uranium are exported abroad. Annual exports involve 2200 MT of natural uranium, 1000 MTU recovered from uranium enrichment tails, and additional amounts of enriched uranium product exported through spot-market operations. The current natural uranium production capacity is capable of supporting uranium exports at the level of 3500 MTU annum. According to Russian officials it can be easily expanded to support export potential of 5000 MTU/y.⁵³³

The domestic and export uranium requirements are met in Russia by procuring uranium from several sources. About 4000 MTU/y is produced by Priargunsky uranium production complex from ores mined from underground and open-pit mines of the Strelitsa district. In addition to mining of natural uranium, Russia produces uranium by reprocessing spent fuel of power reactors and by enriching tails of enrichment plants. Uranium, recovered from spent fuel of VVER-440 and naval propulsion reactors, is fabricated into fuel of RBMK reactors. Recovery of 120 MT of 2.4%-enriched uranium⁵³⁴ at the RT-1 reprocessing plant at Chelyabinsk (the amount of fuel processed in 1992) is equivalent to slightly more than 600 MT natural uranium. The industry plans to cover about 50 percent of RBMK fuel requirements using recovered uranium during the period until 1996, and 100 percent after 1996. Similarly, uranium recycled from fuel of plutonium production reactors is fabricated into fuel of these reactors. The plan calls for closing uranium fuel cycle of military reactors starting in 1994. Enrichment of uranium tails accumulated at enrichment facilities provides another source of uranium. In the process of enrichment, the U-235 content in the tails is increased from 0.36 percent to 0.7 percent, the level of natural uranium.⁵³⁵ The rest of requirements--an equivalent of about 1000 MTU--is covered from the national stocks.

⁵³¹ Natural uranium equivalent, assuming the tails assay to be 0.3 percent. The estimate for nuclear power uranium requirements does not include uranium for three plutonium-production reactors.

⁵³² The figures for uranium shipments from Ukraine and Eastern Europe are actual amounts of uranium rather than natural uranium equivalent requirements at the tails assay of 0.3 percent.

⁵³³ E. Mikerin, "The Uranium Supply Picture through 2010. Russia," International Uranium Seminar 92, USCEA, 20-23 September 1992.

⁵³⁴ The enrichment level of uranium in spent fuel of VVER-440 reactors is 0.8-1.0 percent. RT-1's uranium is 2.4-2.6%-enriched due to presence of HEU fuel of naval propulsion and research reactors, which is reprocessed together with VVER-440 fuel.

⁵³⁵ The Program Of Development Of Nuclear Power.

Uranium Conversion: Except for the graphite-moderated plutonium production reactors, essentially all reactors in Russia use enriched uranium fuel. Before uranium is enriched it is converted into UF_6 , a uniquely suitable feed for a gaseous diffusion and gas centrifuge uranium enrichment facilities. At atmospheric pressure UF_6 sublimates from solid into gas at $57^\circ C$; at elevated pressures (1.5 atmospheres) the substance can be liquefied at temperatures higher than $65^\circ C$. Of special importance for isotopic separation is that UF_6 is a stoichiometric compound (unlike uranium oxides) and that fluorine does not have isotopes others than F-19. UF_6 is a conventional form of uranium in which it is traded on the world's nuclear fuel market or fed into facilities fabricating fuel for power reactors.

In the Soviet Union, development of industrial fluorination technology began in 1947.⁵³⁶ Initially, UF_6 was produced in a relatively ineffective process of direct fluorination of uranium oxide. In the 1950s the process was replaced by the process of fluorination of uranium tetrafluoride (UF_4). The technology was based on dissolution of U_3O_8 in sulfuric acid, electrolytic regeneration of uranyl sulfate, and, in the final step, hydrofluorination. Currently, Russia uses the technology of fluorination in a single-stage flame reactor (fluorination in dust infusions). Introduced into commercial use in 1965, it made possible fluorination of both uranium oxides and tetrafluoride. Uranium conversion occurs in a continuous process and involves the following steps:

- production of elemental fluorine gas (F_2);
- fluorination of powdered uranium compounds in a fluorine flame;
- filtration of ashes and other solid impurities;
- sublimation of UF_6 in cold traps; and
- recycle of un-reacted fluorine and intermediate uranium-bearing compounds.

Two operating uranium conversion plants are co-located with uranium enrichment facilities at Verkh-Neyvinsk and Angarsk in Russia. Assuming that the total capacity of these plants matches the total capacity of the enrichment facilities in Russia and that the average level of enrichment of uranium is 2.81 percent,⁵³⁷ the conversion capacity can be estimated to be about 26,000 MTU/y.⁵³⁸

Uranium Enrichment.

⁵³⁶ *Nuexco Monthly Report*, No. 272.

⁵³⁷ The average enrichment in the USSR in 1990. ("*Uranium In The New World Market: Supply And Demand 1990*," Uranium institute, 1991, p. 210.)

⁵³⁸ Production of 1 kg 2.81% uranium at 0.3% tail assay requires 3.12 kg SWU. Therefore, a total capacity of 13 million SWU per year corresponds to a capacity to produce 4167 MT of 2.81% uranium per year, requiring about 26,000 MT natural uranium.

History and Technology: A coordinated effort on uranium enrichment was initiated in the fall of 1945.⁵³⁹ It included research on gaseous diffusion (I.Kikoin), electromagnetic (L.Artsimovich), and counter-current thermo-diffusion methods (A.Alexandrov and I.Kikoin) of isotope separation. These activities started at the Laboratory 2 of the Academy of Science and were coordinated by the Section 2 (uranium separation, molecular methods) of PGU's Scientific-Coordination Council (Section 2 of the NTS PGU, V.Malyshev). The section was assigned responsibility for technical decisions and recommendations on uranium enrichment. Early in 1946, under the influence of the "Smyth Report" the NTS PGU decided to concentrate research on the gaseous diffusion technology.⁵⁴⁰

To intensify R&D work and to accelerate commercialization of designed equipment, the Government created Special Design Bureaus at the Leningrad Kirov Metallurgical and Machine-Building Plant and Gorki Machine-Building Plant. The Design Bureaus and the plants were intended to compete in designing and manufacturing of gas-diffusion machines and other equipment. The research was also supported by the group of German scientists and technicians working out of the Sukhumi Physical-Technical Institute as well as by research institutes of the Academy of Sciences and various industries.⁵⁴¹

In late 1945 it was decided to start construction of the first gaseous diffusion enrichment plant designated D-1. An unfinished aircraft-production facility at Verkh-Neyvinsk, 50 km northwest of Yakaterinburg (formerly Sverdlovsk) in the Urals, was chosen as a construction site. The plant was

⁵³⁹ The discussion on the development of enrichment technologies in 1945-52 is based on N.Sinev, "Enriched Uranium for Nuclear Weapons and Power," CNIIAtominform, 1991.

⁵⁴⁰ The Smyth Report, published 12 August 1945, confirmed that gaseous diffusion was the preferred technology used by the United States.

⁵⁴¹ Upon entering Berlin in April 1945, the Soviets immediately began to dismantle and ship German industrial equipment to the Soviet Union. They also began to conscript leading German scientists for nuclear research; CIA, *The Problem of Uranium Isotope Separation by Means of Ultracentrifuge*, Report No. DB-0-3-633-414, October 8, 1957, pp. 6. German nuclear research groups were established in the Soviet Union around mid-1946, in parallel to existing Soviet research groups, to pursue uranium isotope separation. Competing German and Soviet research teams investigated each of the three enrichment technologies pursued by the United States during the Manhattan Project, namely, gaseous diffusion, electromagnetic separation, and gas centrifuge; *Ibid.*, p. 8. Two groups of German scientists were located at Sinop and Agudzeri, respectively. These research centers were near Sukhumi on the Caucasian coast of the Black Sea, one about 5 km southeast of Sukhumi. A German research group also worked on the Troepfchen Method, a countercurrent diffusion technique whereby a thin vertical liquid stream enters a tube in which it breaks up into drops. These drops evaporate, and the heavy and light fractions of the fluid evaporate at different rates. The model gases that were used for this method were either chlorine or bromine; *Ibid.*, p. 15. The competition between the Soviet and German research groups was one-sided. While the Soviets received the technical reports of their German counterparts, the Germans, with rare exceptions, received no reports from their Soviet counterparts, and no information as to their actual progress and accomplishments; *Ibid.*, pp. 8, 9, 12.

brought on line in the early 1949. However, technical problems, preventing it from producing weapons-grade material, continued during most of the year. The principal problems were related to poor design, unreliability of equipment, and "corrosion" of UF_6 . The latter, which referred to decomposition of UF_6 into uranium tetrafluoride (UF_4 , called "green powder"),⁵⁴² led to unacceptable losses of UF_6 . As a result, the plant was capable of producing uranium enriched to only 75% U-235, when using an ineffective double-cycle arrangement (double use of the end enrichment stages). The 75%-enriched product was subsequently enriched by electromagnetic method to the weapon-grade level.

The problems were overcome in 1950 and the D-1 plant started production of tens of kilograms of 90%-enriched uranium per year on its 7040 machines organized in 56 cascades. The plant's enrichment capacity was 7500 kilograms separative work units per year (kg SWU/y, often shortened to SWU/y). In 1951 the plant was augmented by the D-3 plant with 6-fold increase in production of 90 percent enriched uranium production. The D-4 plant and the first stage of the D-5 plant were brought into operation in 1953. By that time, weapons-grade uranium was produced by about 15,000 machines of the Ural diffusion plant working around the clock.

"Diffusion machines were actively developed during the first decade [from 1949]. During that period, production techniques were mastered and 16 different models were manufactured. The separation capacity of the last model was 6500 times bigger than the separation capacity of the first model. The electricity consumption rate was reduced from 35,000 to 3500 kWh per SWU. The specific metal requirement decreased to 2 percent of the first model's. The newer diffusion machine models were much larger than the former ones. The flow rate of uranium hexafluoride through the diffusion barriers increased considerably. The production costs of compressors and refrigerators improved, and diffusion characteristics of porous filters improved. However, all gaseous diffusion plants in Russia were phased out due to their high electricity consumption. Gaseous diffusion technology used to produce enriched UF_6 has been completely replaced with gas centrifuge technology."⁵⁴³

In the 1940s, laboratory research on gas centrifuge separation was conducted by the German group led by Dr. Max Steenbeck, a former Siemens Company official in Germany. The group, based at the Sukhumi

⁵⁴² Decomposition of uranium hexafluoride was caused by the presence of moisture in the air, insufficient effectiveness of isolation filters designed to maintain high vacuum, corrosiveness of equipment, and increased temperatures.

⁵⁴³ E. Mikerin, V. Bazhenov, and G. Solovjov, "Directions in the Development of Uranium Enrichment Technology," 1993. According to *Nuexco Monthly Report*, No. 272, 1991, "enrichment provided by gaseous diffusion accounts for less than five percent of their total output."

Physical-Technical Institute at Sinop (a suburb of Sukhumi on the Black Sea coast), was working on both subcritical- and ultracentrifuges designs. This research effort was shifted from Sinop to the Kirov plant in Leningrad by the fall of 1951. By the governmental decree of 1952, the R&D responsibilities for development of industrial application of gas centrifuge technology were assigned to the Leningrad Design Bureau led by N. Sinev. The Bureau was reinforced by the German group transferred to Leningrad in December 1952. Originally, the research was centered around the design offered by Max Steenbek's group. However, in 1953 the work on Steenbeck's design was canceled and the Bureau started to work on indigenous centrifuge designs.⁵⁴⁴ Starting 1954, the research were conducted in cooperation with the Kurchatov Institute of Atomic Energy in Moscow.

Commercialization of the centrifuge technology started with a pilot-scale facility commissioned at Verkh-Neyvinsk on 4 October 1957, some 4-5 years after the first pilot-production centrifuges were built in 1952. The pilot-scale facility contained 2500 centrifuges and was used to validate designs of centrifuges and support equipment.⁵⁴⁵ After a year of successful operation of the pilot plant, a positive evaluation of the process led to the first industrial installation and operation of centrifuges in an existing gaseous diffusion plant 1959. The first industrial plant [perhaps Krasnoyarsk-45] equipped with subcritical gas centrifuges was built and placed into operation in three phases extending from 1962 to 1964.⁵⁴⁶ The centrifuge technology became the backbone of the Soviet enrichment program in the 1970s.⁵⁴⁷

Over the course of 35 years the industry has designed, built and operated five generations (eight models) of centrifuges; and centrifuges of the sixth generation are currently (1993) being built and installed.⁵⁴⁸ All Russian centrifuges are based on subcritical designs.⁵⁴⁹ Centrifuge rotors are made

⁵⁴⁴ Russian designs retained some of ideas developed by the German group. Specifically, N. Sinev, Chief Designer of the Leningrad Design Bureau, mentions the centrifuge's needle bearing and an oil dampener; N. Sinev, *Enriched Uranium for Nuclear Weapons and Power*. By the end of 1953, the Germans were transferred to the research institute of the Ukrainian Academy of Sciences in Kiev to work on unclassified projects. They were repatriated back to Germany in 1956.

⁵⁴⁵ Nuexco, "Conversion and Enrichment in the Soviet Union," *Nuexco Monthly Report*, No. 272, 1991.

⁵⁴⁶ E. Mikerin, V. Bazhenov, and G. Solovjov, "Directions in the Development of Uranium Enrichment Technology Technology," 1993.

⁵⁴⁷ See, *Nuexco Monthly Report*, No. 272, 1991.

⁵⁴⁸ E. Mikerin, V. Bazhenov, and G. Solovjov, "Directions in the Development of Uranium Enrichment Technology Technology," 1993.

⁵⁴⁹ *Ibid.* Starting in 1957, development of every generation of subcritical centrifuges was accompanied by development of their supercritical analog. However, because of increased failure rate, the work on supercritical models were limited to the production of several hundred experimental machines, which were never used in industrial application.

of aluminum reinforced with rings of composite materials. Typically, they operate at 15,000 rpm. The fifth-generation machine has a throughput about 40 percent higher than the fourth generation machines.⁵⁵⁰ The separation capacity of the latest centrifuge model is about ten times higher than the first model.⁵⁵¹

The centrifuges currently in operation in Russia use three to five percent of the electricity required by gaseous diffusion.⁵⁵² Specific energy consumption has dropped more than three-fold from 180 to 50 kWh per SWU; with fourth generation machines operating at about 120 kWh per SWU, and fifth generation machines at 80 kWh per SWU.⁵⁵³ (Sverdlovsk-44, the Ural Electrochemical Combine, employs only fourth and fifth generation centrifuge machines.) The latest centrifuge model, currently being installed in some plants, requires about 50 kWh per SWU.⁵⁵⁴ The Russian gas centrifuge machines are designed to be in continuous operation for 15 years with a failure rate of tenths of percent per year.⁵⁵⁵ Compact unit designs allow easy replacement of failed machines. Production flexibility of the Russian enrichment facilities is achieved by low working inventories of UF₆ in the centrifuges, allowing easy reconfiguration of the cascade for a different product or tails assay.

Several alternatives to the gaseous diffusion and centrifuge methods of uranium enrichment have received attention in Russia, including experimentation with photochemical technology using lasers;⁵⁵⁶ but these have not advanced beyond paper studies. According to the Russian enrichers, accumulated experience in R&D and commercial application of the gas centrifuge technologies in Russia, as well as its potential advances during the next 20-30 years make the technology to remain competitive well into the future.

Enrichment Plant Sites: There are four Russian uranium enrichment plant sites: the Ural Electrochemistry Combine, also called Sverdlovsk-44, near Verkh-Neyvinsk (formerly Kefirstadt), which in turn is near Yekaterinberg (formerly Sverdlovsk); the Siberian Chemical Combine, also called Tomsk-7--the enrichment plant is collocated with the production reactors--just outside

⁵⁵⁰ Ibid.

⁵⁵¹ Ibid.

⁵⁵² Ibid.

⁵⁵³ Ibid.

⁵⁵⁴ Ibid.

⁵⁵⁵ Ibid. In earlier designs, centrifuge's thrust bearings was expected to operate without replacement for three years; in modern designs bearings last for 20 years with the failure rate below 0.2 percent.

⁵⁵⁶ CIA, *USSR Energy Atlas*, January 1985, p. 43.

of Tomsk; the Electrochemistry Combine, also called Krasnoyarsk-45, on the Kan River, 90 km east of Krasnoyarsk and 75 km west of Kansk in Siberia; and the Electrolyzing Chemical Combine at Angarsk, 30 km northwest of Irkutsk, near Lake Baikal.⁵⁵⁷ Each of these sites is near large sources of electricity, which would be needed to operate the gaseous diffusion plants that were previously used at these sites.⁵⁵⁸ There are said to be 10 separate gas centrifuge plants (processing lines or cascades), replacing five gaseous diffusion plants, at these four sites.⁵⁵⁹ Sverdlovsk-44 and Angarsk are the only sites capable of converting U_3O_8 (yellowcake) to UF_6 , the enrichment plant feed material. Krasnoyarsk-45 began operations in 1964. Angarsk was the last of the enrichment sites to be built.

Enrichment Production: As noted above, the Soviets relied on gaseous diffusion technology from 1949 to 1959, shifting to the more efficient gas centrifuge technology during the period 1959 to 1992.⁵⁶⁰ Currently the total enrichment capacity of Russia is estimated to be 13 million SWU/y--now composed entirely of gas centrifuge technology--at the four plant sites.⁵⁶¹ In part, this capacity is used to support fuel requirements for Soviet-built power reactors in Russia and other countries (see Table 23). About 1.29 million SWU/y are used to enrich 0.36% tailings to the level of natural uranium.⁵⁶²

⁵⁵⁷ These sites are identified in Table 1. Verkh-Neyvinsk is at 57° 15'N/59° 48'E; Tomsk-7 is at 56° 37'N/84° 47'E; the Electrochemistry Plant at Krasnoyarsk-45 is at 56° 08'N/94° 29'E; and the city of Angarsk is at 52° 31'N/103° 55'E. Krasnoyarsk-45 is 90 km east of the city of Krasnoyarsk (at 56° 01'N/92° 50'E) and 75 km west of Kansk (at 56° 12'N/95° 43'E).

⁵⁵⁸ CIA, *USSR Energy Atlas*, January 1985, pp. 56-57.

⁵⁵⁹ Christopher Paine, "Military Reactors Go on Show to American Visitors." *New Scientist*, 22 July 1989, p. 22 [condensed from "Soviets Reveal Nuclear Production Complex to visiting Americans," (unpublished)].

⁵⁶⁰ See also, B. A. Semenov, "Nuclear Power in the Soviet Union," IAEA Bulletin, 25, June 1983, p. 55; House Committee on Energy and Commerce, Uranium Enrichment Policy, 98 Cong. 1st sess., 21 October 1983, p. 120. The Soviets assisted China in the construction of a gaseous diffusion plant in the mid-1950s. The Soviets suspended atomic aid and stopped work on the plant sometime between the summer of 1958 and August 1959; Gloria Duffy, "Soviet Nuclear Energy: Domestic and International Policies," RAND Corporation, R-2362-DOE, December 1979, p. 3.

⁵⁶¹ Viktor Mikhailov, in remarks at a meeting in Washington, D.C. hosted by the Committee on International Security and Arms Control of the National Academy of Sciences, 17 February 1993, gave a figure of 20 million SWU/y, but this is higher than other estimates.

⁵⁶² According to Russian sources, if the centrifuge cascades are forced to shut down, there are excessive centrifuge breakdowns when the cascade is placed back into operation. By using enrichment tails, rather than using natural uranium, as the cascade feed material, more separative work is required to achieve the same amount of product. By mining the tails which are free, the enrichment enterprise is able to operate at a higher capacity, preserving equipment and jobs in periods of reduced product demand. At the new tail assay of 0.15% (the figure given at the Yu. Chernilin, "Comparison of Economics of Once-Through and Closed Nuclear Fuel Cycles in Russia," International workshop on Reprocessing of Nuclear Fuel, Storage and Disposition of Civilian and Military Plutonium, Moscow, 14-16 December 1992.) 1.29 million SWU correspond to production of about 1640 MT natural uranium.

Additional 1.3-2 million SWU per year, which corresponds to about 6 percent of the world SWU market, are exported as a part of long-term contracts and spot-market operations.⁵⁶³ According to the estimate of the level of SWU consumption, the plants are operating at about one-half of their capacity. E. Mikerin has stated that Russia can increase its exports capabilities to up to 10 million SWU/y.⁵⁶⁴

The four enrichment plant sites used to be operated as an integrated complex to provide the best use of the facilities. The Ural Electrochemistry Combine (Sverdlovsk-44) at Verkh-Neyvinsk served as the top stages to provide high enriched product for weapons. Sverdlovsk-44 has three centrifuge process lines with a total capacity 2-3 million SWU/y.⁵⁶⁵ Today the four sites operate independently, all producing low enriched product.

A part of the enrichment capacities is used to re-enrich uranium recovered from irradiated fuel and to separate non-uranium isotopes. The enrichment plant in Tomsk is re-enriching uranium recovered from French spent fuel. The centrifuge cascades in Tomsk have already been contaminated with reactor-produced uranium-232 and uranium-236 (and thallium-208, a daughter product of the radioactive decay of U-232)⁵⁶⁶ when recycled uranium was used as enrichment plant feed stock.⁵⁶⁷

"Centrifuge technology is also successfully used in Russia for isotopic separation of other chemical elements. Industrial gas centrifuge units satisfy the demands for stable isotopes of iron, tungsten, xenon, sulfur, molybdenum and a number of other elements. Centrifuge units have also been built for production of some high purity radioactive isotopes, such as Kr-85 and Fe-55."⁵⁶⁸

Sverdlovsk-44 at Verkh-Neyvinsk is the only plant that has exported enriched uranium to the United States. It will be a principal facility involved

⁵⁶³ The Program Of Development Of Nuclear Power in the RF. The projected worldwide enrichment demand for 1995 is 30.398 million SWU. (M. Humphries, "Uranium Enrichment Issues," *CRS Issue Brief*, 5 November 1992.)

⁵⁶⁴ E. Mikerin, "The Uranium Supply Picture through 2010. Russia," International Uranium Seminar 92, USCEA, 20-23 September 1992.

⁵⁶⁵ D. Albright, F. Bekhout, W. Walker "World inventory of Plutonium and Highly Enriched Uranium 1992," SIPRI, Oxford University Press, 1993, p. 55. The Verkh-Neyvinsk plant has produced the low-enriched uranium that has been exported to the West since the 1970s.

⁵⁶⁶ The isotopes U-232 and U-236 in reactor fuel lead to changes in the core reactivity and fuel burn-up. Their presence leads to effective decrease in the level of enrichment of uranium in U-235.

⁵⁶⁷ Only at Tomsk-7 have the gas centrifuge cascades been contaminated with U-232 and U-234 from recycled uranium.

⁵⁶⁸ E. Mikerin, V. Bazhenov, and G. Solovjov, "Directions in the Development of Uranium Enrichment Technology Technology," 1993.

in converting 500 MT HEU to LEU according to the U.S.-Russia HEU agreement. The plant will be producing 1.5%-enriched LEU from enrichment tails.⁵⁶⁹ Subsequently, the material will be blended with HEU from weapons to produce 4.4%-enriched LEU.⁵⁷⁰ Blending and purging of impurities will be carried out in centrifuges. The facility will be capable of converting up to 20 MT HEU a year.⁵⁷¹

As noted previously the Soviet Union stopped production of highly enriched uranium for weapons in 1987 or 1988.⁵⁷² At 0.36 percent tails assay, 185 SWU are required to produce one kg of HEU enriched to 93 percent U-235. Assuming not more than 10 million SWU/y (one-half the current centrifuge capacity) has been devoted to weapons production, a stockpile of 1000 MT HEU for weapons could have been produced since the early 1950s.⁵⁷³ This and the fact that the Soviet warhead stockpile at its peak was 40 percent higher than the U.S. stockpile at its peak, leads us to believe that the Soviet HEU stockpile is significantly larger than that of the United States, possibly somewhat more than 1000 MT.

Fabrication of Uranium Fuel: Virtually all Soviet-designed commercial power reactors are fueled with uranium dioxide ceramics.⁵⁷⁴ The fuel is produced at the three principal fuel fabrication facilities. Enriched uranium hexafluoride is shipped from Russian enrichment plants to the Uibinsky Metallurgical Plant in Ust'-Kamenogorsk (Kazakhstan). There, uranium hexafluoride is reduced to uranium dioxide powder,⁵⁷⁵ which is subsequently granulated in the presence of organic binder, compacted into pellets, and sintered. The Ust'-Kamenogorsk plant produces most of the UO₂ powder and

⁵⁶⁹ At the new tails assay of 0.15%, about 88,000 SWU are required to produce 295 MT of 1.5%-enriched uranium from 0.36%-enriched tails. About 295 MT 1.5%-enriched uranium are required to blend 10 MT HEU to the level of 4.4%.

⁵⁷⁰ *Nuclear Fuel*, 10 May 1993.

⁵⁷¹ E. Mikerin, "The Uranium Supply Picture through 2010. Russia," International Uranium Seminar 92, USCEA, 20-23 September 1992.

⁵⁷² "Since 1988 no highly enriched uranium has been produced for defense purposes;" E. Mikerin, V. Bazhenov, and G. Solovjov, "Directions in the Development of Uranium Enrichment Technology," 1993.

⁵⁷³ Assuming the enrichment capacity devoted to weapon-grade uranium production increased linearly to 9 million SWU over 30 years, and operated at that level for an additional 7 years, the total HEU production would be: $(9 \times 10^6 \text{ SWU/y})[(30 \text{ y}/2) + 7 \text{ y}](185,000 \text{ SWU/MT}) = 1070 \text{ MT}$.

⁵⁷⁴ Some of naval propulsion and research reactors are fueled with metal uranium or uranium alloys.

⁵⁷⁵ The technology, which is likely to be in use in Ust'-Kamenogorsk, involves reduction of UF₆ to UF₄, which is then hydrolyzed by steam in a reaction $\text{UF}_4 + 2\text{H}_2\text{O} \rightarrow \text{UO}_2 + 4\text{HF}$. Alternative process, also developed in Russia, involves hydrolysis of UF₆, production of (NH₄)₂UO₂F₂-type poly-uranium compounds in a reaction with ammonia, and calcining of the compounds to produce U₃O₈ and UO₂.

pellets for Soviet-designed power reactors.⁵⁷⁶ From Ust'-Kamenogorsk fuel pellets are shipped to the Khimconcentrate Plant in Novosibirsk and the Machine Building Plant in Electrostal (30 km east of Moscow), which produce fuel pins and assemblies for VVER-440/1000, RBMK, naval propulsion and research reactors. To cover current fuel requirements, the plants produce about 4000 for Russian and 5000 fuel assemblies for Soviet-built foreign reactors a year.⁵⁷⁷

Although Kazakhstan and Russia are likely to remain principal manufacturers of fuel for VVER and RBMK reactors, their monopoly may have already eroded. Major Western fabricators of PWR fuels—Westinghouse, Framatome, and Siemens—have developed their designs of VVER-440/1000 reactor fuels. Emerging competitiveness of the fuel market in Eastern Europe was demonstrated by Westinghouse winning the tender on supply of fuel for 2 VVER-1000 units which are under construction in Temelin, Czechoslovakia.⁵⁷⁸ In order to retain traditional markets in Eastern Europe and non-Russian states of the Former Soviet Union and to become competitive on the Western fuel fabrication market, the Russian nuclear industry is pursuing an intensive R&D program of improvements in reactor fuel technologies. The program, called the Complex Program "Fuel Rods and Assemblies of NPP Reactors,"⁵⁷⁹ is designed to improve economics of VVER reactors and extend their refueling campaign, as well as to develop fuels for new-generation nuclear reactors. Designated areas of advances include the following:⁵⁸⁰

- stability of properties and quality of uranium oxide ceramics powder;
- pellet fabrication technologies;

⁵⁷⁶ Some pellets for VVER reactors are produced from Ust'-Kamenogorsk powder at the fuel fabrication facility in Novosibirsk. According to *Nuclear Fuel* (16 August 1993), the Electrostal manufacturing complex produces all UO₂ pelletized fuel for VVER-440 reactors. Operating at about half of its capacity, the plant is producing one million fuel rods per year, containing 1,500 MT of UO₂. Also, *Nuclear Fuel* reports the peak production at the Ust'-Kamenogorsk facility to be 5,000-6,000 MT/y.

⁵⁷⁷ The Program of Development of Nuclear Power.

⁵⁷⁸ On 17 May 1993, Westinghouse and the Czech industry signed two contracts totalling \$434 million. The contracts cover instrumentation and control equipment and fuel arrangements for two VVER-1000 units to be constructed at Temelin. The fuel contract involves design and fabrication of the first core and four reloads for each unit together with related services and equipment. Fuel will be fabricated at Westinghouse's fuel division in Columbia, South Carolina; *Nuclear Engineering International*, July 1993, p. 2.

⁵⁷⁹ The Program "TVEL and TVS for NPP reactors" (Concern TVEL, VNIINM, Minatom, 17 April 1992).

⁵⁸⁰ The Concept of Development of Nuclear Power in Russian Federation. 14 July 1992, The Council (Kollegia) of the Minatom RF.

- advanced structural materials and cladding (quality, recrystallization, Zr cladding with less than 0.01 percent Hf, bi-metal cladding, and welding technologies);
- quality control of fabrication process;
- development and commercialization of the technology of gadolinium-based in-fuel-burnable absorbers;⁵⁸¹
- development of VVER fuel rods for dynamic regimes of reactor operation;
- development of plutonium fuel for fast and thermal reactors.

The work is carried out in the Bochvar Institute of Inorganic Materials (VNIINM, Moscow), Institute of Chemical Technologies (VNIChT, Moscow), OKB Gidropress (OKB GP, Nizhni Novgorod), OKB Machine Building (OKBM, Nizhni Novgorod), Research and Design Institute of Energy Technologies (NIKIET, Moscow), and Science Center "Kurchatov Institute."

Nuclear Reactors, Other than Military Production Reactors

Civil Power Reactors: The program of nuclear power in Russia is based on 28 power reactors at nine sites with a combined capacity of 20,242 MW.⁵⁸² At the average load factor of 69.4 percent for VVER, and 65.7 percent for RBMK reactors, the nuclear power generated in 1992 was 119.6 billion kilowatt hours (kwh) of electricity.⁵⁸³ Although the share of nuclear-generated electricity fell from 11 percent in 1991 to 10.1 percent in 1992, the industry was developing at a steady pace. The Unit 4 of the Balakovo nuclear power plant (NPP) near Saratov went critical in late March 1993.⁵⁸⁴ The Unit 3 at the Kalinin NPP (Tver') and Unit 5 at the Kursk NPP are about 70 percent complete and might be started in 1994.

In July 1992, the Minatom put forward the conceptual program of development of nuclear power in Russia (the Concept).⁵⁸⁵ The Concept foresees two phases. During the first phase of "renovation" (1990-2000), the industry would modernize available generating capacities and develop a new generation of enhanced-safety reactors. The installed capacity will increase to 27,000 MW, mainly due to start-up of reactors already under construction. During the second phase (2000-2010), the capacity will increase to 39,000 MW. The additional capacity will be provided by VVER-1000 and new-

⁵⁸¹ In-fuel-burnable-absorber allow extension of refueling campaigns. This leads to reduction in refueling outages and improves economics of a nuclear power plant.

⁵⁸² Not including Balakovo-4 VVER-1000 unit.

⁵⁸³ *Moscow News*, 28 February 1993.

⁵⁸⁴ *Nucleonics Week*, 8 April 1993.

⁵⁸⁵ The Concept of Development of Nuclear Power in Russian Federation. 14 July 1992, The Council of the Minatom RF.

generation reactors. Simultaneously, the process of decommissioning of old reactors will take place: 14 units totalling 7400 MW_e will be shut down by 2010. After 2010, the Concept expects large scale development of nuclear power, including introduction of the closed nuclear fuel cycle and fast reactors. As a result, nuclear power would provide about 30 percent of electricity of Russia. The program was essentially confirmed by the Governmental Decree #1026 directing the Minatom to present its new power reactor projects to environmental and economics ministries for their review and considerations. Projected reactors, Units 5 and 6 in Balakovo, a Voronezh district-heating station, and South-Ural and Beloyarsk BN-800 fast reactors, are planned to come on line by the end of the 1990s. The Minatom will also start feasibility study for the projects of three new nuclear power plants in the Far East and a 630 MW_e unit at the Sosnovy Bor NPP near St.Petersburg.

In 1992, nuclear power of Ukraine generated 73.8 billion kwh electricity or 29.4 percent of its total production.⁵⁸⁶ Power shortages in the republic has forced the government to extend operation of the units 1 and 3 of the Chernobyl NPP. The reactors resumed their operation in late January 1993. This conflicts with the resolution of the Parliament to shut down the plant before 1993. There are 3 units in the republic construction of which is in a fairly advanced stage: the Zaporozhye Unit 6 might be ready for start-up in six months, and the Rovno unit 4 and Khmelnytsky Unit 2 in 18 months. Production of electricity at these reactors would fully compensate the shutdown of the Chernobyl plant. Their start-up, however, may be deferred by the Parliament-declared moratorium on new power reactors.

Kazakhstan is expected to operate the BN-350 fast reactor for another 6-7 years when it might be replaced by a similar reactor. In addition, the republic may choose to construct as many as three new light water reactors. The conceptual program of development of nuclear power in Kazakhstan which is expected to define nuclear power requirements and the choice of nuclear fuel cycle is being drafted by Kazakh authorities in cooperation with the Minatom RF.⁵⁸⁷

In 1992, two RBMK units of the Ignalina plant in Lithuania generated 14.6 billion kwh of electricity, or 80 percent of the total electricity generation in the country. More than half of the plant's output was exported abroad: 33.8 percent to Belarus, 17.2 percent to Latvia, and some to the Kaliningrad area of Russia. The plant is expected to operate for another eight to ten years--time which is needed to consider alternative supply options.⁵⁸⁸

⁵⁸⁶ *Moscow News*, 21 February 1993.

⁵⁸⁷ Interview with Vice-President of the Katep, 6 May 1993.

⁵⁸⁸ *Nucleonics Week*, 8 July 1993; and *Nuclear Engineering International*, July 1993, p. 18.

Naval Propulsion and Research Reactors: At the peak of its activities, the Soviet Navy operated more than 300 propulsion reactors, installed on nuclear submarines and surface combatants. The nuclear Navy and intensity of its operations are shrinking. At present, Russia maintains only three SSNs and one SSBN on patrol at sea.⁵⁸⁹ Most submarines are powered by dual reactors. Typhoon and Delta class submarines have 100,000 and 50,000 shp propulsion units respectively.⁵⁹⁰ Assuming 20 percent thermal efficiency, this corresponds to reactor capacities of about 370 and 185 MW_t.

The Russian nuclear powered commercial fleet⁵⁹¹ consists of four 54 MW-powered icebreakers of the Arctica class (Arctica, Sibir', Russia, Soviet Union), two 32.5-MW powered Taimyr class icebreakers (Taimyr and Vaigach), and one 29.42-MW powered Sevmorput' transport ship.⁵⁹² A new icebreaker Yamal is at sea-trials at present. One more ship is being constructed. After completion of modernization plans, the icebreaker fleet will include 6 icebreakers of the Arctica- and Taimyr class. The icebreaker Arctica will be decommissioned before 2000, and Sibir early in the next century.

The icebreakers are powered with dual reactor propulsion units with one reactor operating at a low power. Starting 1970, the program is based on a standard water-cooled water-moderated reactor KLT-40. The mission of the icebreaker fleet is to ensure 5-6 month-a-year navigation in the eastern part of the Severny Morskoy Put' (Sevmorput', Northern Sea Way, the sea line connecting Murmansk with Russian Arctic ports including Petropavlovsk-Kamchatsky) . The ships cost 60-70 percent more than diesel-propelled icebreakers; however, because of their capability to operate without port calls, total costs are close. The Sevmorput' transport ship is powered by one reactor, fueled with 200 kg 90% HEU. Its primary mission is to provide shipment on the Murmansk-Dudinka (Norilsk industrial area) route.

The information about research reactors, their design features and application is still sketchy and contradictory. Russia operates some 30 research reactors; several more reactors are operating in other former Soviet republics (Table 25). Most of the WWR- (water-water reactor) and IR- (research reactor) type reactors are used for basic research in nuclear physics, production of short-life radioisotopes, neutron-activation analysis, and training purposes. Major nuclear research centers, like the Physics and Power Institute (Obninsk), NIIAR (Dimitrovgrad), Technology Research Institute (St.Petersburg), VNIINM (Moscow), NIKIET (Moscow), NPO Luch

⁵⁸⁹ *Aviation Week and Space Technology*, 23 November 1992.

⁵⁹⁰ Norman Polmer, "Guide to the Soviet Navy," 1986, p.107.

⁵⁹¹ The information is derived from interviews with naval propulsion reactors designers and booklets by the Murmansk Shipping Company, which operates the fleet.

⁵⁹² One more icebreaker is under sea tests, and another one is in a construction phase.

(Kazakhstan), and nuclear weapons laboratories, operate reactors for fuel- and reactor-design related research, development of structural materials, and defense-related activities.

Back-End of the Fuel Cycle

Minatom policy, at least since the mid-1970, has been to close the back end of the civil power reactor fuel cycle, that is, to reprocess the spent fuel from the VVER type power reactors, recycle the recovered plutonium and uranium, and vitrify the high level nuclear waste. The recovered plutonium was intended primarily for LMFBR reactors, although an R&D program also existed for use of MOX in VVERs. To date the overall objective has not been realized. An overview of the principal activities related to the back end of the fuel cycle is provided below. More detailed descriptions of the specific facilities are found under the site descriptions, Chelyabinsk-65, Tomsk-7, and Krasnoyarsk-26, above.

Fuel Reprocessing: In 1976 the RT-1 chemical separation plant at Chelyabinsk-65 was modified to process spent fuel from naval reactors, and in 1978, it shifted from processing military production reactor fuel, to processing spent fuel from naval (both submarine and civil icebreaker) reactors (which apparently occurred first), test reactors, and 210 MW_e and 440 MW_e light-water moderated and cooled power reactors (VVER-210s and VVER-440s). As indicated in Table 23 the six Russian VVER-440s discharge annually about 75 MTHM; the two Ukrainian VVER-440s another 25 MTHM; and the Russian BN-600 and the Kazakh BN-350 discharge 7.4 MTHM and 6.0 MTHM respectively. About 25.4 MT of separated reactor-grade plutonium has accumulated Chelyabinsk-65 through the end of 1992.

Construction of the RT-2 chemical separation plant at Krasnoyarsk-26 was begun in 1976 or 1978. It was designed to process VVER-1000 fuel. The spent fuel storage facility with auxiliary and service buildings was put into service in 1985, but construction of the 1500 MTHM/y chemical separation facility was halted in 1989 as a result of public opposition and lack of funds.

RBMK Fuel Cycle: The low-enriched uranium (about 1.25% U-235) recovered from VVER spent fuel at the RT-1 plant at Chelyabinsk-65 is blended with highly-enriched uranium recovered from spent naval reactor fuel to make fresh fuel (enriched to 2.4% U-235) for RBMK reactors (the graphite-moderated water-cooled reactors of the Chernobyl type).⁵⁹³ Because of its low U-235 concentration there are no plans to reprocess RBMK spent

⁵⁹³ As a safety measure to reduce the positive reactivity void coefficient, beginning 30 March 1987 (just over one year after the accident at Chernobyl Unit 4), the enrichment of RBMK fuel was increased from 2% to 2.4%. It would have taken about three years—three annual refuelings—to complete the process for each reactor.

fuel.

As of the end of 1992, there was about 7,700 MTHM of RBMK spent fuel in storage at the reactor sites, containing about 32 MT of plutonium, distributed as follows:

Country	Spent Fuel (MTHM)	Plutonium (MT)
Russia	5,500 ⁵⁹⁴	23 ⁵⁹⁵
Ukraine	1,500 ⁵⁹⁶	6
Lithuania	700	3

Up to 35,000 MTHM of spent fuel is projected to accumulate over the lifetimes, assumed here to be 40 years, of all the RBMK reactors.⁵⁹⁷ The RBMK fuel is being kept in the reactor building for three to five years and, afterwards, in pools of water in special onsite buildings. Each special store has the capacity to hold 17,500 spent fuel assemblies, representing about 2000 MTHM. This is sufficient storage capacity for a plant with four reactor units for 10 years. Stores are now (1993) in operation at the St. Petersburg and Kursk nuclear power stations, and are under construction at the Smolensk nuclear power plant. Due to the delay in a project for a centralized store for spent fuel assemblies from RBMKs, plans to double the capacity of each plant store are under way. Minatom does not plan to reprocess the RBMK spent fuel but to dispose of it. Minatom recently favors disposal of such spent fuel in the permafrost. Since Novaya Zemlya has been used as a test site, Minatom considers this area more politically acceptable than other potential disposal sites in northern Siberia.⁵⁹⁸

Mixed-Oxide (MOX) Fuel Fabrication and Use: Early research on plutonium fuel were initiated in Bochvar's Institute of Inorganic Materials (VNIINM, Moscow) in the 50's. Since then, the industry has operated a number of research installations fabricating plutonium into fuel which was tested in critical assemblies, research and power reactors (See Tables 18 and 19). At present, the principal work on design and fabrication of plutonium fuel, and reactor core concepts is carried out in the VNIINM, Physics and

⁵⁹⁴ E.G. Kudriavtsev, "Russian Prospects for Plutonium Accumulation and Utilization," Minatom, 1992.

⁵⁹⁵ V.N. Sololin, "Utilization of Nuclear Materials Released as a Result of Nuclear Disarmament," International Symposium on "Conversion of Nuclear Warheads for Peaceful Purposes," Rome, Italy, 15-17 June 1992; reported about 25 MT of plutonium in about 6000 MTHM as of the beginning of 1992.

⁵⁹⁶ E.G. Kudriavtsev, "Russian Prospects for Plutonium Accumulation and Utilization," Minatom, 1992.

⁵⁹⁷ B. Zakharkin (VNIINM), "Reprocessing and the Future of Nuclear Fuel Cycle in Russia," paper presented at the international workshop "Reprocessing of Nuclear Fuel, Storage and Disposition of Civilian and Weapons Plutonium," 14-16 December 1992, Moscow.

⁵⁹⁸ *NUKEM Marketing Report*, February 1993, p. 39. NUKEM reported 60,000 MT of RBMK spent fuel in storage, an obvious error. The NUKEM number is assumed to be ten times too high.

Power Institute (FEI, Obninsk), Institute of Atomic Reactors (NIAR, Dimitrovgrad), Khlopin's Radium Institute (St.Petersburg), and Production Association Mayak (Chelyabinsk-65). The R&D program has fruited in MOX fuel fabrication technologies and experience in use of plutonium fuel in research and BN-type power reactors.

The principal MOX fuel technology is based on the developed in the VNIINM ammonia process. The technology involves granulation of co-precipitated U/Pu hydroxides using surface agents, production of oxide powder and fuel pellets, and conventional process of fabrication of fuel pins and assemblies.⁵⁹⁹ Mechanical and reactor features of produced MOX fuel are close to those of uranium oxide fuel. Another technology was developed in the NIAR. NIAR's technology is based on pyroprocessing, electrochemical granulation and vibrocompaction of Pu and U oxides. Both technologies have been validated at laboratory and pilot-scale facilities operating at the NIAR and PO Mayak. About 2000 fuel pins have been fabricated and subjected to reactor tests.⁶⁰⁰ In 1984, the industry initiated construction of the industrial MOX fabrication plant "Shop-300." A fully automatic production line with the design throughput of 5-6 MTPu a year, would produce conventional pelletized fuel for BN-800 LMFBR reactors of the South-Ural and Beloyarsk nuclear power plants. Financial problems⁶⁰¹ and uncertainty with the BN-800 reactors put the MOX plant on hold when it was about 50 percent constructed.

Russia has no commercial size MOX fuel fabrication plant in operation. The government plan for further development of nuclear power calls for completion of the "Shop-300" MOX plant and construction of three BN-800 reactors at Chelyabinsk-65 and one at Beloyarskaya.⁶⁰² BN-type reactors are designed for both production of power and utilization of plutonium. With

⁵⁹⁹ The technology involves dissolution of plutonium and uranium in nitric acid and their oxidation to the valence 6, co-precipitation by peroxide and flocculation in the presence of high-molecular surface agents (polymers), filtering and reduction of co-precipitated uranium and plutonium to oxides at 120-150°C, and heating the product at 800°C to produce stoichiometric powder. The process is controllable and stable. It allows production of granulate with specified bulk density, particle size, and flowability. (V.Soloukhin, "Conversion of Nuclear Warheads for Peaceful Purposes," Rome, June 1992.)

⁶⁰⁰ The operating parameters for the fuel are as follows: the cladding temperature of 690°C, linear power density of 490 W/cm and burn-ups up to 10 percent.

⁶⁰¹ Minatom's experts estimate the total cost of the project to be about \$30 million. (International workshop "Reprocessing of Nuclear Fuel, Storage and Disposition of Civilian and Weapons Plutonium," 14-16 December 1992, Moscow.)

⁶⁰² Under the decree "On Construction of Nuclear Power Plants on the Territory of the Russian Federation," adopted by the government, the first two BN-800 reactors are to be constructed by the year 2000—one at the South-Urals plant at Chelyabinsk-65 and the other at Beloyarskaya. Two additional BN-800 reactors at the South-Ural plant are to be brought on line by 2006. The BN-600 reactor is to be decommissioned around 2005. (The Concept of Development of Nuclear Power in the Russian Federation. 14 July 1992, the Council of the Minatom RF.)

current design of reactor cores, BN-600 and BN-800 reactors are capable of utilization of about 0.75 MTPu⁶⁰³ and 1.6-1.8 MTPu a year with the initial loads of 1.2 and 2.3 MTPu respectively. Minatom has conducted technical and economical evaluation of several options of utilization of plutonium in BN-type reactors. They include use of MOX fuel in BN-type reactors with traditional designs of reactor cores and uranium oxide blankets, modernized cores and thorium metal blankets, and use of new "cold"⁶⁰⁴ "kermet" fuel in reactors with advanced cores and thorium blankets.⁶⁰⁵ On the basis of this analysis, the industry has proposed a concept of utilization of plutonium from weapons which comprises the following elements: a) long-term storage of plutonium, b) fabrication of plutonium into MOX fuel for BN reactors using existing technologies, c) development of Mayak-type nuclear centers comprising power reactors, fuel fabrication, and reprocessing facilities, and d) development of a dedicated plutonium burner which would also produce U-233 for light water reactors.

In Russia, use of plutonium in thermal reactors has always been perceived both unsafe and ineffective. The R&D program on use of MOX fuel in VVER-1000 light water reactors was not initiated until recently, when it became apparent that the program of fast reactors may not be completed or that fast reactors may not be able to handle accumulated stockpiles of plutonium. Currently, the research program is coordinated by the Khlopin's Radium Institute. It is assumed that a MOX fabrication technology will be based on that developed for production of fast reactor fuel. More research is needed for the development of a reactor-core concept. If the results of the research will be positive, a MOX plant fabricating fuel for VVER-1000 reactors may be constructed at Krasnoyarsk near reprocessing facility RT-2 after the year 2005.⁶⁰⁶ It is estimated that one VVER-1000 reactor would consume about 0.35 MTPu a year at the initial load of 1.0 MTPu.⁶⁰⁷

⁶⁰³ At about 50 percent MOX fuel. Some 1 MTPu a year can be consumed by the BN-600 with a modified core.

⁶⁰⁴ Because of high thermal conductivity, the temperature at the center-line of a fuel pin of cold fuel would not exceed 600-700°C (against 2000-2500°C in uranium oxide ceramic fuels). Use of "cold" fuel would allow substantial increase in reactor safety.

⁶⁰⁵ V. Murogov, "Energy Conversion of Weapons Plutonium," paper presented at the international workshop "Reprocessing of Nuclear Fuel, Storage and Disposition of Civilian and Weapons Plutonium," 14-16 December 1992, Moscow.

⁶⁰⁶ The Concept of Development of Nuclear Power in the Russian Federation. 14 July 1992, the Council of the Minatom RF.

⁶⁰⁷ Because of different neutronics parameters (the fraction of delayed) the fraction of military plutonium in the 0.35 MTPu total can not exceed one third. V. Murogov, discussion at the international workshop "Reprocessing of Nuclear Fuel, Storage and Disposition of Civilian and Weapons Plutonium." 14-16 December 1992, Moscow.

Table 1
Principal Nuclear Weapon Research, Test and Production Facilities

DESIGN LABORATORIES

All-Russian Scientific Research Institute of Experimental Physics (VNIIEF)

Arzamas-16

at Sarova, Nizhniy Novgorod Oblast

All-Russian Scientific Research Institute of Technical Physics (VNIITP)

Chelyabinsk-70

20 km north of Kasli, Urals region

TEST SITES

Central Test Site

Novaya Zemlya

Northern and Southern Test Areas
two islands north of the Arctic Circle

Semiplatinsk (or Kazakh) Test Site (permanently closed in 1991)

Semiplatinsk-21

Shagan River, Degelen Mountain, and Konyastan test areas
south of Semiplatinsk, Kazakhstan

WARHEAD PRODUCTION (ASSEMBLY) FACILITIES**Sverdlovsk-45**

at Nizhnyaya Tura, 200 km north of Yekaterinberg, Urals region

Zlatoust-36

at Yuryuzan, 85 km southeast of Zlatoust, Urals region

Penza-19

at Kuznetsk, 115 km east of Penza

Arzamas-16

at Sarova, Nizhniy Novgorod Oblast

PLUTONIUM AND TRITIUM PRODUCTION REACTORS

Mayak Chemical Combine

Chelyabinsk-65 (formerly Chelyabinsk-40)

at Lake Kyzyltash, near Kasli and Kyshtym, Chelyabinsk Oblast, Urals region

Siberian Chemical Combine

Tomsk-7

on the Tom River 15 km northwest of Tomsk in Siberia

Mining and Chemical Combine

Krasnoyarsk-26

on the Yenisey River 10 km north of Dodonovo near Krasnoyarsk in Siberia

URANIUM ENRICHMENT FACILITIES

Ural Electrochemical Combine

Sverdlovsk-44

near Verkh-Neyvinsk, near Yekaterinburg, Urals region

Siberian Chemical Combine

Tomsk-7

on the Tom River 15 km northwest of Tomsk in Siberia

Electrochemistry Combine

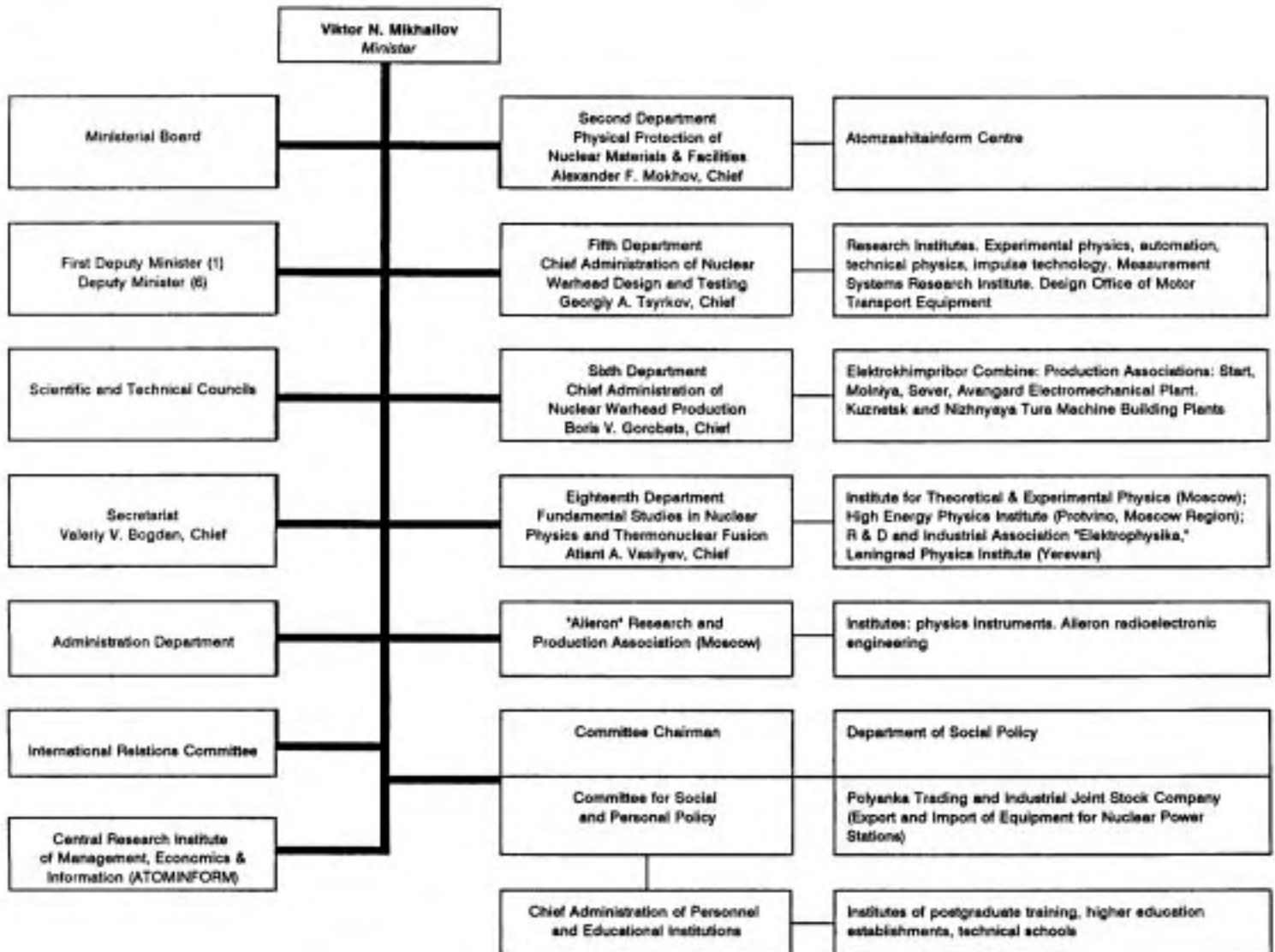
Krasnoyarsk-45

on the Kan River between Krasnoyarsk and Kansk, Siberia

Electrolyzing Chemical Combine

at Angarsk, 30 km northwest of Irkutsk in Siberia

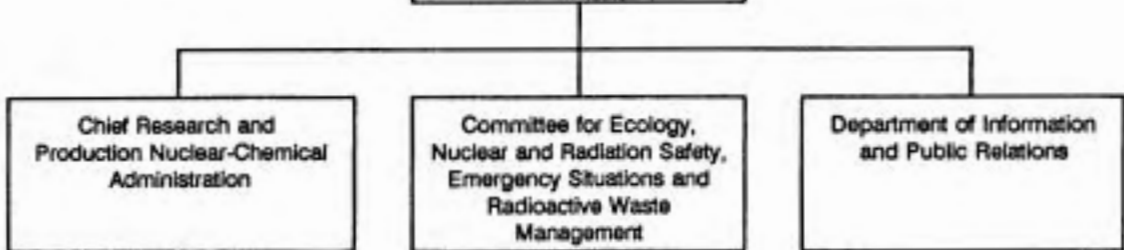
Table 2
Organizational Charts of the Ministry of Atomic Energy







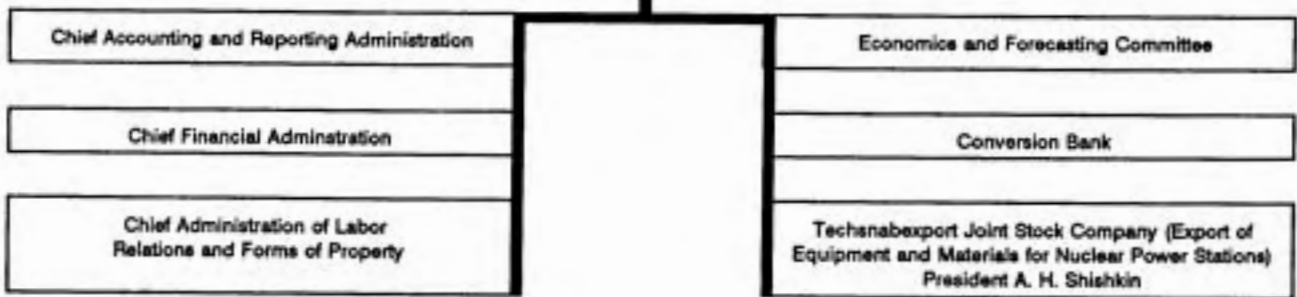
Nikolai N. Yegorov
Deputy Minister

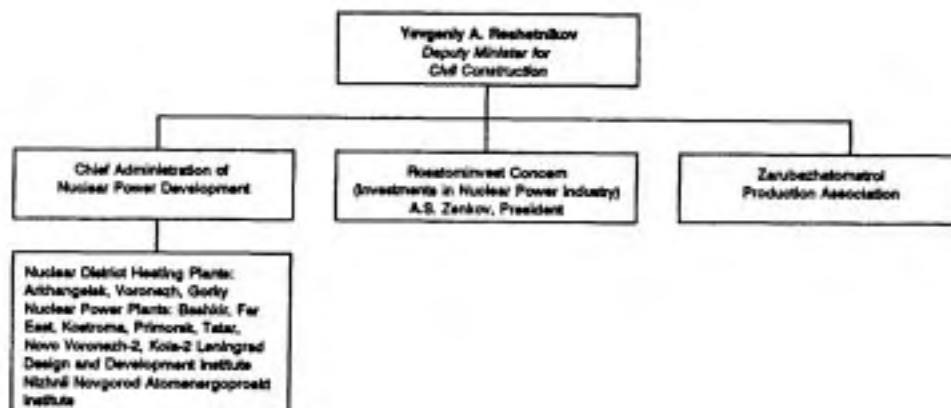
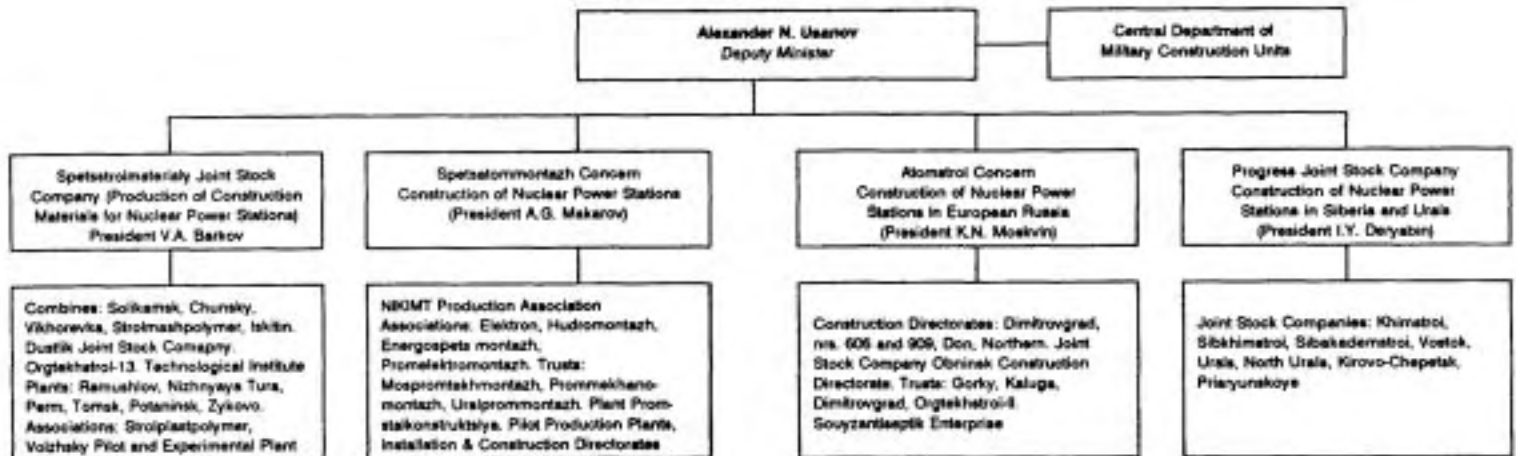


Mayak Production Association (Chelyabinsk) Combines: Uralian (Yekaterinburg), Siberian (Tomsk), Krasnoyarsk Augarsk (Irkutsk Region), B.P. Konstantinov Chemical Combine (Kirovo-Chepetsk, Kirov Region); Electrochemical Plant; Stable Isotopes Institute; Nuklid Center



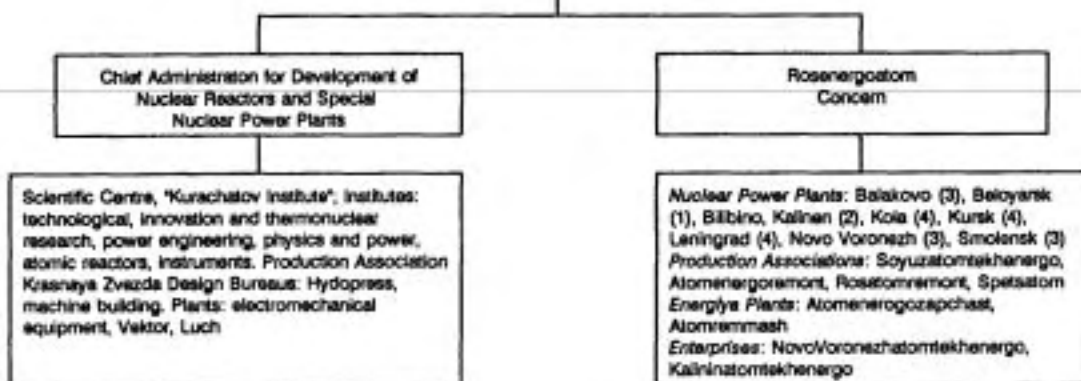
Yuri L. Tyehkov
Deputy Minister







Viktor A. Sidorenko
Deputy Minister



Alexander G. Meshkov
Deputy Minister



Table 3
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 (1 MT plutonium alloys and PuO₂ fuel manufactured in the 1960s and 1970s)

"Zhemchug" operated from 1986-1987 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 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 construction 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