Science & Global Security, 19:28–45, 2011

ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2011.566459

Routledge
Taylor & Francis Group

The History of Plutonium Production in Russia

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For almost 50 years, the production and processing of weapon fissile materials was the primary mission of the Soviet nuclear complex. The cloak of secrecy on all nuclear weapons activities was lifted in 1995. However, the Soviet Union did not declare the amount of fissile-material that it produced for military purposes, and Russia did not reconsider the release of this information. Non-governmental analysts have made estimates of Russia's stocks of weapon-grade plutonium based on assumptions about the power history of the production rectors but such estimates are uncertain. This article attempts to provide improved estimates of production and current holding of weapons plutonium in Russia based on recent publications of historical documents and memoirs on the design and operation of the production reactors.

Russia has not published a comprehensive account of fissile-material production for military purposes during the Soviet and post-Soviet period. Non-governmental analysts, however, have made estimates of Russia's stocks of weapon-grade plutonium based on assumptions about the power history of the production reactors.[1] Such estimates are uncertain, but new publications of historical documents and memoirs on the designs and operations of the former production reactors allow improved estimates.[2]

Based on this improved public information, it is estimated that 145 ± 8 tons of weapon-grade plutonium were produced. This includes 15 tons of plutonium produced after September 1994 by three plutonium-production reactors that continued operating to supply district heat and electricity to the Siberian cities of Tomsk and Zheleznogorsk. Under the 1997 Russian-U.S. Plutonium Production Reactor Agreement, the Russian government committed that this plutonium would not be used in weapons. It is being stored at the production sites in oxide form and is subject to bilateral transparency measures to provide assurance that it will not be used in weapons.

Received 7 October 2010; accepted 16 November 2010.
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About 17 tons of Russia's weapon-grade plutonium have been used in nuclear-weapon tests or lost in waste and in warheads in three submarines that sank.

Under the Year-2000 Russian-U.S. agreement on the disposition of excess weapons plutonium, the Russian Government has committed that 25 tons of the military stock plus 9 tons of the post-September-1994 stock will be fabricated into fuel for Russia's demonstration breeder reactors.

This will leave a total of 88 ± 8 tons of weapon-grade plutonium available for weapons plus 6 tons of the post-September-1994 stock. This is much more than the U.S. stockpile of 38 tons and much more than the approximately 25 tons that would be required to sustain the stockpile of about 4,600 operational and active reserve warheads that Russia is believed to retain.[3]

At its Mayak RT-1 reprocessing plant in the Urals, Russia has separated reactor-grade plutonium from the spent fuel of first-generation light-water power reactors (VVER-440s), its demonstration fast-neutron reactors, and its naval, ice breaker, isotope production, and research reactors.

As of the end of 2009, 47.7 tons of reactor-grade plutonium had been accumulated.[4] This civilian plutonium is being saved to fuel plutonium breeder reactors.

Design and Operation of the Production Reactors

Almost all Russia's plutonium was produced in graphite-moderated reactors. Each reactor is built around a cylindrical stack of graphite blocks (Figure 1).[5]

The graphite blocks in the stack have gaps between them to allow for circulation of nitrogen coolant. The stack also is pierced vertically with channels for fuel and water coolant and rests on a supporting structure with holes under the channels to allow discharge of the irradiated fuel. Each channel is lined with a thin-walled aluminum-alloy tube. Most channels contained 70 fuel rods (Figure 2) but some are used for control rods. Cooling water flows through the tubes and around the fuel rods.[6]

The Soviet Union built fourteen of these graphite-moderated water cooled production reactors at three sites in Russia: six at the Mayak Production Association in Ozersk (formerly Chelyabinsk-65) near Chelyabinsk in the Urals; five at the Siberian Chemical Combine in Seversk (formerly Tomsk-7) near Tomsk; and three at the Mining and Chemical Combine in Zheleznogorsk (formerly Krasnoyarsk-26) near Krasnoyarsk. Twelve were designed to produce plutonium and two to produce tritium and other isotopes. In addition four heavy-water-moderated production reactors were operated at the Mayak site.

The leaders of the Soviet atomic project constantly pressed for more plutonium. In response, efforts were made to operate the reactors at higher power. The design power of the first production reactor at Mayak, reactor ("A") was

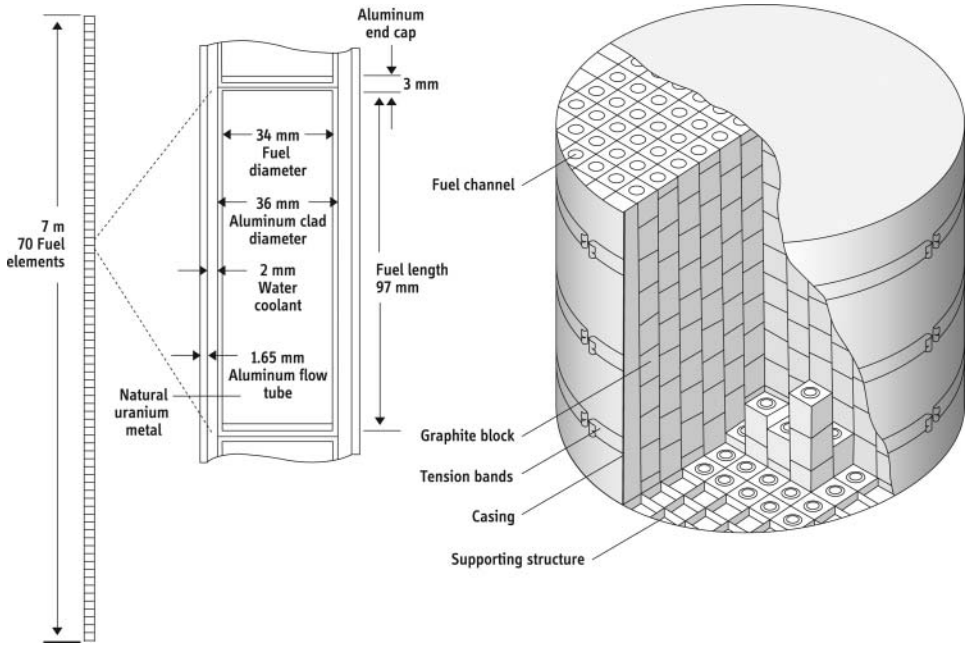

Figure 1: Production-reactor graphite stack. Sources: Burdakov, Ozersk, 1996, and Newman et al., PNL-9982, 1994.

initially 100 megawatt thermal (MWt). After obtaining experience at this power, Igor Kurchatov, the scientific leader of the Soviet nuclear-weapon program, suggested operating it at up to 170–190 MWt during the winter and 140–150 MWt during summer when the cooling water was warmer. That allowed the reactor to produce up to 130–140 grams of plutonium per day. After it was found that a higher percentage of plutonium-240 could be tolerated in weapon plutonium, Kurchatov also proposed extending the amount of time the fuel spent in the reactor to increase the concentration of plutonium in the irradiated uranium.[7]

In 1952, a systematic scientific-technical study was initiated on how to further increase the operating power levels of the production reactors by[8]:

1. Increasing the flow of cooling water through the reactor cores
2. Increasing the corrosion resistance of the channel liners and fuel cladding
3. Diminishing the rate of graphite oxidization, and
4. Increasing the internal operating temperature of the fuel elements.

The cooling water throughput was increased by allowing more space for water flow between the channel wall and the fuel.[9] The corrosion problem was solved by selecting appropriate aluminum alloys and adding sodium

Figure 2: Loading fuel elements into a channel while the reactor was operating. Source: Radiant Power Engineering. *Siberian AES: History with Continuation,* 2008.

bi-chromate to make the cooling water more alkaline (pH of 6.0–6.2). The problem of graphite oxidization was solved by using nitrogen instead of air for graphite cooling. By the end of the 1950s, improvements had also been introduced in fuel design, including: uranium alloying to reduce radiation-induced swelling; thermal hardening of the uranium rods; improvements of cladding corrosion resistance; and quality-control during fuel production.

These innovations made it possible to boost the reactor power levels several fold, as described below.

PLUTONIUM PRODUCTION

Figure 3 summarizes the estimated annual quantities of plutonium produced at each of the three plutonium production sites separately and combined.

Mayak Production Association (Chelyabinsk-65)

The periods of operation of the five graphite-moderated Mayak production reactors and their original design and final upgraded operating power levels

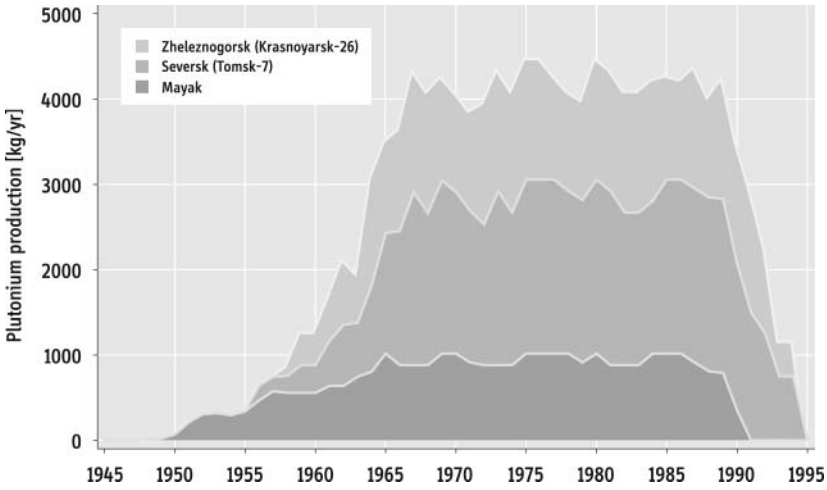

Figure 3: Russia's estimated annual production of weapon-grade plutonium by site and in total (kilograms/year). Production from the sites is shown cumulatively so that the combined production was about 4.5 tons/year during the period 1965–90.

are shown in Table 1. All had a single-pass cooling system in which cooling water was pumped from an external body of water through the cooling channels and discharged into open water ponds.

Reactor A

The first plutonium-production reactor ("A") was designed under the leadership of N. A. Dollezhal to operate at 100 MWt.[10] The reactor has 1149 vertical fuel and control channels in a graphite block of total mass 1050 tons. All but 25 channels were loaded with natural uranium fuel with a total mass of about 120–130 tons. Seventeen channels were used for control rods, and eight for ex-

Table 1: The five Mayak graphite-moderated production reactors.

Reactor name	Power (MWt) (design/upgraded)	Start-up date	Shutdown date
A	100/900	19 June 1948	16 June 1987
AV-1	300/1200	5 April 1950[a]	12 August 1989[b]
AV-2	300/1200	6 April 1951[c]	14 July 1990[d]
AV-3	300/1200	15 September 1952	1 November 1990[e]
AI-IR	40/100	22 December 1952	25 May 1987

[a] B. V. Brokhovich, *op. cit.*, p. 78.
[b]N. S. Burdakov, *op. cit*.
[c]V. N. Novoselov, V. S. Tolstikov, Sekrety "sorokovki" (Secrets of "Fortieth"), Ekaterinburg, IPP Uralskiy rabochiy, 1995.
[d]N. S. Burdakov, *op. cit*.
[e]*Ibid*.

periments. The maximum design operating temperature of the graphite core was 220°C. The maximum design heat production per fuel element in the central channels was 3.45 kWt. The reactor's original production rate was 0.1 kg of plutonium per day with an average of 0.1 kg of plutonium per ton of irradiated uranium fuel.[11]

Reactor A first went critical on 10 June 1948, and reached its design power level of 100 MWt12 days later. The fuel was discharged after about 100 days irradiation and reprocessed after 30–40 days of cooling in a storagepool.[12] The first plutonium metal was separated on 16 April 1949.

The early period of operation revealed many technological deficiencies. The main difficulties were corrosion of the aluminum channel liners and fuel-element cladding, swelling and breakage of uranium rods, and leakage of cooling water into the graphite core. After each water leak, the reactor was shut down for up to ten hours to air-dry the graphite. By January 1949, water leakage had become so frequent that it was decided to stop reactor operation and replace all the channel liners. This took about three months and the reactor was put in operation again on 26 March 1949. During 1948 and 1949, Reactor A produced 16.5 kg and 19 kg of plutonium respectively.[13]

Reactor A's plutonium production during the period 1950–1954 is estimated assuming that the average reactor power was 180 ± 5 MW.[14] Ninety-five of the approximately 130 tons of natural uranium in its core were discharged after 94 effective-full-power-days of operation.[15] Taking into account the time required to reload fuel and to carry out preventive maintenance, the total duration of one cycle would have been 103 days. Approximately 340 tons of spent fuel containing about 58 kg of plutonium therefore would have been discharged from the reactor annually.

The next stage of upgrading Reactor A's power started in 1954 with an increase of its cooling water throughput to 7000 m^3/hr and the discharge water temperature to 95°C. Nitrogen was now used to cool and dry the graphite stack and the graphite temperature was increased from 300 to 675°C. The reactor operated at an average power of about 650 MWt until October 1963, producing about 152 kg of plutonium annually.[16] The frequency of stoppages increased to 165 per month in 1963, however, and it was finally decided to renovate the reactor.

Reactor A resumed operation in April 1964 and operated at an average power 900 MWt from 1965 until it was shut down on 16 June 1987. Assuming that there were two shutdowns of 180 days each for major maintenance, the reactor produced 4.6 tons of plutonium during this period (Table A.1).

AV Reactors

On 25 September 1948, it was decided to construct three AV-type reactors with a capacity to produce of 200–250 grams of plutonium per day. These

reactors were designed by the Experimental Design Bureau for Mechanical Engineering (OKBM) design bureau under the supervision of chief designer A. Savin.[17] All have 1996 channels, 65 of which are used for control rods.The design power and annual plutonium-production capacity were 300 MWt and about 100 kg plutonium per year, respectively.[18] Each channel was equipped with a leak detector. This made it possible to replace tube liners without shutting down the reactor.

In their first year, operating at design power, the AV reactors each produced about 260 grams of plutonium per day.[19] During its first several years of operation the reactor AV-3 was used to produce both tritium and plutonium. Starting in their second year of operation, the power of the reactors was gradually increased and reached 600 MWt by 1963.[20] The first renovations of the AV reactors were carried out after 6–7 years of operation. Major upgrades were made in the beginning of 1960s after the second capital renovation, when important problems with the channel liners and fuel elements were solved. Thereafter, power levels of 1200 MWt and annual plutonium production of 270 kg/year were sustained by all three reactors until their shutdown (Table A.1).[21]

AI-IR Reactor

The AI reactor, which was put into operation on 22 December 1951 with a design power of 40 MWt,[22] was originally designed to produce tritium.[23] Its graphite stack had 248 channels. The reactor was initially fueled with uranium enriched to about 2 percent uranium-235. The decrease in the uranium-238/uranium-235 ratio, from about 140 in natural uranium to about 50, reduced plutonium production and made more neutrons available for tritium production. The reactor produced a considerable amount of plutonium as well but, because of the high burnup of the fuel and the resulting high percentage of plutonium-240, the plutonium was not used in weapons.

During 1952–1956, the power level of the AI reactor was approximately 50 MWt. In 1956, it was reconstructed,[24] fueled with uranium enriched to about 10 percent, and its power level increased. In 1966, the reactor was overhauled and, starting in January 1967, the fuel enrichment increased again to 80–90 percent. From 1967 to 1987, it operated with an average power of 100 MWt. During this period, the reactor was used primarily for irradiation tests of candidate channel-liner and fuel-element-cladding materials. It also produced Cobalt-60 and Polonium-210. It was shut down on 25 May 1987.

Heavy-Water Reactors

Four heavy-water-moderated and cooled production reactors were also built at the Mayak site (Table 2). All were designed by OKBM.

The OK-180 reactor was loaded with 15 tons of uranium fuel and 37.4 tons of heavy water and was able to produce 0.1 kg of plutonium per day or 32 kg

Table 2: Mayak heavy-water reactors.

Name	Power (MWt) (design/upgraded)	Start-up	Shutdown
OK-180	100/233[f]	17 October 1951	3 March 1966
OK-190	300	27 December 1955	8 November 1965
OK-190M	300	16 April 1966	16 April 1986
LF-2 "Ludmila"	800	May 1988	In operation

[f] G. Chernetskya, "Reactornomu zavody—50 let" ("Reactor plant's 50 years"), *Chelyabinsk,* 2000, No. 2, p. 27, <http://www.libozersk.ru/pbd/mayak/link/43.htm>

per year.[25] Although initially intended to produce plutonium, after two years of operation it was loaded with 2 percent enriched uranium and used to produce uranium-233, cobalt-60, phosphorus-32, and tritium.[26] The other three heavy-water reactors were used to produce tritium for weapons and other isotopes. The only heavy-water reactor still operating, the LF-2 reactor or "Ludmila," is producing some tritium but 75 percent of its capacity is used for medical isotope production.[27]

Light-Water Reactor

The reactor "Ruslan" is a graphite-reflected light-water pool reactor with a design power about 800 MWt.[28] It was put into operation on 12 June 1979 to produce tritium. Starting in 1985, its power was increased to 1100 MWt. While this reactor is currently used mainly to produce tritium, it is also used for "doping" electronic silicon with phosphorous.[29]

The reactor-by-reactor, year-by-year estimates of plutonium production at the Mayak site are summarized in Table A.1.

Siberian Chemical Combine (Tomsk-7)

Five plutonium-production reactors were built and operated at the Tomsk-7 site (see Table 3).[30] All were graphite-moderated, light-water-cooled reactors. The first, I-1, had a single-pass cooling system, while the other four had closed primary cooling circuits with heat exchangers to generate steam for electricity generation and district heat.

The I-1 and EI-2 reactors were designed by NIKIET (Research and Development Institute of Power Engineering, chief designer N. Dolezhal). I-1 has 2001 channels (65 channels for control rods) and its design and power were practically the same as those of the AV reactors. The EI-2 reactor was the first dual-purpose reactor constructed in the U.S.S.R. Its primary role was plutonium production but the fission heat released during this process was utilized

Table 3: Tomsk-7 production reactors.

Name of reactor	Type	Power (MWt) (design/upgraded)	Start-up date	Shutdown date
I-1	once-through	400/1200	20 November 1955	21 September 1990
EI-2	closed-circuit	400/1200	24 September1958	31 December 1990
ADE-3	closed-circuit	1450/1900	14 July 1961	14 August 1990
ADE-4	closed-circuit	1450/1900	26 February 1964	20 April 2008
ADE-5	closed-circuit	1450/1900	27 June 1965	5 June 2008

to generate 100 MW of electricity and 300 MW of heat for district heating. The reactor's graphite stack has the same number of channels as the I-1 reactor but the primary cooling-water circuit is closed and operated at higher pressure and temperature than in the once-through I-1. As a result of the added complexity, the operators were confronted with difficulties, especially during the first years.

The three ADE reactors also were designed by OKBM to produce district heat and electricity as well as plutonium and to operate at 1450 MWt. Their graphite stacks have 2832 channels each, of which 132 were used for control rods. To increase the neutron flux in the outer core, 92 fuel channels were loaded with 90 percent enriched "spike" cermet fuel.[31] The reactor cores each contained more than 300 tons of natural uranium fuel and, with their power upgraded to 1900 MWt, discharged about 69 kg of plutonium after 42 equivalent full-power days.[32] Annually, more than 1200 tons of irradiated fuel, containing approximately 500 kg of plutonium, was discharged from each reactor (Table A.2).[33]

Mining and Chemical Combine (Krasnoyarsk-26)

Three plutonium production reactors of the AD and ADE types were built at the Zheleznogorsk (Krasnoyarsk-26) site between 1958 and 1963 (Table 4). They were located in underground tunnels to protect them from U.S. nuclear attack. Like the ADE-type reactors in Tomsk-7, the Krasnoyarsk reactors were designed by the OKBM with a design power of 1450 MWt each. The AD reactor had once-through cooling. The ADE-1 and ADE-2 reactors were designed to be dual-purpose, but the ADE-1 was operated in a once-through mode.

The Krasnoyarsk-26 reactors produced an estimated 45.7 tons of weapon-grade plutonium, including 4.5 tons of plutonium produced during 1995–2010 while the ADE-2 reactor was operated at reduced power exclusively to produce district heat (Table A.3).

Figure 4 gives the estimated cumulative amounts of plutonium produced at the three plutonium production sites separately and together.

Table 4: Krasnoyarsk plutonium-production reactors.

Reactor	Type	Power (MWt) (design/upgraded)	Start-up date	Shutdown date
AD	once-through	1450/2000	25 August 1958	30 June 1992
ADE-1	once-through	1450/2000	20 July 1961	29 September 1992
ADE-2	closed-circuit	1450/1800	January 1964	15 April 2010

Uncertainties

The uncertainties of the above estimates stem primarily from the uncertainties of the power levels of the individual production reactors and the assumed durations of their operation at those power levels.

The most important uncertainty relates to the rates at which the powers of the reactors were increased above their original design levels and the power levels to which they were boosted. The estimates made here assume that, for the first and second-generation reactors (A, AV and I), the process of power ramp-up took 6–12 years, while, for the third generation reactors, it took 3–5 years. This leads to a ±5 tons uncertainty in plutonium production. Assuming that the uncertainty in the upgraded reactor power levels is ±5 percent gives another ±6 tons uncertainty.

With regard to the duration of the startup period for each reactor, the estimates made here assume a startup period of three weeks. But it took more

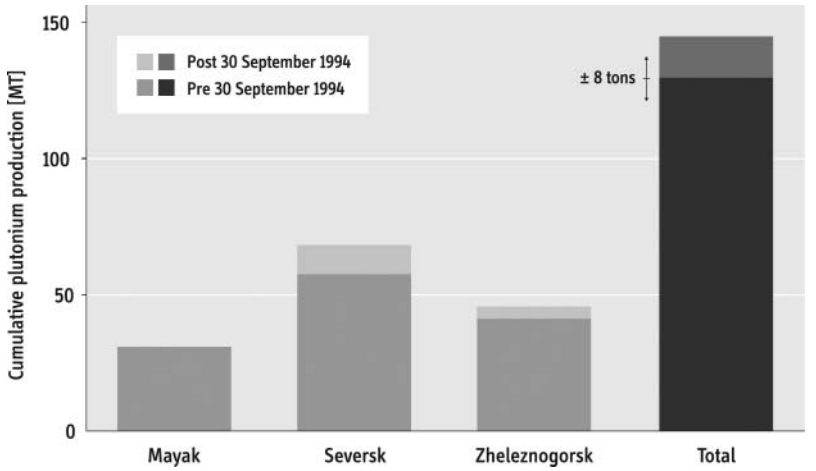

Figure 4: Estimated production of weapon-grade plutonium by site and total (metric tons). In exchange for U.S. assistance in refurbishing and building replacement coal-fired district-heating plants, Russia has agreed not to use plutonium produced after 30 September 1994for weapons.

than one month to bring some reactors up to their design power. These uncertainties result in an additional uncertainty of about ±0.3 tons plutonium.

With regard to shutdowns due to operating problems, most were relatively short and the reactors went back into operation after 20–30 minutes. But it took days to weeks to restore normal operation after an overheating and meltdown of fuel elements and aluminum channel liners. Such accidents happened about 150 times. Assuming that cleanup and repairs were accomplished on average in 4 to 10 days, the resulting uncertainty would be about ±0.75 tons of plutonium.

Assuming that the above uncertainties are random and uncorrelated, the total uncertainty of Russia's cumulative production of weapon-grade plutonium would be around ±8 tons.

Plutonium Losses and Uses

Some of the plutonium produced in the production reactor fuel was not recovered and ended up in high-level waste. Some was used in nuclear tests and critical assemblies and a small amount was lost in the warheads in three submarines that sank.

Reprocessing Losses

In the beginning of the 1950s, about 13 percent of the plutonium in the production-reactor fuel was being lost to high-level waste.[34] By the middle 1960s, the losses had decreased to 3–5 percent. Based on this information, the quantity of plutonium in reprocessing waste is estimated to be about 5.5 tons. In that case, 139 ± 8 tons of weapons plutonium would have been recovered from the production reactors.

Fabrication Losses

Some quantity of plutonium was lost during the fabrication of plutonium weapon-components. Based on the U.S. experience where such losses were about 5 percent, the quantity of plutonium lost in this way is estimated to be 7 tons.

Use in Nuclear Tests

The Soviet Union tested a total 939 nuclear explosive devices.[35] Assuming that each device contained on average 4 kg of plutonium, 3.9 tons of plutonium would have been used in tests.

Use in Critical Assemblies

About 0.54 tons of weapon-grade plutonium is currently in critical assemblies.

Lost Warheads

Three Soviet submarines equipped with 25 nuclear warheads containing a combined 0.1 tons of plutonium were lost.[36]

The above estimates of production, losses and uses are summarized in Table 5.

Table 5: Production, removals, and stocks of Russian weapon-grade plutonium.

	Material Balance Category	Plutonium (tons)
Production	Mayak Site	30.9
	Seversk Site	68.3
	Zheleznogorsk Site	45.7
	Total	144.9
Removals	Waste	−5.5
	Losses in fabrication	−7.0
	Tests	−3.9
	Losses of warheads	−0.1
	Research assemblies	−0.5
	Total	−17.0
Stocks (2010)		127.9
Declared excess		−34.0
Not available for weapons		−6.0
Available for weapons		87.9

APPENDIX A. ESTIMATED PLUTONIUM PRODUCTION BY REACTOR AND YEAR

Table A.1: Mayak site (all values in kilograms).

	Reactor					Annual	Cumulative
Year	A	AV-1	AV-2	AV-3	OK-180	total (kg)	total (kg)
1948	16					16	16
1949	19					19	35
1950	30	39				69	104
1951	58	100	50		3	211	315
1952	58	100	100	24	25	307	622
1953	58	108	108	20	25	319	941
1954	58	108	108	20		294	1235
1955	76	135	108	20		339	1574
1956	152	162	135	20		469	2043
1957	152	162	162	100		576	2619
1958	152	81	162	162		557	3176
1959	152	162	81	162		557	3733
1960	152	162	162	81		557	4290
1961	152	162	162	162		638	4928
1962	152	162	162	162		638	5566
1963	152	270	162	162		746	6312
1964	103	270	270	162		805	7117
1965	207	270	270	270		1017	8134
1966	207	135	270	270		882	9016
1967	207	270	135	270		882	9898
1968	207	270	270	135		882	10780
1969	207	270	270	270		1017	11797
1970	207	270	270	270		1017	12814
1971	103	270	270	270		913	13727
1972	207	135	270	270		882	14609
1973	207	270	135	270		882	15491
1974	207	270	270	135		882	16373
1975	207	270	270	270		1017	17390
1976	207	270	270	270		1017	18407
1977	207	270	270	270		1017	19424
1978	207	270	270	270		1017	20441
1979	103	270	270	270		913	21354
1980	207	270	270	270		1017	22371
1981	207	135	270	270		882	23253
1982	207	270	135	270		882	24135
1983	207	270	270	135		882	25017
1984	207	270	270	270		1017	26034
1985	207	270	270	270		1017	27051
1986	207	270	270	270		1017	28068
1987	100	270	270	270		910	28978
1988		270	270	270		810	29788
1989		250	270	270		790	30578
1990			130	220		350	30928
Totals:	6,138	8,508	8,407	7,822	53	30,928	

Table A.2: Siberian chemical combine (all values in kilograms).

Reactor: Year	I-1	IE-2	ADE-3	ADE-4	ADE-5	Annual total (kg)	Cumulative Total (kg)
1955	10					10	10
1956	170					170	180
1957	170					170	350
1958	170	29				199	549
1959	170	155				325	874
1960	170	155				325	1199
1961	170	155	202			527	1726
1962	170	155	392			717	2443
1963	85	155	392			632	3075
1964	270	78	392	268		1008	4083
1965	270	155	392	392	202	1411	5494
1966	270	260	250	500	292	1572	7066
1967	270	260	500	500	500	2030	9096
1968	270	260	500	250	500	1780	10876
1969	270	260	500	500	500	2030	12906
1970	135	260	500	500	500	1895	14801
1971	270	260	500	500	250	1780	16581
1972	270	130	500	250	500	1650	18231
1973	270	270	500	500	500	2040	20271
1974	270	270	250	500	500	1790	22061
1975	270	270	500	500	500	2040	24101
1976	270	270	500	500	500	2040	26141
1977	270	270	500	500	500	2040	28181
1978	135	270	500	500	500	1905	30086
1979	270	135	500	500	500	1905	31991
1980	270	270	500	500	500	2040	34031
1981	270	270	500	500	500	2040	36071
1982	270	270	250	500	500	1790	37861
1983	270	270	500	250	500	1790	39651
1984	270	270	500	500	250	1790	41441
1985	270	270	500	500	500	2040	43481
1986	270	270	500	500	500	2040	45521
1987	270	270	500	500	500	2040	47561
1988	270	270	500	500	500	2040	49601
1989	270	270	500	500	500	2040	51641
1990	202	270	250	500	500	1722	53363
1991			500	500	500	1500	54863
1992			250	500	500	1250	56113
1993				250	500	750	56863
1994				500	250	750	57613
1995–2008				5300	5400	10700	68313
Totals:	8,237	7,452	14,020	19,460	19,144	68,313	

Table A.3: Mining and chemical combine. All values in kilograms.

Reactor: Year	AD	ADE-1	ADE-2	Annual total (kg)	Cumulative total (kg)
1958	101			101	101
1959	378			378	479
1960	378			378	857
1961	378	130		508	1365
1962	378	378		756	2121
1963	189	378		567	2688
1964	505	378	368	1251	3939
1965	505	189	378	1072	5011
1966	505	505	378	1188	6199
1967	505	505	405	1415	7614
1968	505	505	405	1415	9029
1969	505	505	202	1212	10241
1970	252	505	405	1162	11403
1971	505	252	405	1162	12565
1972	505	505	405	1415	13980
1973	505	505	405	1415	15395
1974	505	505	405	1415	16810
1975	505	505	405	1415	18225
1976	505	505	405	1415	19640
1977	505	505	202	1212	20852
1978	252	505	405	1162	22014
1979	505	252	405	1162	23176
1980	505	505	405	1415	24591
1981	505	505	405	1415	26006
1982	505	505	405	1415	27421
1983	505	505	405	1415	28836
1984	505	505	405	1415	30251
1985	505	505	202	1212	31463
1986	505	252	405	1162	32625
1987	505	505	405	1415	34040
1988	252	505	405	1162	35202
1989	505	505	405	1415	36617
1990	505	505	405	1415	38032
1991	505	505	405	1415	39447
1992	250	360	405	1015	40462
1993			405	405	40867
1994			405	405	41272
1995—2010			4462	4462	45734
Totals:	15,433	14,184	16,317	45,734	

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5. N.S. Burdakov, *Nekotoryestranitsyizistoriirazvitiyatechnologiipromyshlennyhurangrafitivyhreactorov (Some Pages from the History of Technology Development for Production of Uranium-graphite Reactors)*, Ozersk, 1996; D. F. Newman et al., "Summary of Near-term Options for Russian Plutonium Production Reactors," PNL-9982, Pacific Northwest Laboratory, Richland, Washington, July 1994.

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15. This corresponds to 0.17 kg of plutonium per ton of fuel. Lev Ryabev, "Igor Kurchatov's Suggestion on Increasing Plutonium Production at *A* reactor, 9 April 1949," *op. cit*.

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26. Lev Ryabev, *op. cit.*, Document 187, "B. Vannikov and Others report to L. Beriya on Reordering of the Factory No. 3 (OK-180) for Production of Uranium-233," 6 May 1952,Vol. III, *Atomic Bomb, 1945–1954*, Book 1; A.K. Kruglov, "O pervykh v nasheystranereactorakh s tyazheloyvodoy" ("About the First Heavy-water Reactors in our Country"), in *Creation of the First Soviet Nuclear Bomb* (Moscow: Energoatomizdat, 1995), p. 313.

27. V. Gubarev, "Ruslan and Ludmila: Reactors for Thermonuclear Weapons," *Nauka i Zhizn*, No. 6, 1997.

28. B.V. Brokhovich, *op. cit.*, p. 130.

29. V.M. Kuznetsov, "Production Association Mayak: The History of Association," <http://www.libozersk.ru/pbd/Mayak60/link/237.htm. When stable silicon-30 captures a neutron, it becomes silicon-31, which decays with a half-life of 2.6 hours to stable phosphorus-31.

30. The EI-2 reactor was initially put into operation in February 1958 in a once-through mode pending installation of the steam generator and turbine. It shifted to dual-purpose operation on 24 September 1958, P.A. Zhuravlev, *op. cit.*, pp. 252–254.

31. The cermet fuel contains 8.5 percent UO_2 dispersed in aluminum. The concentration of uranium-235 in the cermet fuel is the same as in the natural uranium fuel and therefore generates the same amount of heat but the near-absence of uranium-238 in the fuel reduces its neutron absorption and thereby offsets the greater leakage of neutrons out of the reactor's surface from the outer portion of the core.

32. The natural uranium was discharged with a burnup of 468 MWd/ton and contained 420 grams of plutonium per ton of uranium. Thus, at this burnup, the reactors produced approximately 0.90 grams of plutonium per MWd. An additional 65 MWt was generated by the spike fuel. Overall therefore, the reactor generated about 0.87 grams of plutonium per MWd.

33. The estimates were made assuming that the reactors were operated at design power during their first several years. Also, it has been assumed that, beginning in

1995, after the order for weapon-grade plutonium was canceled, the reactors ADE-4 and ADE-5 operated at 75 percent power, i.e., 1425 MWt.

34. Lev Ryabev, *op. cit.*, Document No. 300, "Summary of Information on Nuclear Reactors."

35. I.A. Andrushin, A.K. Chernyshev, Yu. A. Yudin, *Ukrochenieyadra (Subduing of the Nucleus)*, Sarov, 2003, p. 164.

36. The submarine K-129 sank in 1968 with three ballistic missiles each equipped by one warhead and two nuclear-armed torpedoes. The submarine K-219 sank in October 1986 with sixteen ballistic missiles, each equipped with one nuclear warhead, and two nuclear-armed torpedoes. The submarine Komsomolez sank in 1989 with two nuclear-armed torpedoes.