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History of Highly Enriched Uranium Production in Russia

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Between 1949–1963, the Soviet Union built four large industrial uranium-enrichment plants. All initially used gaseous diffusion for isotope separation. Starting in 1964, however, the Soviet Union began introducing gas centrifuges and this transition was completed in the early 1990s.

In 1989, the Soviet government announced that "it is ceasing the production of highly enriched uranium."[1] In fact, all production of highly-enriched uranium (HEU) had already stopped in1988 and, because of the huge excess quantities of HEU that have become available as a result of the down-sizing of the Soviet Cold War nuclear stockpile, it apparently has not resumed since.

We estimate that by the time the production of HEU ended, the Soviet Union had produced about 1250 ± 120 tons of 90 percent-enriched uranium. This number does not include the enriched uranium that was used to manufacture naval fuel, fuel for research reactors, and fast reactors, most of which was produced as less than 90 percent enriched HEU.[2] Of the 1250 tons of HEU, 500 tons have been committed to be blended down to low-enriched uranium (LEU) to be sold to the United States, with about 400 tons already blended down as of September 2010. A total of 90 tons of HEU were consumed in separate programs for tritium-production reactor fuel and research-reactors, in "spike fuel" for the plutonium-production reactors, in nuclear weapon tests, and lost to processing waste.

It is estimated that Russia had 760 tons of HEU remaining as of September 2010 and that its total holdings will have been reduced to about 655 tons by the end of the HEU blend-down program in 2013. This includes material in and available for weapons and reserved for fueling naval, research and civilian

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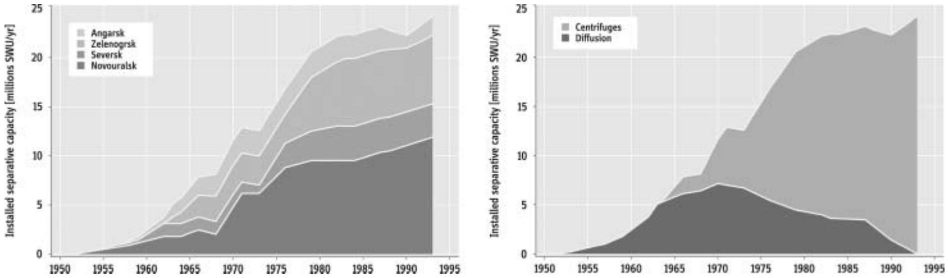

Figure 1: Growth of Soviet/Russian installed enrichment capacity (millions SWU/y) by site (left) and technology (right) from 1950 through 1993.

reactors. At 20 kg per warhead, this would be sufficient for more than 30,000 warheads. Obviously, more could be declared excess.

Figure 1 shows the estimated evolution of installed separative work capacity by enrichment facility and by technology. Cumulatively, about 400 million Separative Work Units (SWU) had been produced by the end of 1987. Below, it is estimated that 107 million of these SWU were used to produce fuel for Russia's power reactors and for export; 28.5 million to produce HEU fuel with various enrichment levels for Russia's naval and icebreaker reactors; and 0.5 million to produce medium-enriched uranium fuel for research reactors. This would leave 264 million SWU available to produce weapon-grade uranium.

These estimates are based on a large array of data on the history of the Soviet enrichment program that is summarized in Appendix A. Most of the uncertainty is related to dates of plant modernization and equipment upgrades. Overall, the uncertainty in the cumulative production of SWUs is estimated to be about ±5 percent.

Another source of uncertainty in estimates related to production of enriched uranium is the lack of information about the percentage of uranium-235 remaining in the depleted uranium "tails." The central estimate provided here assumes that the gaseous diffusion process and the centrifuges operated with tails assays of 0.3 percent and 0.25 percent respectively.[3] Taking into account that centrifuges produced about 70 percent of all separative work until 1988, the average tails assay would have been about 0.265 percent. This value is used in all estimates of enriched uranium production in this paper. Assuming that the actual average value falls between 0.25 and 0.3 percent, the resulting uncertainty in the HEU production also would be about ±5 percent.

Non-weapon Requirements for Separative Work and HEU

In addition to production of HEU for nuclear weapons, the Soviet Union and Russia enriched uranium for reactor fuel for power reactors, naval reactors, plutonium and tritium-production reactors, and research reactors.

Fuel for Nuclear Power Reactors

By the time the Soviet Union ended production of HEU in 1988, it had built a fleet of 76 nuclear power reactors of several different types, most of which used LEU fuel.[4] In calculating the SWU requirements for power reactor fuel, it is assumed that, by 1988, the Soviet Union had produced enough enriched uranium to support reactor operations through the end of 1989.

Reactors of the most popular class at the time were light-water reactors (LWRs) with a gross electrical generating capacity of 440 MWe (VVER-440).[5] The Soviet Union's next-generation LWR was the 1000 MWe VVER-1000.[6] These reactors used fuel with enrichment of 3.5 percent and 4.4 percent respectively.

In addition, the Soviet Union built graphite-moderated RBMK reactors until the 1986 Chernobyl accident, which used fuel with an enrichment of 1.8 to 2 percent.[7] Their fuel was produced by enriching uranium and, between 1981 and 1991, also by blending down HEU recovered in the course of reprocessing naval and research-reactor fuel at the Mayak RT-1 plant.[8]

The Soviet Union also built and operated four small EGP-6 graphite-moderated reactors to generate heat as well as electricity for the north-Siberian gold-mining town of Bilibino. These reactors are designed to produce 62 megawatt thermal (MWt) of heat each and use 3 to 3.6 percent enriched uranium in their cores.[9] Two graphite-moderated reactors, AMB-100 and ABM-200, part of the Beloyarsk nuclear power plant, used fuel with enrichments ranging from 1.5 percent to 21 percent with an average enrichment of about 3 percent.[10] They were shut down in 1983 and 1989 respectively. The fuel for these reactors originally contained about 210 tons of LEU, which required 0.8 million SWU to produce.

Finally, the Soviet Union operated two liquid-sodium-cooled fast-neutron reactors: the BN-350 in Shevchenko (now Aktau), Kazakhstan, and BN-600 at the Beloyarsk nuclear power plant. These two reactors began producing electricity in 1973 and 1980 respectively. The BN-350 used uranium in the range of 20 percent enrichment in its core.[11] The BN-600 used fuel with enrichments ranging from 17 to 33 percent.[12]

Beginning in the 1970s, the Soviet Union supplied enrichment services to Western Europe for a total of 40 million SWU by the end of 1988.[13]

Table 1 summarizes the estimates of SWU requirements for nuclear-power fuel. Altogether, the Soviet Union had used about 107 ± 7 million SWU to enrich power-reactor fuel by the time it stopped producing HEU.

Naval Reactors

Starting with the *K-3* submarine, which entered sea trials in 1958, the Soviet Union and Russia built 255 nuclear-powered submarines of more than 20 different types. Most were equipped with twin reactors, for a total of

Table 1: Estimated SWUs used to produce nuclear-power-reactor fuel through 1987.

Reactors	Power, MW(e)	Years of operation	Number of units	Enrichment of fuel (percent)	Total enriched uranium produced (tons)	Cumulative separative work, (millions of SWUs)
VVER-440	440	1972–	36	3.5	6,200	29.0
VVER-1000	1000	1981–	17	4.4	2,200	14.2
RBMK-1000	1000	1974–	18	1.8–2.4	3,600[1]	6.6
LWGR	12	1974–	6	1.5–21	270	1.0
	108	1964–83				
	160	1967–90				
BN-350	90	1973–99	1	17, 21, 26	72	4.5
BN-600	600	1980–	1	17, 21, 26	92	11.3
Export						40
TOTAL						107

[1] Takes into account savings from recycling reprocessed uranium.

456 nuclear reactors. Five nuclear-powered military surface ships collectively contained a total of 10 reactors, and 10 civilian Arctic icebreakers and container ships were equipped with 17 reactors that used HEU fuel.[14] With the exception of eight submarines that used liquid-metal-cooled reactors, the reactors were water-cooled and went through three generations of development. It is estimated these naval reactors, in total, required about one-quarter as much enrichment work as the power reactors.

The Soviet Union's first-generation submarine reactors, known as VM-A, used 6 to 21 percent enriched fuel.[15] A typical core contained about 250 kg of uranium.[16] Two first-generation VM-A reactors were installed in each of 55 submarines that were built in the 1950s and 1960s, most of which remained in service until the late 1980s. The available information on their operation and overhauls suggests that submarines of this class were refueled three to four times during their service lives.

Second-generationVM-4 reactors, installed in submarines starting in the late 1960s, used 21 percent enriched fuel.[17] According to one estimate, their cores each contained about 550–660 kg of uranium.[18] The initial design of the VM-4 reactor apparently called for reactor refueling about every eight years.[19] This means that submarines that were built in the late 1960s and early 1970s went through at least two refueling operations. It is assumed that submarines built after 1975 were refueled only once because fleet operations were dramatically scaled down in the 1980s and a large number of submarines were decommissioned in the 1990s (Figure 2).[20]

The design thermal power of third-generation OK-650 submarine reactors was 190 MWt, more than twice that of their predecessors' 90 MWt. They

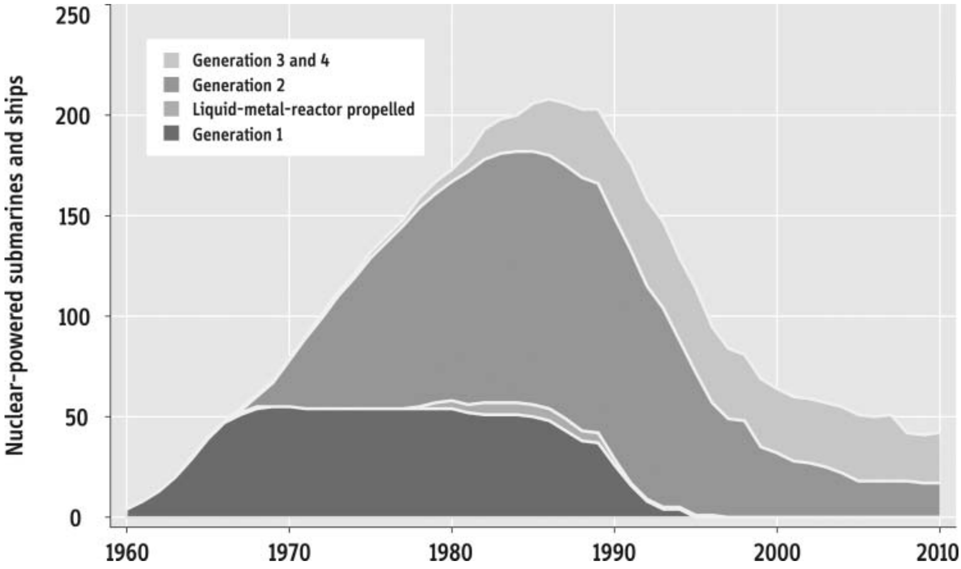

Figure 2: Soviet/Russian nuclear-powered submarines and ships by generation of nuclear-propulsion reactors.

reportedly use fuel elements with at least two levels of enrichment: 21 percent and 45 percent.[21] An OK-650 reactor core is estimated to contain 200 kg.[22] Submarines with third-generation reactors began entering service in 1981 and it is therefore unlikely that they required refueling during the 1980s. In the 1990s, the intensity of their operations was drastically scaled back. As a result, between 1992–2008 the Northern Fleet refueled only one submarine with a third-generation reactor.[23] It is assumed that all but one submarine equipped with third-generation reactors still operate with, or were decommissioned with their initial cores.

In recent years the Russian Navy has completed construction of only two new nuclear-powered submarines, the ballistic-missile submarine, *Yuri Dolgoruki,* in 2009, and the attack submarine, *Severodvinsk,* in 2010. Each is believed to have one fourth-generation reactor. The fuel inventory per reactor is assumed to be the same as third-generation reactors and is included in the totals for the third-generation reactors.

The Soviet Union also developed and built eight submarines powered by liquid-metal-cooled reactors: an experimental one-of-a-kind Project 645 (*November*) submarine with two reactors; and a series of Project 705 (*Alfa*) ships that had single reactors of a different type. Both types of reactors used molten-lead-bismuth alloy as a coolant and 90 percent-enriched uranium as their fuel. It is estimated that each core contained 200 kg of uranium-235.[24] The Project 645 submarine had its two reactors refueled in 1967. None of Project 705 submarine reactors were refueled, but one ship had its entire reactor compartment replaced after an accident.[25] This means that the eight submarines used a total of 12 cores.[26]

The military nuclear-powered surface ships built in the Soviet Union included four large missile cruisers of the Project 1144 (*Kirov*) class and one service ship of the Project 1941 class. Each ship had two water-cooled nuclear reactors of the KN-3 class, which appear to be similar to the third-generation submarine reactors. Therefore, it is assumed that each of these reactors contained 200 kg of uranium-235 in uranium enriched to between 21 and 45 percent.[27] Of these ships, only the fourth Project 1144 cruiser (*Piotr Velikiy*) is currently in active service and most likely has not yet required refueling of its reactors.

Russia also built nine nuclear-powered icebreakers and one container ship. The first nuclear icebreaker, *Lenin*, used two different types of reactors during its lifetime: in the period between 1959 and 1967, three OK-150, which were each refueled once; and during 1970–1989, two OK-900. Since the OK-150 used LEU fuel and required relatively little enrichment work, the six cores of this type are not counted in the aggregate numbers.[28] After 1967, the three OK-150 reactors on Lenin were replaced by two reactors of the OK-900 type, similar to those used on the six icebreakers of the *Arktika* class. These reactors used HEU fuel with two zones enriched to 36 percent and 60 percent.[29] A normal reactor core load contains 302 kg of uranium.[30] Assuming (rather arbitrarily) that about one third of the core contains 60 percent enriched uranium, it is estimated that each core contains about 130 kg of uranium-235. About 70 OK-900 reactor cores have been used so far.[31]

The *Sevmorput* container ship and *Taimyr* and *Vaigach* icebreakers use KLT-40 and KLT-40M reactors respectively (each ship has one reactor). These reactors use fuel enriched to 90 percent. A fresh reactor core contains 167 kg of uranium and 150 kg ofuranium-235.[32] Prior to 2000, the reactor cores on these three ships were replaced five times.[33] Assuming that this refueling rate continued, they received an additional five cores between 2000 and 2010, for a total of 13 KLT-40 reactor cores. These estimates are summarized in Table 2.[34]

If all HEU used to manufacture naval fuel up until today was produced before 1988, its production would have consumed about 28.5 million SWU. The accuracy of this estimate is estimated to be 20 percent or ±6 million SWU.

Research Reactors

The Soviet Union built about 170 research reactors and critical and subcritical assemblies, a large fraction fueled with HEU. About 70 HEU-fueled research reactors are currently located at the nuclear weapon laboratories and other Rosatom research institutes, other Russian research and graduate-educational institutes, and agencies. A number of reactors fueled with Soviet

Table 2: Enriched uranium requirements of Soviet and Russian naval reactors.

	Ships	Reactors	Number of cores	Total uranium-235 (tons)	Enrichment (percent)	Total uranium (tons)	Millions of SWU
Submarines 1st generation	55	110	466	27.5	20	137.5	5.6
2nd generation	143	269	686	82.3	21	392	16.8
3rd generation	41	60	61	12.2	21, 45	29.0 (21%)	1.2
						13.6 (45%)	1.3
With liquid-metal-cooled reactors	8	9	12	2.4	90	2.7	0.5
Small	8	8	8				
Military surface ships	5	10	14	2.8	21, 45	6.7 (21%)	0.3
						3.1 (45%)	0.3
Civilian ships	10	17	70	9.1	36, 60	14 (36%)	1.1
						7.0 (60%)	0.9
			13	1.95	90	2.17 (90%)	0.4
TOTAL				138			28.5

and Russian HEU are also located in the former Soviet republics and in other foreign countries.[35]

Most research reactors operate at relatively low power. Their fuel requirements therefore are not as large as those of power reactors or production reactors.[36] Overall, however, research reactors consumed considerable amounts of enriched uranium. Data on the operating histories of reactors suggest that, by the end of 2009, the research reactors that were designed and built by the Soviet Union had used about 6 tons of HEU with enrichment of 36 percent, 1.2 tons of 80 percent enriched uranium, and 11.3 tons of 90 percent HEU.[37]

In addition, a substantial amount of HEUis held up in cores of critical assemblies and pulsed reactors. For example, two critical assemblies at the Institute of Physics and Power Engineering (IPPE) in Obninsk were reported to hold 8.7 tons of uranium with enrichment of 36 percent and 90 percent.[38] Most of this material, however, has not been exposed to any significant burnup, so it should be considered part of the HEU inventory.

Production of 6 tons of 36 percent enriched uranium used in research reactors required about 0.5 million SWU. In addition to that, by the end of 2009 research reactors used about 12.3 tons of 90 percent HEU (this assumes that the 80 percent enriched uranium was produced by diluting weapon-grade HEU). Accuracy of these estimates is estimated to be no better than 20 percent.

Plutonium and Tritium-production Reactors

The Soviet Union built and operated a fleet of dedicated production reactors that provided materials for its nuclear weapons. Plutonium-production reactors were built at: Ozersk (Chelyabinsk-65), Seversk (Tomsk-7), and Zhelesnogorsk (Krasnoyarsk-26). Four graphite-moderated plutonium-production reactors (A, AV, AV-2, and AV-3) were built at the Mayak facility in Ozersk during 1948–1952 and operated until the late 1980s. Another graphite-moderated reactor at Mayak (AI) was used to produce tritium. Mayak also operated four heavy-water reactors (HWR) that were dedicated to tritium production (OK-180, OK-190, OK-190M and *Lyudmila*).[39] A light-water tritium-production reactor, known as *Ruslan*, began operations in 1980. *Ruslan* and *Lyudmila* are the only two production reactors that continue to work to this day, producing a range of isotopes and maintaining the capability to produce tritium.

The Siberian Chemical Combine in Seversk built five graphite-moderated plutonium production reactors during 1955–65 (I-1, EI-1, ADE-3, ADE-4, and ADE-5). The first three were shut down in 1990. The last two operated until 2008 because they produced district heat and electric power in addition to plutonium.

Finally, three graphite-moderated plutonium-production reactors were built underground during 1958–64 at the Mining and Chemical Combine in

Zheleznogorsk (AD, ADE-1, and ADE-2). The first two were shut down in 1992. ADE-2 continued to operate until 2010 because it too produced district heat and electric power.

All graphite-moderated reactors, with the exception of the AI reactor at Mayak, used natural uranium as their primary fuel. They also used HEU-containing "spike" fuel elements in some of the channels, however. For example, each of the ADE reactors had in their cores about 100 HEU fuel rods that contained a total of about 80 kg of 90 percent enriched uranium.[40] These fuel rods reportedly stayed in the core for about two and a half years of normal operation, which corresponds to one ADE reactor consuming about 32 kg of 90 percent HEU per year while it produced about 500 kg of weapon-grade plutonium. Assuming that the other graphite production reactors also used HEU spike fuel starting in 1955 and that the HEU requirements stayed constant, it is estimated that plutonium production reactors together used about 9 tons of 90 percent HEU in the course of producing an estimated 145 tons of weapon-grade plutonium.[41]

The AI reactor began operating in 1952 with 2 percent enriched uranium in its core.[42] In 1958, the enrichment level was increased to about 10 percent. It was further increased to 80 percent in 1967, and finally to 90 percent in 1969.[43] The reactor's nominal thermal power was also increased from about 40 MWt to 100 MWt.[44] The reactor was shut down in 1987. Assuming that it operated with a 70 percent capacity factor, it would have used the equivalent of about 2 tons of 90 percent HEU during its lifetime.

The heavy-water tritium production reactors built by the Soviet Union also used enriched uranium fuel. The first, OK-180, which had a design power of 100 MW (later increased to about 250 MW)[45] used natural uranium fuel when it first started in 1951 but was switched to uranium with 2 percent enrichment in 1954. Its core contained 15 tons of uranium.[46] The reactor operated until 1966.[47] The OK-190, similar to OK-180, but larger, began operations in 1955 and was shut down in 1965.[48] It was then replaced by the OK-190M reactor, which operated during 1966–86.[49] In the early 1960s fuel elements were developed for the OK-180 and OK-190 that contained 80 percent enriched uranium.[50] It is estimated that these reactors used about 5.5 tons of 90 percent HEU during their cumulative 42 reactor-years of operation.[51]

To replace the OK-class HWR, which were plagued by heavy-water leaks, the Soviet Union built two new reactors: *Ruslan*, a light-water reactor that began operating in 1979; and LF-2, also known as *Lyudmila*, a HWR that began operating in 1988. Both reactors continue to operate today, producing various isotopes as well as maintaining a tritium production capability. Each reactor reportedly has a design thermal power of 1000 MWt and uses HEU fuel. Each could use about 550 kg of 90 percent HEU annually.[52] By the end of 2010, the two reactors accumulated about 52 reactor-years and therefore would have required a total of about 28.5 tons of 90 percent HEU.

Overall, production of plutonium and tritium for weapons as well as other isotopes required about 45 tons of 90 percent HEU with an estimated uncertainty of about 20 percent.

Other Removals

During 1949–90, the Soviet Union carried out 715 test detonations of 969 nuclear devices.[53] No information of the amount of HEU used in the tests is available. The amount of HEU used in the test program can be estimated, however, based on the information about the test yields. Of the 969 explosive devices, 677 yielded less than 20 kilotons (kt), 183 had yields of 20–150 kt, 78 from 150 kt to 1.5 megatons (Mt), 25 from 1.5 to 10 Mt, and 6 had yields of more than 10 Mt of chemical explosive equivalent. The tests that involved devices with yields of less than 20 kt were most likely tests of plutonium fission primaries. Tests with larger yields may have involved operational warheads. We assume rather arbitrarily that on average warheads with yield of 20–150 kt used 15 kg of HEU, and tests with yields of 150–1500kt used 25 kg of HEU. Larger tests probably used from 50 to 100 kg of HEU. Overall, we estimate that the Soviet nuclear testing program consumed about 7 tons of HEU. Uncertainty of this estimate is probably quite high, and we assume it is no better than 50 percent. However, it does not contribute significantly to the accuracy of the final estimate of the size of the HEU inventory.

The most important reduction in the size of Russia's HEU inventory has been as a result of the 1993 agreement between Russia and the United States, sometimes known as the "Megatons to Megawatts" deal. Under this agreement, Russia agreed to down-blend 500 tons of weapon-origin HEU with an average enrichment of 90 percent and sell the resulting LEU material to the United States to be used in power reactor fuel.[54] The first shipment of LEU from Russia to the United States took place in 1996 and, as of September 2010, Russia had blended down 400 tons of weapon-grade HEU.[55] The 500 tons of HEU will have been blended down in 2013 and it is unlikely that the deal will be extended beyond that.

The Material Conversion and Consolidation (MCC) program, which is run by the U.S. National Nuclear Security Administration, eliminates excess non-weapons HEU from various Russian facilities by buying it and having it down-blended to LEU at agreed Russian facilities. The goal of the program is to eliminate 17 tons of HEU by the end of fiscal year 2015. At the end of 2009, the program had down-blended 12.6 tons of HEU.[56]

As was mentioned in the discussion of production of LEU for power reactors, during 1981–91 the Soviet Union blended down reprocessed uranium from the RT-1 reprocessing plant to produce fuel for RBMK reactors. This process consumed, in addition, an estimated 1.8 tons of fresh 90 percent HEU.[57]

Russia's HEU Inventory

As estimated above, by the time the Soviet Union stopped production of highly enriched uranium for weapons, its enrichment plants had produced about 400 million SWU. Of this amount, about 67 million SWU was used to produce LEU for fuel power reactors in the Soviet Union, Eastern Europe, and Finland, and a further 40 million SWU were used to enrich LEU for Western Europe. Production of naval-reactor fuel used about 28.5 million SWU and 0.5 million SWU went into production of medium-enriched fuel for research reactors. Thus, the separative work capacity available for producing weapon-grade uranium would have been about 264 million SWU.[58]

Assuming that the Soviet Union produced its weapon-grade HEU from uranium recovered from plutonium production with a uranium-235 concentration of 0.667 percent, 264 million SWU would produce about 1250 tons of 90 percent HEU from about 280,000 tons of reprocessed uranium.[59] The actual amount of HEU produced was somewhat larger, since we assume that the HEU of medium and high enrichment for naval reactors was produced before the end of HEU production. For example, naval reactors used more than 130 tons of uranium-235 in HEU of different enrichment levels (this required about 28.5 million SWU which have been accounted for in the SWU balance).[60]

Uncertainty of this estimate is dominated by the uncertainty in the amount of separative work available for HEU production and, to a smaller extent, the uncertainty in the estimate of the average tails assay used in production of enriched uranium. Assuming that the accuracy of the cumulative SWU production is 5 percent or ±20 million SWU and taking into account uncertainties in the amount of separative used for non-weapon related enrichment, the amount of SWU used to produce HEU is 264 ± 22 million SWU, which translates into ±110 tons accuracy of the HEU amount. The assumed 5 percent uncertainty in the average tails assay corresponds to the accuracy of ±40 tons of HEU. Assuming that these two values are statistically independent, the uncertainty in the amount of produced HEU is about ±120 tons.

Of the total of 1250 tons of HEU produced by the end of 1988, 500 tons have been set aside for down-blending as part of the HEU-LEU deal (400 tons had been blended down as of September 2009). In addition, 12.6 tons of HEU had been blended down by the MCC program. Plutonium and tritium production reactors have consumed about 45 tons of HEU. About 1.8 tons of HEU were spent in the RBMK reactor fuel production process during 1981–91. It is estimated that nuclear tests required about 7 tons of HEU. In the United States, the "normal operating losses" were determined to be 4.9 tons ofuranium-235.[61] Given that the Soviet Union produced almost twice as much HEU as the United States, its operating losses are estimated to be 10 tons of HEU. These removals are summarized in Table 3.

Table 3: Estimate of Russia's HEU stock.

Production	HEU in tons (amount remaining to be down-blended)
Produced as HEU (minus naval fuel and MEU fuel for research and fast-neutron reactors)	1,250
Removals	
Down-blended by HEU Deal (remaining, September 2010)	400 (+100)
Pu and tritium production reactors	45
Down-blended by MCC program	12.6 (+4.4)
Research reactors	12.3
Nuclear tests	7
RT-1 plant	1.8
Losses to waste	10
Total removals	489 (+104.4)
Total as of September 2010 (rounded)	760 (−104.4)

Combining these numbers, as of September 2010, Russia could have about 760 tons of HEU. This includes 104.4 tons that are committed to down-blending programs. While accuracy of estimates of some removals is relatively poor, it does not significantly affect the uncertainty of the final number. The overall uncertainty is taken to be ±120 tons or about 15 percent.

APPENDIX A. HISTORY OF SOVIET/RUSSIAN ENRICHMENT CAPACITY

Russia's four enrichment plants are the:

- Urals Electrochemical Combine (UEKhK) in Novouralsk (57.2744 N, 60.1071 E, designated as Sverdlovsk-44 during the Soviet period)
- Isotope Separation Plant at the Siberian Chemical Combine in Seversk (56.6188 N, 84.8636 E, Tomsk-7)
- Electrochemical Plant in Zelenogorsk (56.1139 N, 94.5008 E, Krasnoyarsk-45)
- Electrolyzing Chemical Combine in Angarsk (52.4655 N, 103.8751 E).

The operating history of these facilities is described briefly below.

The Urals Electrochemical Combine at Novouralsk (Sverdlovsk-44)

The first gaseous diffusion isotope separation plant, D-1 in Sverdlovsk-44, became operational in November 1949.[62] Initially, the plant was able to produce about 0.178 kg of 75 percent enriched HEU per day.[63] Uranium had to be enriched to weapon-grade (90 percent) at the SU-20 electromagnetic isotope separation facility at the Electrokhimpribor plant in Sverdlovsk-45 (currently Lesnoy). By the end of 1952, however, after modernization of the existing machines and installation of new ones, the D-1 plant was able to produce "tens of kilograms of HEU annually."[64] These numbers are consistent with an initial capacity of about 0.01 million SWU/year.

A second enrichment facility, D-3, equipped with more advanced machines began producing 90 percent HEU sometime between 1952–53, increasing the combined separative capacity of the Urals Electrochemical Combine six-fold. This suggests that the D-3 facility had a capacity of 0.05 million SWU/year.[65] The D-4 and the SU-3 intermediate-enrichment plants began operations in 1954 and 1955 respectively, with the capacity of each plant estimated to have been 0.1 million SWU/year.

The last gaseous diffusion facility at the Novouralsk, D-5, was brought into operation in several stages during 1955–57 using next-generation machines. After it reached full capacity, the total output of the Novouralsk combine was described as 100 times larger than that of the D-1 facility in 1950.[66] (The D-1 plant was dismantled when the first stages of D-5 began operation.) Taking into account data on the productivity of the diffusion machines, it is estimated that D-5 had a capacity of 0.65 million SWU/yr.[67] This means that the combined production capacity of the D-3, SU-3, D-4, and D-5 UEKhK diffusion plants reached 0.9 million SWU/y at the end of 1957.

During 1958–62, the gaseous-diffusion facilities at Sverslovsk-44 underwent upgrades.[68] The modernization program was said to have doubled the separation capacity of Sverdlovsk-44, i.e., to about 1.8 million SWU/yr in 1962.[69] The D-3, D-4, and SU-3 facilities were shut down and dismantled in 1966–67. During 1970–87, the D-5 plant underwent further modernization.[70]

In the meantime, a pilot centrifuge facility was installed in the former D-1 plant and began operation in 1957 with about 2,400 second-generation centrifuges.[71] The plant's enrichment capacity was reported to be 0.0015 million SWU/yr, which is consistent with estimates of the separative capacity of Soviet 2nd-generation centrifuges.[72] The success of the pilot plant led to a decision to build a full-scale facility in Novouralsk. The new facility, Plant 53 (GTZ-1), apparently using 3rd-generation centrifuges, was brought on-line in three phases during 1964–66 and increased the overall capacity in Novouralsk by about 40 percent.[73] This means that the new plant had a capacity of about 0.72 million SWU/y.[74]

In 1967, the Urals Combine began to replace its diffusion cascades with centrifuge cascades.[75] Fifth-generation centrifuges were installed in the buildings of the D-4 diffusion plant and D-1 pilot centrifuge plant with floor areas of about 60,000m^2 each.[76] This resulted in an increase in the estimated capacity of the plants, to more than 2 million SWU/yr. In 1971, with two additional centrifuge plants in operation in new buildings (Plants 24 and 45), the total capacity of the centrifuges at Sverdlovsk-44 reached 4.88 million SWU/yr. Another 1.3 million SWU/yr was still provided by the D-5 diffusion plant, the last diffusion plant in Sverdlovsk-44.

Dismantlement of D-5 began in 1973, when the Combine began the next wave of expansion of its centrifuge capacity. At this stage, the centrifuges in Plant 53 were replaced with fifth-generation machines. New centrifuges were also deployed in the D-5 plant (now known as Plant 54). The D-5 buildings were also used to host the Chelnok facility, which was built in 1973 to allow the Combine to export enrichment services. Assuming that the centrifuges deployed at this stage were similar to the ones installed at the Plants 24 and 45 by 1979, when the modernization was completed, the total enrichment capacity of the Urals Electrochemical Combine had reached 9.5 million SWU/yr.

The next wave of modernization, which involved installation of centrifuges of the sixth generation, began around 1984.[77] By 1993, when this process was completed, the full capacity of the Novouralsk plant was about 11.9 million SWU/y.

The Siberian Chemical Combine at Seversk (Tomsk-7)

The Tomsk-7 Isotope Separation Plant (ZRI) began operation in July 1953 and reached full capacity in 1961, when all of its six buildings became operational.[78] An estimate based on the data about historical growth of separative capacity in Seversk suggests that at that point the total separative capacity of the Isotope Separation Plant had reached about 1.3 million SWU/yr.[79] The plant operated in this configuration until 1973, when Tomsk-7 began the process of replacing its gaseous diffusion facilities with gas centrifuges. Conversion of the first two buildings was probably completed by 1976 and the third by 1982. At that point the plant had a capacity of about 3.5 million SWU/yr, most of which was provided by centrifuges. Diffusion machines in the last two buildings at ZRI were dismantled by 1993. By that time fifth-generation centrifuges in one of the buildings had been replaced by sixth-generation machines bringing the total capacity of the plant to about 3.4 million SWU/yr.

Electrochemical Plant at Zelenogorsk (Krasnoyarsk-45)

The Krasnoyarsk-45 plant began producing enriched uranium in October 1962.[80] The gaseous-diffusion equipment was deployed in three buildings (902, 903, and 904). Assuming that the machines installed in Krasnoyarsk-45 were similar to those deployed at the time in Sverdlovsk-44 and Tomsk-7, each building provided about 0.65 million SWU/yr and the plant provided about 1.95 million SWU/yr of separative capacity when they became fully operational in 1970.

Deployment of centrifuges at Zelenogorsk began shortly after the first diffusion facility went into operation. The first centrifuges, installed in building 901 (formally known as the "chemical purification plant") began operating in June 1964. The plant reached its original design capacity in 1970.[81] The centrifuges deployed at the facility were most likely fourth-generation machines, which would mean that the plant had a capacity of about 1 million SWU/yr, bringing the total capacity of the plant to 3 million SWU/yr.[82]

In 1976, Krasyoyarsk-45 began to replace its gaseous-diffusion capacity and the old centrifuges in building 901 with fifth-generation centrifuges. The first of the gaseous-diffusion buildings had been converted to centrifuges by 1979 and the second one by 1983. This brought the total capacity of the plant to about 6.2 million SWU/yr in 1983. Gaseous-diffusion machines in building 902 remained in operation until 1990, when it was converted to activities not related to enrichment. In 1988, the Zelenogorsk plant apparently began to transition to sixth-generation centrifuges and the total capacity of the plant reached 7 million SWU/yr in 1993.

Electrolyze Chemical Combine at Angarsk

This plant produced its first enriched uranium in October 1957 and installation of equipment in the four buildings of the plant was completed in 1963. Assuming that the gaseous diffusion machines at Angarsk were similar to those deployed in Novouralsk and Seversk in 1963, the plant could have had a capacity of about 1.3 million SWU/yr. This capacity had almost doubled by 1970 after the older machines installed in the first two buildings were replaced by new or upgraded ones. It is estimated that the plant had a capacity of about 2.6 million SWU/y until about 1982, when some of the diffusion machines began to be dismantled. The Angarsk plant was the last one to be converted to centrifuges, apparently because of concerns about operating centrifuges in a seismically active area. The problem of developing centrifuges that can withstand seismic events was solved in the late 1980s and installation began in 1990. By 1993 all the gaseous diffusion capacity had been taken out of service. At that point the plant provided about 2 million SWU of separative capacity and continued to increase it by installing additional new centrifuges.

NOTES AND REFERENCES

1. V. F. Petrovsky, Deputy head of the USSR Delegation to the 44th UN General Assembly, in "Statement on the Item Entitled 'Report of the International Atomic Energy Agency,'" 25 October 1989. Quoted in Thomas B. Cochran, Robert S. Norris, and Oleg A. Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin*, (Westview Press, Boulder, 1995), p. 52.

2. Production of this HEU is accounted in the separative work capacity that was available for HEU production.

3. The exact tails assays are unknown. Enrichment tails have been reported to contain from 0.2 percent or 0.24 percent to 0.36 percent uranium-235, Oleg Bukharin, "Russia's Gaseous Centrifuge Technology and Uranium Enrichment Complex," Program on Science and Global Security, Princeton University, January 2004, p. 29. It is likely that some gaseous diffusion cascades operated with higher than 0.3 percent tails assays and some centrifuge cascades with lower than 0.25 percent.

4. Reactor data are from the IAEA Power Reactors Information System (PRIS), <http://www.iaea.org/programmes/a2>.

5. Each VVER-440 contained in its core 42 tons of uranium enriched to 3.5 percent in uranium-235. By the end of 1989, the 36 reactors of this class had accumulated 336 full reactor-years of operation. Assuming that annual refueling replaced one third of the core, the total amount of uranium consumed by VVER-440 reactors was equivalent to 148 full cores (6,200 tons). Producing this amount of LEU would have required 29 million SWUs. Refueling frequency from Mashinostroitelny Zavod Elemash, "VVER-440 Nuclear Fuel," <http://www.elemash.ru/en/production/Products/NFCP/VVER440>.

6. Each VVER-1000 core contained 71 tons of uranium enriched to 4.4 percent. This reactor operated on a cycle in which one fourth of its core was replaced annually. The 17 reactors of this class that were producing electricity as of 1989 required the equivalent of 31 full cores or 2200 tons of LEU for their operations through the end of 1989. Production of this LEU required 14.2 million SWU. Data on refueling are from"VVER-1000 Nuclear Fuel," <http://www.elemash.ru/en/production/Products/NFCP/VVER1000>.

7. Since RBMKs are capable of refueling without shutting down, their LEU requirements are estimated based on fuel burnup. By the end of 1989, 18 RMBK reactors had generated about 860,000 gigawatt-hours of electric energy, which, assuming a heat to electricity conversion efficiency of 30 percent, corresponds to 120,000 GWt-days of thermal power. Assuming that the reactors operated at design fuel burnup of 22.2 MWt days of fission heat generated per kg of uranium, RBMK reactors required 5,500 tons of LEU. Burnup data from D. J. Bradley and David R. Payson, *Behind the Nuclear Curtain: Radioactive Waste Management in the Former Soviet Union* (Columbus, OH: Battelle Press, 1997), p. 93.

8. The amount of 2 percent enriched uranium produced by blend-down of HEU from reprocessed breeder, naval and research-reactor fuel has been estimated to be 1900 tons. Oleg Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science & Global Security* 6 (1996): 64–65. This process also consumed about 1.8 tons of fresh 90 percent HEU, which will be accounted for later. Producing the remaining 3600 tons of LEU required by the RBMKs through 1989 would have used about 6.6 million SWU.

9. By 1989, the EGP-6 reactors had used about 60 tons of fuel, which would require about 0.2 million SWU to produce. Based on data in V. I. Kalinkin et al., "Khranenie Otrabotavshego Yadernogo Topliva Energeticheskikh Reaktorov (Storage of Spent Nuclear Fuel of Power Reactors)," (Preprint VNIPIET, St.-Petersburg, 2009), p. 13.

10. The active zone of the first BN-350 core contained about 210 fuel assemblies with two different initial enrichment levels: 17 percent and 26 percent. The total mass of uranium in the core was 6.4 tons, originally containing 1.3 tons of uranium-235. In 1976 the core was modified to contain fuel elements with three enrichment levels: 17 percent, 21 percent, and 26 percent.The modification increased the mass of uranium-235 to 1.43 tons, N. V. Gorin, Ya. Z. Kandiev, and Yu. I. Chernukhin, "Validation of Nuclear and Radiation Safety of a Container for Spent AMB Reactor Fuel Assemblies at the Beloyarskaya Nuclear Power Plant," *Atomic Energy* 100 (2006): 6, 396.

11. The BN-350 is estimated to have required 4.5 million SWU to produce its fuel, assuming that the average fuel burnup was 50,000 MWd/ton and the lifetime average

thermal power of the reactor was 580 MWt. It is estimated that the BN-350 used two full "old-type" cores during its first three years of operation and about 14 new-type cores before the end of 1998, when the reactor was finally shut down. The BN-350 would have required about 32 tons of uranium with 17 percent enrichment, 17 tons of 21 percent enriched uranium, and 50 tons of 26 percent enriched uranium. I. I. Vasilyev et al., "Narabotka radionuklidov v Aktivnoi Zone Reaktora BN-350," (presentation at Kazatomexpo 2010, MAEK Kazatomprom, Aktau, 2010). This assumes that all enriched uranium used to manufacture new BN-350 fuel was produced before 1988.

12. The BN-600 is estimated to have required 8.1 million SWU to produce its fuel. The initial BN-600 reactor core contained 8.26 tons of enriched uranium in 369 fuel assemblies with enrichments of 21 percent and 33 percent. The reactor went critical in 1981 and operated with its original fuel configuration until 1987. During that time, it was refueled at least six times, i.e., used seven full cores or 58 tons of enriched uranium. Of these, 33 tons contained uranium enriched to 21 percent and 25 tons to 33 percent, corresponding to a total requirement of 3.2 million SWU. In 1987, the size of the core was increased to 11.63 tons uranium with three different enrichment levels: 17 percent; 21 percent; and 26 percent. This modification significantly reduced fuel failures and the reactor operated without unscheduled refueling. During 1987–90 it operated at average fuel burnup of 45,000 MWd/ton, and after that with burnup of 60,000 MWd/ton. This means that the BN-600 operations after 1987 required about 185 tons of enriched uranium fuel through the end of 2009: 68, 47 and 70 tons were uranium with enrichment levels of 17 percent, 21 percent, and 26 percent respectively. It is assumed that this material was produced before 1989 and required 8.1 million SWU, bringing the total SWU requirement for BN-600 fuel to 11.3 million SWU. The data on BN-600 is from Yu. K. Buksha et al. "Operation Experience of the BN-600 Fast Reactor," *Nuclear Engineering and Design* 173 (1997): 67–79. Estimates of the fuel consumption are in agreement with information on the amount of spent fuel of BN-350 and BN-600 reactors reprocessed at Mayak. By 2002, Mayak had reprocessed 250 tons of spent fuel from these reactors, Vladimir Korotkevich, Evgeny Kudryavtsev, "Tekhnologia i Bezopasnost obrashcheniya s obluchennym yadernym toplivom v Rossiiskoi Federatsii (Technology and Safety of Handling of Irradiated Nuclear Fuel in Russian Federation)," *Bulletenpo atomnoy energii, TsNIIAtominform*, No. 12, (2002), 26.

13. Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *op. cit.*, p. 68.

14. This does not include three OK-150 reactors on the nuclear-powered icebreaker *Lenin*.

15. Reistad, Ole, Mærli, Bremer, and Bøhmer, "Russian Naval Nuclear Fuel and Reactors, "*Nonproliferation Review* 12(2005): 1, 173; V. A. Lebedev, "Yadernaya energetika i atomny podvodny flot (Nuclear Power Industry and Nuclear Submarine Fleet)," ProAtom.ru, 18 May 2009, gives the numbers 6, 7.5, and 21 percent for enrichment of uranium in fuel of first-generation reactors. See also International Atomic Energy Agency, "Predicted Radionuclide Release from Marine Reactors Dumped in the Kara Sea," IAEA-TECDOC-938, (April 1997), p. 21. For the purposes of this estimate, the average enrichment in the first-generation reactor fuel is assumed to be 20 percent, so that each core would have contained about 50 kg of uranium-235.

16. P. M. Rubtsov and P. A. Ruzhanskii, "Estimate of the Radiation Characteristics of Spent Fuel from Submarine and 'Lenin' Icebreaker Reactors Scuttled in the Region of the Archipelago Novaya Zemlya," *Atomic Energy* 81 (1996): 3, 657.

17. V. M. Kuznetsov, "Energeticheskie bloki atomnogo podvodnogo flota (Power reactors of the nuclear submarine fleet)," 24 January 2007, <http://www.proatom.ru>.

18. Ole Reistad and Povl L. Ølgaard, "Russian Nuclear Power Plants for Marine Applications," Nordic Nuclear Safety Research (NKS) Report, NKS-138 (April 2006), p. 33,

35. It is assumed that each core contained 600 kg of 20 percent enriched uranium or 120 kg of uranium-235.

19. A. Vyrsky, V. *Ulyanov, Istoriya podvodnogo flota Rossii* (History of the Russian Submarine Fleet), Moscow, 2002.

20. For the data on the annual number of Russian submarine patrols, see Hans Kristensen, “Russian Strategic Submarine Patrols Rebound,” Federation of American Scientists Strategic Security Blog, 17 February 2009, <http://www.fas.org/blog/ssp/2009/02/russia.php>.

21. Kuznetsov, *op. cit.*

22. Ole Reistad and Povl L. Ølgaard, *op. cit.*, p. 36.

23. V.A. Vinokurov, “Perezaryadk akorabelnykh reaktorov (Refueling of ship reactors),” 10 September 2009, <http://www.proatom.ru>.

24. Ole Reistad and Povl L. Ølgaard, *op. cit.*, p. 40.

25. Thomas Nilsen, Igor Kudrik, and AlexandrNikitin, “The Russian Northern Fleet,”*Bellona Report,* No. 2: (August 1996), p. 96.

26. The Soviet Union also constructed eight small nuclear-powered submarines and special-purpose underwater ships. These are small underwater ships of the Project 1851 (3 ships), Project 1910 (3), and Project 10831 (1) classes, and a submarine of the Project 651E class. The amount of uranium-235 used in these ships reactors is assumed to be small compared to the uncertainty of the overall estimate.

27. The service ship of the Project 1941 class was decommissioned almost immediately after it entered service, so its reactors were not refueled. The two lead cruisers of the Project 1144 class, completed in 1981 and 1985, were removed from service in 1999. They may therefore have had their reactors refueled in the late 1980s. The third ship of this class, *Admiral Nakhimov*, was completed in 1989 and decommissioned in 1999, most likely with its original reactor cores. Construction of the fourth Project 1941 cruiser, *Piotr Velikiy*, was completed in 1998.

28. The initial core of each OK-150 reactor has been estimated to contain 85 kg of uranium-235 in 5 percent enriched uranium. Ole Reistad and Povl L. Ølgaard, *op. cit.*, p. 18. After refueling, the amount of uranium in one of the reactors was increased so that the three reactors together contained 279 kg of uranium-235 in 5 percent enriched uranium. “Predicted Radionuclide Release from Marine Reactors Dumped in the Kara Sea,” *op. cit.*, p. 21.

29. N.N. Melnikov et al., “Long-term Safe Storage of Spent Nuclear Fuel from Ship Power Units in Underground Storage Facility in the North-west Region of Russia,” in Ashot Arakelovich Sarkisov, Alain Tournyol Du Clos, eds., *Scientific and Technical Issues in the Management of Spent Fuel of Decommissioned Nuclear Submarines* (Dordrecht: Springer, 2006), p. 285.

30. N.N. Melnikov et al., *op. cit.,* p. 278.

31. The refueling history of the OK-900 reactors has been reported for the period before 2000. During 1970–99, icebreakers with these reactors received 33 new reactor cores in addition to 12 initial cores. Four icebreakers continued operating after 1999, with one, *Arktika*, decommissioned in 2008 and one, *50 Let Pobedy* entering service in 2007. Assuming the same refueling rate, we can estimate that operations of the icebreaker fleet in 2000–2010 required about 25 new reactor cores. Ole Reistad and Povl L. Ølgaard, “Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications,” Nordic Nuclear Safety Research (NKS) Report, NKS-139 (April 2006), 26.

32. Ole Reistad and Povl L. Ølgaard, "Russian Nuclear Power Plants for Marine Applications," *op. cit.*, p 23.

33. "Ole Reistad and Povl L. Ølgaard, "Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications," *op. cit.*, p. 26.

34. The Soviet Union apparently used some of the HEU recovered from the spent fuel of plutonium and tritium production reactors to manufacture naval fuel, see Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *op. cit.,* p. 69. Assuming that this was the practice during 1981–91, the Soviet Union would have recovered about 7 tons of reprocessed HEU from 17 tons of fresh HEU that had been used in production-reactor fuel by the end of the 1980s. There is almost no information about the scope of this program, but since there are some disadvantages of using high burn-up reprocessed uranium as a fuel, this practice was probably rather limited and, for the purposes of this estimate, the SWU savings that resulted are not taken into account.

35. Pavel Podvig and Susan S. Voss, "Use of Highly-enriched Uranium in Russian Reactors," (Proceedings of the 50th Annual Meeting of the Institute for Nuclear Material Management, 12–16 July 2009), Pavel Podvig, "Consolidating Fissile Materials in Russia's Nuclear Complex," Research Report 7, International Panel on Fissile Materials, May 2009.

36. Ole Reistad, and Styrkaar Hustveit, "HEU Fuel Cycle Inventories and Progress on Global Minimization," *The Nonproliferation Review* 15, (2008): 2, 265–287.

37. Based on data in Reistad and Hustveit, *op. cit.*

38. Reistad and Hustveit, *op. cit.*, p. 268. Also, according to Rosatom data, in 2002, the Obninsk institute stored 14.4 tons of spent research reactor fuel containing 12.8 tons of uranium-235 (see Korotkevich and Kudryavtsev, *op. cit.*, p. 25). Most of this material appears to be HEU from various decommissioned critical assemblies and therefore can be considered part of the HEU stock. This number most likely includes the 3.5 tons of HEU in BFS-1 and BFS-2 critical assemblies mentioned in the text. The only reactor that exposed HEU fuel to significant burn-up was BR-10 fast reactor. This reactor consumed an estimated 1.5 tons of 90 percent HEU.

39. During 1951–53, OK-180 produced plutonium.

40. D. F. Newman, C. J. Gesh, E. F. Love, and S. L. Harms, "Summary of Near-Term Options for Russian Plutonium Production Reactors,"PNL-9982 (UC-520), Pacific Northwest Laboratory, Richland, WA, July 1994.

41. The total amount of weapon-grade plutonium produced in the Soviet Union and Russia is estimated to be 145 tons, of which 1235 kg had been produced before 1955, see Diakov, "The History of Plutonium Production in Russia," in this issue.

42. V. F. Konovalov et al., "Development of Uranium and Lithium Elements for Production of Plutonium and Tritium," in A. M. Petrosyants, ed., *Russia's Nuclear Industry* (Moscow: Energoatomizdat, 1999).

43. AID-80 and AID-90 uranium-oxide fuel elements respectively. The reactor may have also used AID-21 fuel elements with 21 percent enrichment, which were developed around the same time. Konovalov et al., *op. cit.*

44. I. N. Beckman, *Radiokhimiya*, Moscow, 2006.

45. V. I. Sadovnikov and A. P. Zharov, *Istoriya atomnoy promyshlennosti SSSR* (*History of the Nuclear Industry of the USSR*), Ozersk, 2000.

46. B. L. Ioffe, O. V. Shvedov, "Heavy Water Reactors and Nuclear Power Plants in the USSR and Russia: Past, Present, and Future," *Atomic Energy* 86 (1999): 4, 297.

47. The reactor was also used to produce plutonium in 1951–53, Diakov, "The History of Plutonium Production in Russia," in this issue.

48. G.V. Kiselev, V.N. Konev, "History of the Realization of the Thorium Regime in the Soviet Atomic Project," *Uspekhi FizicheskikhNauk*, 177 (2007): 12, 1361–1384.

49. V. I. Sadovnikov and A. P. Zharov, *op. cit*.

50. Ye. N. Sokolov et al., "The 50-Year History of the Central Machine-Building Design Bureau," in A. M. Petrosyants, ed., *Russia's Nuclear Industry* (Moscow: Energoatomizdat, 1999).

51. This assumes that the reactors operated at a uranium-235 burn-up of about 60 percent and a capacity factor of about 70 percent.

52. This assumes that the reactors operated at uranium-235 burn-up of 60 percent and with a capacity factor of 70 percent. This is in agreement with the data on reprocessing of fuel of the Ruslan and Lyudmila reactors at the RT-1 facility at Ozersk. By 2002, the RT-1 had plant reprocessed 20 MTHM of HEU fuel of these reactors. Vladimir Korotkevich, EvgenyKudryavtsev, *op. cit.,* p. 26.

53. Pavel Podvig, ed., Russian Strategic Nuclear Forces, (Cambridge: MIT Press, 2001), p. 480.

54. Oleg Bukharin, "Understanding Russia's Uranium Enrichment Complex," *Science & Global Security* 12 (2004): 202–204.

55. "Material for 16,000 Nuclear Warheads Eliminated by Megatons to Megawatts," US Enrichment Company press release, 9 September 2010.

56. U.S. Department of Energy, "FY 2011 Congressional Budget Request: National Nuclear Security Administration*,"* DOE/CF-0047*,*February 2010, p. 377.

57. Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *op. cit*., pp. 64–65.

58. Earlier estimates also accounted for production losses that were taken to be about 3 percent of the total separative capacity. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (New York: Oxford University Press, 1997), p. 112. We do not take this into account here, since the actual production capacity is not known with this level of accuracy.

59. This estimate is consistent with the statement made by Viktor Mikhailov, then Minister of Atomic Energy, in 1993. Commenting on the U.S.-Russian HEU-LEU deal, Mikhailov said that "The 500 metric tons of HEU that is up for sale represents somewhere around 40 percent of all reserves that we [Russia] possess." (*NUKEM Market Report*, 17 September 1993). This suggests that the Soviet Union had about 1250 tons of HEU at the time. Detailed comparison of these estimates is difficult since it is not known what was included in the number given by Mikhailov. This number probably would not include HEU produced for naval fuel and fuel of some research and fast reactors, which also is not accounted for in our estimate. Mikhailov's number, however, would also not include HEU consumed in production reactors, nuclear tests, and losses, while our estimate does include these amounts. Our estimate is also consistent with the data on the amount of reprocessed uranium available for enrichment. By the end of 1988 the Soviet Union had produced about 115 tons of plutonium, which required about 280,000 tons of natural uranium fuel at 420 grams of plutonium produced per ton of uranium irradiated (Diakov, "The History of Plutonium Production in Russia," in this issue). On using reprocessed uranium to produce weapon-grade HEU see Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia,"*op. cit.*, p. 63.

60. The Soviet Union and Russia reprocessed most of the spent fuel of naval reactors. We estimate that unreprocessed naval fuel contains about 10 tonnes of HEU (90 percent equivalent).

61. Highly Enriched Uranium: Striking a Balance; A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996, Rev. 1, Draft, U.S. Department of Energy, January 2001 (publicly released in 2006), p. 92.

62. The first machines installed at D-1 were OK-7, OK-8, OK-9, and later OK-6, A. K. Kruglov, *Kak sozdavalas atomnaya promyshlennost v SSSR (This is How the Nuclear Industry of the USSR was Created)*, TsNIIAtominform, Moscow, 1995, p. 183.

63. Yu. V. Yegorov et al., *Ostanovitsya, Oglyanutsya (To Take a Pause and Look Back)*, Ekaterinburg, UMTs UPI, 2009, p. 10.

64. OK-6 machines were added to the upper cascade. Yegorov et al., *op. cit.,* Kruglov, *op. cit.,* p. 187.

65. D-3 was equipped with T-45, T-46, T-47, and T-49 machines, Yu. L. Golin et al., “Urals Electrochemical Combine (UEKhK), in A. M. Petrosyants, ed., *Russia’s Nuclear Industry*, Moscow, Energoatomizdat, 1999.

66. The D-5 plant was equipped with OK-26 and T-51 machines, Golin et al., *op. cit.*

67. For data on productivity of diffusion machines, see Kruglov, *op. cit.* p. 191.

68. Golin et al., *op. cit.*

69. On doubling of productivity of the UEKhK, see Golin et al. *op. cit.*

70. Golin et al., *op. cit.*

71. Viktor Myasnikov, *Oruzhie Urala*, Ekaterinburg, Pakrus, 2000.

72. Albright et al., *op. cit*., p. 106.

73. Yu. V. Yegorov et al., *op. cit*., p. 136.

74. This is in agreement with the information that the first plant had 700,000 centrifuges, assuming that third-generation centrifuges had a capacity of about 1 SWU/yr. For the number of centrifuges see Viktor Myasnikov, *Oruzhie Urala (The Armaments of Urals)*, Ekaterinburg, Pakrus, 2000, for the capacity of centrifuges see Albright et al., *op. cit.,* p. 106.

75. Yegorov et al., *op. cit*., p. 136.

76. The D-3 and SU-3 plants were shut down in 1967. Installation of centrifuges was completed in 1971. This is in agreement with the reports of numerous failures of fifth-generation centrifuges that the Soviet Union had to deal with in 1972. Oleg Bukharin, “Russia’s Gaseous Centrifuge Technology and Uranium Enrichment Complex,” Program on Science and Global Security, Princeton University, (January 2004), p. 11.

77. Deployment of sixth-generation centrifuges reportedly began in 1984. Bukharin, “Understanding of Russia’s Uranium Enrichment Complex,” *op. cit.*, p. 197.

78. V. M. Kondakov, “Siberian Chemical Combine,” in A. M. Petrosyants, ed., *Russia’s Nuclear Industry* (Moscow: Energoatomizdat, 1999).

79. K. Ye. Galetskaya, “Tekhnologii razdeleniya izotopov naprimere Sibirskogo khimicheskogo kombinata” (“Isotope Separation Technologies: the Example of the Siberian Chemical Combine”), Seversk, 2008.

80. Oleg Bukharin, Thomas Cochran and Robert Norris, "New Perspectives on Russia's Ten Secret Cities, Natural Resources Defense Council,"(October 1999), p. 33.

81. *Elektro-khimicheskii zavod.Istoriya (Electro-chemical combine. History),* Krasnoyarsk regional information center, Rosatom, <http://www.krasminatom.ru/enterprises/ehz/history.html>.

82. This assumes that fourth-generation centrifuges had about 40 percent higher capacity than third-generation machines. Albright et al., *op. cit.*, p. 106.