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Analysis of the Size and Quality of Uranium Inventories in Russia

Oleg Bukharin[a]

Little official information is available regarding the uranium inventories and the history of the production and use of uranium in Russia. Some estimates, however, can be made based on careful analysis of the programs for the production of fissile materials for weapons, naval propulsion, and power reactors, and on reasonable assumptions about the evolution of the Soviet/Russian enrichment complex.

INTRODUCTION

Estimation of inventories of natural and highly–enriched uranium (HEU) is essential for developing effective strategies to control fissile materials, designing international cooperative measures of transparency to deal with arms reductions, and assessing the future of nuclear power. Unfortunately, both for security and commercial reasons, many countries have kept confidential at least some critical inventory data. This is especially true in the case of Russia where official information regarding production and consumption of uranium is virtually non–existent. The analytical task of estimating Russian uranium inventories is further complicated by the complexities of Russia's nuclear fuel cycle, close integration of its defense and civilian programs, and recycle of uranium recovered from irradiated reactor fuel. For these reasons, at present, existing public data do not allow highly accurate independent estimates of the inventories of natural and enriched uranium in Russia. However, the data do allow some rough estimates of the inventories, albeit with considerable uncertainties.

PRODUCTION AND USE

Figure 1 shows the production and use of natural and highly-enriched uranium, from which one could estimate the current inventories. Uranium for the Soviet nuclear program was produced domestically and imported from East

a Research Staff Member, Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey.

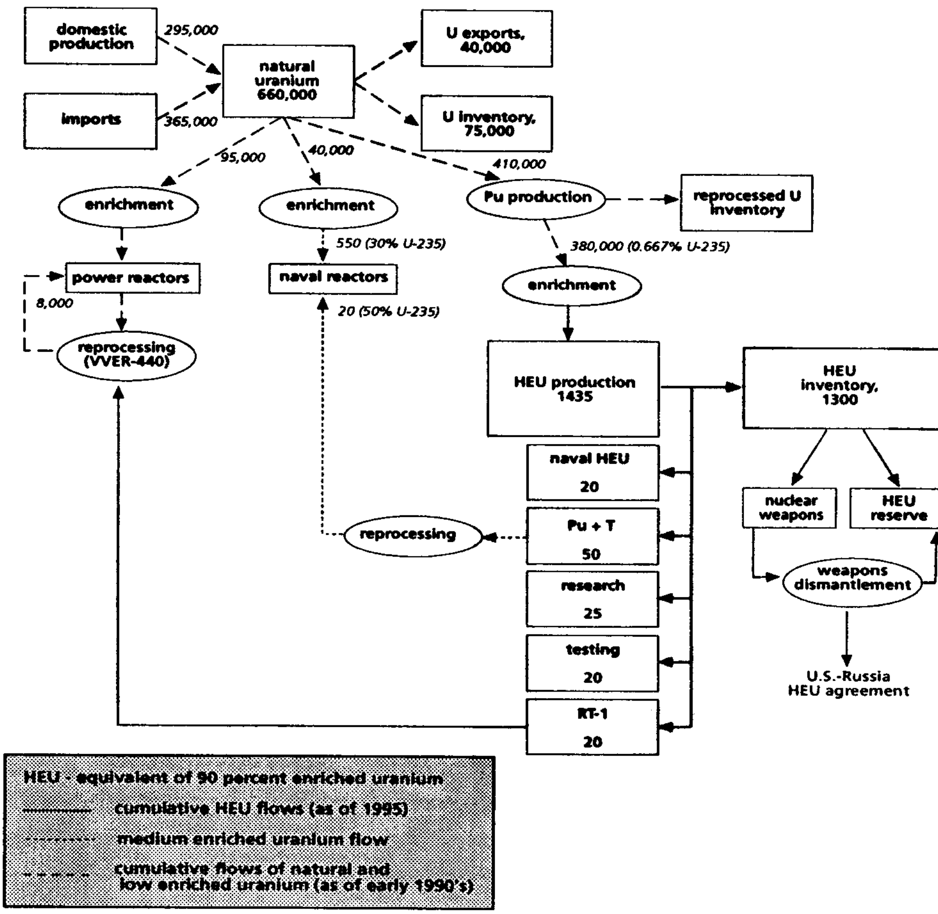

Figure 1: Production and use of natural and highly enriched uranium (metric tons).

European countries. Natural uranium was primarily used to produce plutonium for nuclear weapons, medium–enriched uranium for naval propulsion reactors, and low–enriched uranium for nuclear power reactors. Virtually all HEU was produced from uranium recovered from irradiated fuel of the plutonium production reactors. The assessment of the total production, uses and recycle of natural and uranium and HEU makes it possible to estimate the size and to evaluate the quality of Russia's uranium inventories. It also makes possible identification of major sources of uncertainties, the resolution of which would provide for improved inventory estimates.

PRODUCTION AND IMPORTS OF NATURAL URANIUM

Production of uranium in the Soviet Union began in 1945 at the Taboshar deposit in Tajikistan.[1] In the late 1940's and in the 1950's, the level of production was increased through the expansion of the Taboshar operation and development of relatively small deposits in Central Asian republics, Russia, and Estonia. Uranium mining and processing were also organized and expanded in Eastern Europe.

Shortage of uranium remained a major constraint on the Soviet nuclear program until new large uranium production centers were brought into operation in the 1960's and early 1970's. These centers—Tselynny and Kascor in Kazakhstan, Navoi in Uzbekistan, and Priargunsky in Russia—formed a backbone of the Soviet uranium complex. Significant imports continued from Czechoslovakia, East Germany, Hungary, and Bulgaria. In the 1970's and 1980's the total production amounted to perhaps 20,000 (metric) tons uranium per year or more, a significant part of it coming from Czechoslovakia and East Germany.[2]

Reductions in defense requirements in the second half of the 1980's and the stagnation of nuclear power after the Chernobyl disaster of 1986 led to drastically reduced demand for uranium, the production began to decrease shortly after 1988. By the time of the Soviet break–up in the fall of 1991, production had fallen by 40 percent compared to its peak level of the mid–1980's.[3] Subsequent disintegration of the Soviet uranium complex dramatically reduced the natural uranium base available to Russia.

How much uranium the Soviet nuclear complex had received by that time is not known. Some data suggest that the Soviet Union produced approximately 250,000 tons. According to OECD experts, as much as 340,000 tons might have been mined in the USSR before 1991.[4] We assume a cumulative Soviet production of 295,000 tons. In addition, large quantities of uranium for use by the Soviet Union were produced in Eastern Europe. Approximately 220,000 tons were produced by the Wismut complex in East Germany by the time the operation was shut down in 1990.[5] As of 1992, the cumulative uranium production in the Czech Republic was 100,590 tons and in Hungary 19,880 tons.[6] Approximately 25,000 tons were produced in Bulgaria.[7] Mining of uranium in Mongolia did not start until 1989 and the level of production has been relatively low since.[8] Thus, the total amount of natural uranium mined domestically and imported to the Soviet Union by the early 1990's can be estimated at 660,000 tons.[9]

Uranium mining and processing presently continues in Russia at the Priargunsky Mining and Chemical Combine. With the capacity of 4000 t/y, in 1993 the complex produced 2300 tons. It is expected that the production will

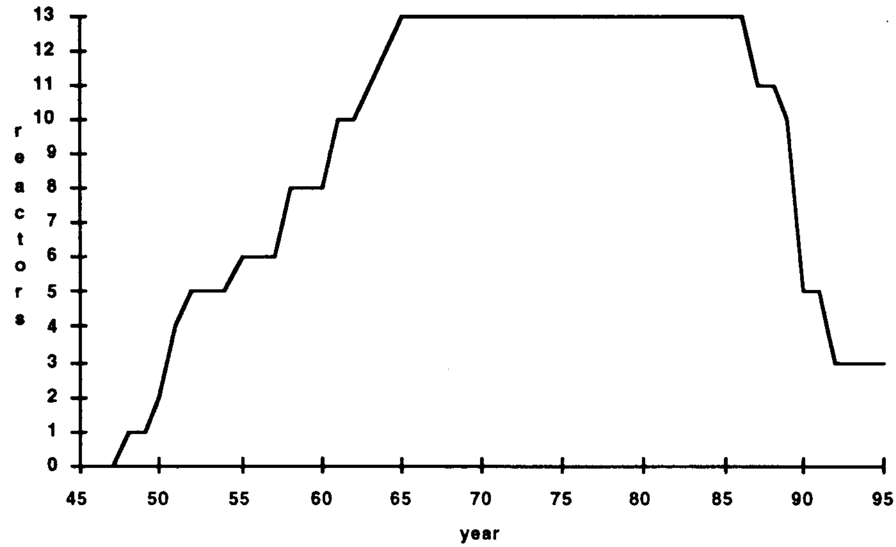

Figure 2: Russia's plutonium production reactors.

Source: T. Cochran, R.S. Norris and O. Bukharin "Making the Russian Bomb: From Stalin to Yeltsin," Westview Press, 1995.

continue to decrease.[10] The Russian government has announced that all newly produced uranium will be available for exports.

USE OF NATURAL URANIUM

Natural uranium produced in the Soviet Union and Eastern Europe was used for the production of plutonium for weapons, medium–enriched uranium for naval reactors, and low–enriched uranium for Soviet–made power reactors (see figure 1). The remains were used for the build–up of a strategic reserve of natural uranium. Since 1988, the Soviet Union/Russia also has exported natural and enriched uranium.

Production of Plutonium for Weapons

The Soviet Union/Russia produced an estimated 177 tons plutonium for weapons.[11] The first Soviet plutonium production reactor was brought into operation at the Mayak site in the Urals in 1949. By 1969, plutonium was generated in 13 reactors located at three sites and having combined capacity of 22,565 MWt (see figure 2).[12] Ten plutonium production reactors were shut down between 1987 and 1992. The remaining three reactors produce heat and electricity for the local populations and are likely to operate well beyond 2000, until alternative power sources become available.[13]

Assuming that the reactors were transferred to a closed nuclear fuel cycle in 1991, the total natural uranium requirements for the plutonium production program were approximately 410,000 tons.[14] Irradiated fuel was reprocessed, and, prior to 1989, recovered uranium was used for the production of HEU. Thus, HEU and plutonium production were interconnected.

Reprocessed uranium (approximately 99.2 percent of the original amount) contained 0.667 percent U–235 as well as reactor–produced isotopes U–232 and U–236.[15] With one percent reprocessing losses, the amount of recovered uranium available for HEU production can be estimated at approximately 380,000 tons.[16] We estimate the cumulative reprocessed uranium requirements for HEU production at 373,000 tons (see below).

Production of Enriched Uranium for Naval Reactors

An estimated 468 reactors have been installed on 258 submarines and surface ships of the Soviet/Russian Navy and the icebreaker fleet (see figure 3). Of them, 24 are believed to have been designed to use uranium enriched to 90 percent U–235 (see below). We assume that HEU for these reactors was drawn from the HEU stockpile. Most reactors, however, were fueled with uranium enriched to 21–45 percent U–235.[17] The production of this medium–enriched uranium constituted a major natural uranium and enrichment requirement.

Assuming that the reactors were designed to have three refuelings over their lifetime (approximately 30 years), approximately 1800 medium–enriched reactor cores were fabricated for the naval propulsion program. Assuming that a typical reactor core contains 315 kg uranium and that the average enrichment is 30 percent U–235, 570 tons 30–percent enriched uranium was used to produce fuel for naval reactors.[18] An estimated 20 tons uranium of medium enrichment was recovered from irradiated HEU fuel of the material production reactors (see below) and fabricated into fuel of naval reactors. The rest, 550 tons, were produced by enriching natural (and, possibly, reprocessed) uranium. We estimate the natural uranium and enrichment requirements at 40,000 tons and 33 million SWU.[19]

Production of Low–Enriched Uranium for Civil Power Reactors

Prototypes of graphite–moderated, water–cooled reactors (RBMK) and pressurized water reactors (VVER–440) were started up at the Beloyarsk and Novovoronezh nuclear power plants in 1964. The large-scale deployment of

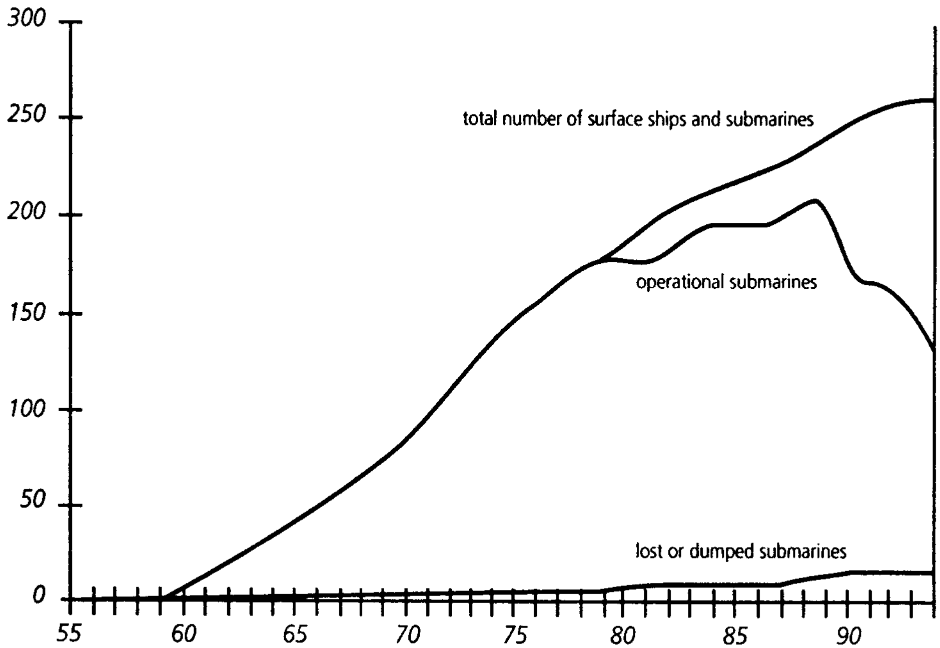

Figure 3: Soviet/Russian nuclear-powered Navy.

Source: O. Bukharin and J. Handler "Russian Nuclear-Powered Submarine Decommissioning," Science and Global Security, 1995, Volume 5, pp. 245-271.

nuclear power reactors in the Soviet Union and Eastern Europe began in the early 1970's; the rate at which power reactors were deployed peaked in the 1980's (see figure 4). The natural uranium feed and enrichment requirements through 1989 can be calculated on the basis of the annual requirements per reactor and the cumulative number of reactor–years of operation plus two years of forward requirements (see tables 1 and 2).

The calculations should be corrected for uranium and SWU savings which were realized by recycling uranium recovered from irradiated fuel of power reactors (mainly VVER–440). Reprocessing of VVER–440 fuel was started in 1978 at the RT–1 radiochemical plant in the Urals.[20] Between 1981 and 1991, reprocessed uranium was recycled in RBMK reactors.[21] (Thereafter, RT–1 recovered uranium has been used to make fuel for the plutonium production reactors.) The RT–1's throughput averaged 200 tHM/y. We assume that the uranium output, approximately 190 tons 1.25–percent enriched uranium, was blended with HEU (1.8 tons 90–percent U–235) to achieve required level of enrichment (approximately 2 percent U–235). Thus, over 10 years, the plant

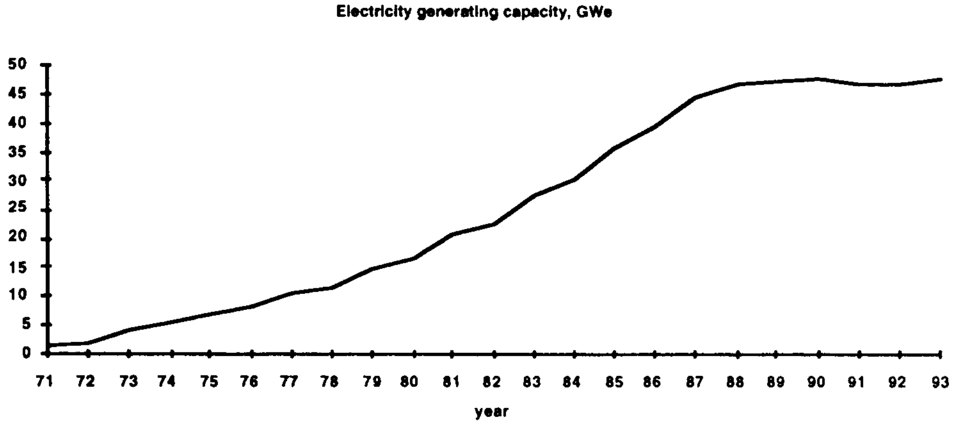

Figure 4: Electricity generation capacity of Soviet-built nuclear power reactors.

produced estimated 1,900 tons 2–percent enriched uranium, allowing savings of approximately 8,500 tons natural uranium and 3.5 million SWU. The recycle of reprocessed uranium reduced the natural uranium requirements for the nuclear power program from 103,500 to 95,000 tons (as of 1989).

Use of Uranium in the 1990's

Russia continues to have considerable uranium requirements to provide fuel for its plutonium production and power reactors. Additional amounts of uranium are used to fabricate fuel for power reactors in Lithuania, Kazakhstan, Ukraine, and East European countries. These requirements are met, in part, by recycling reprocessed uranium and by enriching uranium tails.

The three plutonium production reactors still in operation require 3,600 tons of uranium per year. The reactors discharge 3,500 tons of 0.667–percent uranium. Blending reprocessed uranium from plutonium reactors with approximately 100 tons 1.25–percent uranium recovered at the RT–1 reprocessing plant from spent fuel of VVER–440 reactors and with 1 ton of 90–percent enriched uranium would result in 3,600 tons of uranium with the same enrichment as natural uranium.[22] However, because reprocessed uranium is used on a once–through basis, only half of reprocessed uranium can be recycled in the production reactors.[23] To cover the fuel requirements of the plutonium production reactors, reprocessed uranium is likely to be blended with natural uranium.

Table 1: Cumulative natural uranium and SWU requirements (until 1989).

reactor type	reactor years plus two years of forward requirements	SWU cumulative, million	U feed cumulative, thousand tons
VVER-440	387[a]	20.9	37.8
VVER-1000	90	11.4	18.9
RBMK-1000	169[b]	15.7	37.1
BN-350/BN-600	18/10	4.27/3.6	5.4/4.5

a. Including normalized 20 and 26 reactor years of operation of VVER-210 and VVER-365 reactors.
b. Taking into account the closure of Chernobyl-4 and operation of Ignalina 1-2 at 1250 MWe.

Table 2: Uranium and SWU requirements per reactor for Soviet-designed power reactors.

reactor type	enrichment, %	amount of fuel, t/yr[54]	SWU requirements, x 10^6 SWU/y	U requirements, t/y
RBMK-1000	1.8-2.4 (av.2.1)	50	0.093	220
VVER-440	3.5	12.5	0.054	98
VVER-1000	4.4	21	0.127	210
BN-350/600	20/25	6.2/7.4	0.237/0.353	298/446

Russia's 27 commercial power reactors require an estimated 3,200 t/y of natural uranium.[24] In addition, Russia uses 1300–1400 t/y to fabricate low–enriched uranium (LEU) fuel for Soviet–built reactors in former Soviet republics and in Eastern Europe.[25] The nuclear power requirements are likely to be covered by uranium produced by enriching tails associated with the past enrichment production. The enrichment of tails was begun after the HEU production stopped in 1988, and a significant fraction of the enrichment capacity became surplus. Actual production is not known but is probably on the order of a few thousand tons of natural uranium per year and is enough to cover the nuclear power requirements.[26]

In 1988 the Soviet Union began to export natural and low–enriched uranium to the West. The exports grew sharply until 1992, when the U.S. Department of Commerce restricted imports of uranium to the U.S. from the countries of the former Soviet Union. A restrictive policy on uranium imports from the former Soviet Union to Euratom countries was also applied by the Euratom Supply Agency. Exports of uranium from Russia and other former Soviet republics, however, continued. Market analysts believe that by 1995, the total exports of uranium from the former Soviet republics amounted to 40,000 tons.[27]

PRODUCTION AND USE OF HEU

Production of HEU

The production of HEU for weapons purposes continued from 1950 to 1988.[28] A complete history of the Soviet enrichment program remains classified. However, the following milestones in the program are known:

- The production of HEU by gaseous diffusion plants began in 1950.[29]
- Industrial deployment of the centrifuge technology began in 1962.[30]
- The gaseous diffusion technology was phased out completely in 1991.[31]
- After the transition to the centrifuge technology, the combined enrichment capacity increased by a factor of 2.4 and amounted to 20 million SWU/y.[32]
- Between 1973 and 1988, the Soviet Union exported to the West 40 million SWU.[33] The exports involved production of low–enriched uranium for Western customers from foreign uranium feed.

To calculate the HEU production we make the following additional assumptions:

- The enrichment capacity grew linearly from zero in 1950 to 8.3 million SWU in 1962 and to 20 million SWU in 1991.[34]
- Reprocessed uranium was enriched from 0.667 to 90 percent U–235. (From here on, unless indicated specifically, HEU means an equivalent of 90 percent enriched uranium.) A tails assay averaged 0.36 percent U–235 between 1950 and 1962, and 0.3 percent U–235 between 1962 and 1988. (Natural uranium was used to produce fuel for power and naval reactors.)

During the gaseous diffusion period (1950 to 1962) the enrichment complex produced 49.8 million SWU, which corresponds to 270 tons HEU.

During the second period (1963 to 1988) the complex produced 365.9 million SWU. Of this, an estimated 32.7 and 52.4 million SWU were used in the naval and power reactor programs respectively; an additional 40 million SWU were exported to the West. We estimate that the remaining 240.8 million SWU were used to produce 1200 tons of HEU.

Assuming 3–percent processing losses, the cumulative HEU production between 1950 and 1988 can be estimated at 1430 tons.

Use of HEU in Weapons

Reportedly, the Soviet stockpile peaked in the early 1980's at 45,000 warheads. Given an average HEU content of 15 kg per warhead, 675 tons HEU were fabricated into weapons components.[35] Additional amounts of HEU were probably assigned to the strategic reserve.

In the late 1980's, the Soviet Union undertook a program of warhead dismantlement, and today the number of warheads is estimated at 20,000–30,000.[36] The corresponding HEU content then might be 300–450 tons. Some 200–400 tons HEU may have been recovered from weapons and put into storage at the dismantlement sites, Tomsk–7 and Chelyabinsk–65. In the fall of 1994, Russia started blending HEU to LEU under the U.S.–Russian HEU agreement. (Six tons HEU are to be blended to LEU and delivered to the U.S. in FY 1995; 12 tons are to be blended and delivered in 1996.)

Russia is expected to reduce its arsenal to 5,000 to 10,000 nuclear warheads by 2003.[37] The HEU content corresponding to a stockpile of this size would be 75 to 150 tons. Thus, approximately 500–600 tons HEU eventually might become surplus in Russia.

Use of HEU in Nuclear Material Production Reactors

In Russia, a small amount of 90–percent enriched uranium is used in both the plutonium and tritium production reactors. The plutonium production reactors use a ring of HEU rods for levelizing power distribution inside the reactor core. Reportedly, three 2000 MWt reactors consume 250 kg HEU per year.[38] On this basis we estimate the cumulative HEU use in the plutonium production reactors at 23.5 tons (as of the end of 1994).

The production of tritium has taken place at Mayak in Chelyabinsk–65 since the early 1950's.[39] The tritium production reactors have the driver–target configuration in which the HEU driver produces neutrons to irradiate target materials (lithium–6 targets for tritium production). By 1995, the tritium production reactors generated a total of 17.5 million MWday.[40] At 75 percent fuel burnup, approximately 25 tons 90–percent enriched uranium is required to produce this amount of energy.[41]

Irradiated HEU fuel from the material production reactors was reprocessed to recover enriched uranium. At a burnup of 75 percent, 1 ton of 90–percent HEU is converted to 0.42 tons uranium containing approximately 53 percent U–235 and 23 percent U–236. Thus, the material production reactors yielded approximately 20 tons of medium enriched uranium. Most of it is believed to have been fabricated into naval reactor fuel (see above). (This material would have to be diluted to reduce concentrations of U–234. Also, higher concentrations of U–235 would be needed to offset the presence of the neutron–absorbing isotope U–236.)

Other HEU Uses

Substantial quantities of HEU were used in other defense and civilian programs.

Naval Propulsion

An estimated 24 naval reactors have been fueled with HEU.[42] We assume 20 tons HEU was used to produce initial and replacement cores for these reactors.[43]

Research installations

There are currently 43 research reactors and 52 critical and 18 subcritical assemblies in Russia.[44] Several reactors were built and operated in other former Soviet republics and foreign countries. These facilities were designed to use uranium of different levels of enrichment; the amount of fuel per reactor varied from few kg to several hundred kg. We assume that 25 tons HEU was used to fuel research facilities.[45]

Nuclear testing

Reportedly, 1100 nuclear detonations have taken place in the Soviet Union between 1950 and 1989.[46] Assuming 15 kg HEU per detonation, 16.5 tons HEU was consumed in the testing program.

Dilution of reprocessed uranium

Assuming that 1.8 tons HEU per year was used between 1981 and 1991 to adjust the enrichment level of reprocessed uranium at the RT–1 plant, the total HEU requirements for this purpose amount to 18 tons.

URANIUM INVENTORIES

The Size of the Uranium Inventories

The uranium inventories in Russia are composed of natural uranium, HEU, depleted uranium, and reprocessed uranium (see table 3).

During the past few years, the production and domestic uses of natural uranium have been in relative equilibrium with each other with a small deficit compensated from the national uranium stocks. Therefore, the size of the natural uranium inventory in Russia is primarily determined by the production and use of uranium in the Soviet Union prior to its break–up in 1991 and by uranium exports to the West after 1988.

By the early 1990's, the Soviet Union had produced and imported from Eastern Europe 660,000 tons of uranium. As of the early 1990's, an estimated 450,000 tons and 95,000 tons of uranium were used in the defense and nuclear power programs. After the break–up of the Soviet Union in 1991, production and domestic use of uranium have been in equilibrium with each other. The natural uranium inventory was reduced from approximately 115,000 to 75,000 tons by exports to the West.

Between 1950 and 1989, the USSR produced 1430 tons HEU. Approximately 130 tons was used for the production of plutonium and tritium, for blending with reprocessed uranium, in research and naval reactors, and in nuclear tests. The remaining inventory is 1300 tons HEU.

The principal component of the remaining inventories is the stockpile of *depleted uranium* (in the form of UF6 and metallic uranium). An estimated 130,000 tons of uranium tailings was left after enrichment of natural uranium for nuclear power and naval reactors; and approximately 370,000 tons of tailings resulted from the enrichment of reprocessed uranium to HEU. The U–235 content of the tailings ranges from 0.18 to 0.4 percent.

There is also an inventory of *reprocessed* uranium. We estimate that approximately 30,000 tons of uranium recovered from irradiated fuel of plutonium production reactors has not been used for HEU production.[47] (The inventory might be smaller if reprocessed uranium was used in making naval fuel.) Whether and how this material has been used is not known. There might also be a relatively small inventory of 2.0–2.4 percent enriched uranium recovered from irradiated fuel of VVER–440 and naval reactors.

Quality of the Uranium Inventories

The recycle of reprocessed uranium has had a considerable impact on the quality of the Russian uranium inventories. Contamination of HEU with U–232, U–236, and transuranic elements has already delayed the implementa-

Table 3: Major uranium inventories in Russia in 1995 (tons).

HEU (equivalent of 90 percent U-235)	1,300
natural uranium	75,000
uranium tailings	
from enrichment of unirradiated uranium	130,000
from enrichment of reprocessed uranium	370,000
reprocessed uranium	<30,000

tion of the U.S.–Russia HEU agreement and further delays are possible.[48] In fact, Minatom's representative has already indicated that because of technical difficulties and in order to avoid uranium market disruptions, Russia would prefer to blend no more than 12–15 tons HEU per year, as compared to the originally planned blending rates of 10 t/y during the first five years and 30 t/y thereafter.[49]

Removal and dilution of contaminants require extensive additional processing of HEU, including a double–cycle of solvent extraction and use of 1.5–percent enriched blending stock.[50]High concentrations of the uranium isotope U–234 require use of a blending material derived from U–234 depleted tailings.[51] It took Russian facilities more than a year to develop an industrial infrastructure for these purposes.[52] This processing has increased operational costs and reduced net profits.

The use of reprocessed uranium has resulted in contamination of a significant part (up to 90 percent) of the Russian enrichment complex. Reportedly, Yekaterinburg–44 is the only facility in Russia which has a fraction of its capacity (an estimated 2–3 million SWU/y) that has not been used to enrich reprocessed uranium and can be used to produce market quality enriched uranium product.

The stocks of natural uranium may have a quality problem as well. As a result of long–term storage in rusty drums, the material might require additional cleaning. The extent of this problem, however, is not known.

UNCERTAINTIES

In Russia, virtually all information regarding the uranium inventories, and the production and use of fissile material is classified. Any inventory analysis, therefore, is somewhat speculative and uncertain. The primary uncertainties associated with the HEU inventory relate to the following:

- The history of the enrichment capacity build–up. Because of a gap between enrichment technology advances and the capability of the industry to mass–produce and install new equipment, the proposed model of linear growth of the enrichment capacity might have resulted in an overestimate of the cumulative value of the enrichment work.

- Enrichment tails assay. The HEU inventory is very sensitive to the levels of the enrichment tails assays. For example, the decrease of the U–235 concentration from 0.36 to 0.3 for the gaseous diffusion period and from 0.30 to 0.25 for the centrifuge period would lower the HEU inventory estimate from 1300 tons to 1155 tons.

- HEU use in the material production reactors. The amount of HEU used for the production of plutonium and tritium might be higher if the level of fuel burnup was 25–50 percent rather than the suggested burnup of 75 percent.

- Production inventories (amounts of material in the production pipeline) and processing losses.

- The size of the nuclear weapons arsenal and the average HEU content per weapon.

With respect to the natural uranium inventories, the principal uncertainties are associated with the lack of the following information:

- Cumulative production and imports of uranium.

- Use of reprocessed uranium for the production of enriched uranium for weapons and naval fuel.

- Cumulative HEU and plutonium production.

- Use of reprocessed uranium in the late 1980's and early 1990's.

- Fabrication and processing losses at various stages of the uranium fuel cycle.

Examination of the uncertainty factors indicates that the proposed estimates of the HEU and natural uranium inventories are likely to be in the upper and lower parts of the respective ranges.[53] More accurate estimates must await improved data regarding the history of fissile material operations in the Soviet Union and Russia.

NOTES AND REFERENCES

1. The decision to start the production was made in 1942. However, by 1945 the facility produced only 7 tons. This was not enough even for the first experimental plutonium production reactor F–1 at the Kurchatov Institute, uranium requirements of which were covered by the 100 tons stock seized in defeated Germany.

2. The combined capacity of the Soviet uranium production complex was 17,900 tons. (Robin Bhar "Uranium: from Ore to Concentrate," *UI Briefing*, No. 93/6, The Uranium Institute, 1993.) In addition, several thousand tons per year was imported from the East European countries.

3. In 1992 the ex–Soviet producers produced 11,020 tons. (Robin Bhar "Uranium: from Ore to Concentrate," *UI Briefing*, No. 93/6, The Uranium Institute, 1993.) The 40–50 percent reductions in uranium output of the Kazakhstan complexes over the period 1988–91 are described in: V.Ponomarev "The Nuclear Industry in Kazakhstan and Kyrgizstan," *Central Asia Monitor*, No. 3, 19, pp. 33–34.

4. *"Report on the OECD NEA Uranium Group Mission to the USSR,"* OECD, 1991, p. 20. OECD experts point out that this might be an overestimate.

5. "Review of Wismut Reclamation," *UX Weekly*, Volume 9, Issue 33, p. 4.

6. *The Global Uranium Market: Supply and Demand 1992–2010*, Uranium Institute, June 1994, pp. 44–45.

7. Between 1945 and 1994, 25,060 tons were mined in Bulgaria. (Communication with Jeff Combs, September 1995.) In the recent years, the rate of production has been under 100 t/y.

8. The total production between 1989 and 1992 was 549 tons. (Communication with the staff of the Nuclear Assurances Corporation International, September 1995).

9. Some estimates suggest a cumulative production of 740,000 tons natural uranium. (J.Stein, "World Uranium Stockpiles: Potential Impact," paper presented at the International Uranium Fuel Seminar, Beaver Creek, Colorado, September 25–28, 1994.)

10. Most uranium has been mined from open pit and underground mines and milled in the heap leach or alkaline leach process with subsequent purification of uranium by ion exchange resins. As of 1992, only 9 percent of the production (or approximately 250 t) was produced from ISL operations. Presently, the underground mining is being phased out.

11. Other estimates suggest that the Soviet Union and Russia produced 125 tons plutonium. These estimates account for outages for repair and maintenance, lower capacity of some of the reactors and other factors reducing the efficiency of the operation. (A.Diakov, "Utilization of Already Separated Plutonium in Russia and International Security Problems: Consideration of Short– and Long–Term Options," paper presented at the GLOBAL conference, Paris, September 1995 (unpublished)).

12. Five graphite reactors were built in Chelyabinsk–65 (Mayak), three in Krasnoyarsk–26, and five in Tomsk–7.

13. According to the "Agreement Between the Government of the United States of America and the Government of the Russian Federation Concerning the Shutdown of Plutonium Production Reactors and Cessation of the Use of Plutonium for Nuclear Weapons," signed by U.S. Vice President Gore and Russia's Prime Minister Chernomyrdin on 23 June 1994, Russia agreed to shut down permanently by no later than the

year 2000 all 13 of its graphite–moderated plutonium production reactors. (T.Cochran, R.S.Norris, and O.Bukharin, *"Making the Russian Bomb: From Stalin to Yeltsin,"* Westview Press, 1995, p. 52.) However, the reactors in Krasnoyarsk–26 (1) and Tomsk–7 (2) may continue to work beyond 2000, until replacement sources of heat and electricity become available. In October 1994 Russia stopped using freshly produced plutonium in weapons; presently, plutonium is converted to oxide and placed in storage.

14. The reactors produced 187,868,000 and 11,279,000 MWdays power through 1988 and during 1989–1990. One 2000 MW reactor uses 1200 t/y. ("Report of Working Group on Nuclear Reactors," Meeting between the United States and the Russian Federation on the Replacement of Russian Plutonium Production Reactors, March 16, 1994.) Assuming a capacity factor 0.8, the reactor requirements are 386,000 and 23,000 tons before and after 1989 respectively. Fuel fabrication losses are assumed to be 1 percent. Power generation data are from T.Cochran, R.S.Norris and O.Bukharin, *"Making the Russian Bomb: From Stalin to Yeltsin,"* Westview Press, 1995, pp. 278–282.

15. Assuming fuel burnup of 400 MWd/t. The isotopic composition of reprocessed uranium is as follows: U–232 – 1.382E–16, U–233 – 5.597E–17, U–234 – 2.137E–09, U–235 – 6.668E–03, U–236 – 7.470E–05, and U–238 – 9.933E–01. (Communication with Thomas Cochran, 11 April 1995. Data derived from computer simulation.)

16. Additional 23,000 tons (0.667 percent U–235), recovered after 1988, presumably was re–enriched and recycled or placed in storage.

17. Submarines of the first and second generations use approximately 21–percent enriched uranium; submarines of the third generation are propelled by reactors with two–three enrichment zones with the level of enrichment varying between 21 and 45 percent U–235. Some submarines and icebreakers use 90–percent enriched uranium.

18. One fuel assembly of a second–generation reactor of the VM–4A type contains 1.4 kg of 20–percent enriched uranium. (O.Bukharin and W.Potter "Potatoes were Guarded Better," The Bulletin of the Atomic Scientists, May/June 1995, pp. 46–50. A typical core contains 225 fuel assemblies (V.Kurnosov, V.Perovsky, "On Improving the System of Spent Fuel Management at the Russian Naval Facilities," paper presented at the NATO workshop, June 1995, Moscow). Thus, one reactor core contains 315 kg uranium.

19. Use of reprocessed uranium (recovered from natural uranium fuel of the plutonium production reactors) would reduce natural uranium requirements for the naval program. Calculations of the HEU inventory, however, are essentially insensitive to this factor.

20. The plant processes fuel of VVER–440 and BN–600 reactors, fuel of naval and research reactors, and HEU fuel of plutonium– and tritium-production reactors. RT–1's output is uranium "plav", $UO_2(NO_3)_2 6H_2O$ with the enrichment of 2.0–2.5 percent U–235. To achieve the required level of enrichment, the material is mixed with HEU solution at RT–1. The level of enrichment could also be adjusted at the fuel fabrication plant at Ust'–Kamenogorsk. (Yu.Bibilashvilli, F.Reshetnikov "Nuclear Fuel Cycle with Reactors VVER, RBMK, BN in Russia," *Izvestia Vuzov* (in Russian), No. 2–3, 1994, pp. 55–65.)

21. The process has never been licensed for industrial application and the fuel fabrication plant in Ust'–Kamenogorsk stopped using reprocessed uranium some time in 1992. The principal problem is elevated personnel exposure due to the presence in uranium of gamma–emitting U–232 decay products.

22. Three 2000–MWt plutonium-production reactors discharge 3,535 tons of 0.667–percent uranium per year. In 1992, RT–1 processed 120 tHM of spent fuel mainly from VVER—440 reactors and recovered 114 tons 1.25–percent enriched uranium. (T.Cochran, R.S.Norris, and O.Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin*, Westview Press, 1995, p. 52.)

23. Communication with Russian nuclear industry official (May 1995).

24. O.Bukharin, "Integration of the Military and Civilian Nuclear Fuel Cycles in Russia," *Science and Global Security*, 1994, Volume 4, pp. 385–406.

25. Russia covers 100 percent uranium requirements of Lithuania and Kazakhstan (298 and 80 t/y) and covers uranium deficit for Ukraine (700 t/y) and Eastern Europe (300 t/y). (The Program of Development of Nuclear Power in the Russian Federation for the period until 2010. Moscow: Minatom, 1992.)

26. In 1992, approximately 40 percent of Minatom's enrichment capacity was dedicated to the enrichment of tails. (See, Yu.Bibilashvilli and F.Reshetnikov, "Nuclear Fuel Cycle with Reactors VVER, RBMK, BN in Russia," *Izvestia Vuzov* (in Russian), No. 2–3, 1994, pp. 55–65.) According to Russian nuclear industry sources, uranium tails are stripped to 0.11 percent U–235. Assuming uranium is enriched from 0.3 (see below) to 0.7 percent U–235, and the available enrichment capacity is 8 million SWU/y, the amount of natural uranium equivalent produced in 1992 can be estimated at 6,300 t/y.

27. Additional 23,000 tons may have been moved to Western Europe physically but not transferred to utilities. (Communication with J.Stein, April 24, 1995.)

28. Statement by V.F.Petrovsky, Deputy head of the Soviet Delegation to the 44th UN General Assembly, 25 October 1989. The statement reads that "this year it is ceasing the production of highly enriched uranium." However, it is believed that the USSR actually stopped producing HEU for weapons sometime in 1988.

29. In 1950, the gaseous diffusion plant D–1 at Sverdlovsk–44 began producing tens of kilograms of HEU/y. The plant was brought on line in 1949 but did not produce appreciable quantities of enriched uranium until 1950 because of multiple technical problems.

30. The first industrial centrifuge enrichment plant was commissioned at Sverdlovsk–44 in 1962.

31. The last gaseous diffusion plant was shut down at Tomsk–7 in 1991.

32. Information about the 2.4–fold increase in the enrichment capacity is from: E.Mikerin, V.Bazhenov, and G.Solovyev, "Directions in the Development of Uranium Enrichment Technology," 1993.

33. D.Albright, F.Berkhout, and W.Walker, "*World Inventory of Plutonium and Highly Enriched Uranium*," SIPRI (New York, Oxford University Press, 1993), p. 60.

34. The "linear" assumption could have resulted in an overestimate of the total SWU production. According to D.Albright, who has taken into account the logic of the production and deployment of centrifuges of various generations, the total SWU production in the USSR through 1987 can be estimated at 282–384 million SWU. (Personal communication, spring 1995.)

35. HEU requirements may vary significantly depending on the type of a warhead. A typical secondary component of a thermonuclear warhead may contain 15 or more kg HEU; a gun–type artillery shell may use 50 kg HEU. The level of HEU enrichment is also different for different types of warheads. Reportedly, many Russian warheads use 36 to 98 percent enriched uranium.

36. According to U.S. CIA estimates of May 1992, the Russian stockpile at that time was 30,000 plus or minus 5,000 warheads. (*Hearings before the House Committee on Appropriations*, DOD Appropriations for 1993, Part 5, 6 May 1992, p. 499.) Russia continues to dismantle weapons at a rate of 1,500 to 2,000 per year.

37. According to the joint Bush/Yeltsin statement of 17 June 1992, the strategic arsenals of the two countries will be reduced to 3,000–3,500 warheads by 2003 and would roughly correspond to the projected START II force levels ("Joint Understanding," Arms Control Today, 6/92, p. 33.). In addition, Russia will have a stockpile of tactical and reserve warheads.

38. This corresponds to the HEU share in the power output in the reactor core of approximately 8 percent.

39. Tritium production at Chelyabinsk–65 began in the early 1950's in a graphite–moderated plutonium-production reactor, AV–3. Around 1954, production of tritium was started in a 100–MW heavy water reactor (HWR) OK–180 (Chelyabinsk–65, start–up 1951). The second HWR (OK–190) began operation in 1955. The first HWR reactor was shutdown in 1965 and was replaced by a 1000- MW light-water reactor, Ruslan, which started operation in 1979. The second HWR, OK–190, was upgraded in 1965–66 and worked until 1986. It was replaced by a 1000 MW LWR, Ludmila. Ruslan and Ludmila are used to produce tritium, other isotopes (plutonium–238, cobalt–60, carbon–14, etc.), and to irradiate silicon rods.

40. Cochran et al. p. 282.

41. Fission of 1.05 g U–235 is equivalent to 1 MWday.

42. These include seven single-liquid-metal reactor submarines of the Alfa class, one double–LMR November–mod submarine, one double–PWR C3I vessel, and five double–PWR and three single–pressurized-water reactor icebreakers.

43. Assuming 100 reactor cores, each containing 200 kg HEU.

44. Of these, 6 research reactors, 4 critical assemblies and 1 subcritical assembly are under construction; 14 facilities are being decommissioned.

45. In 1992, E.Mikerin indicated that 1.5 tons HEU per year had been used to fabricate fuel for research and naval reactors. At such a rate, 45 tons HEU would have been used over a 30-year period. If 20 tons were used in naval reactors, 25 tons were used in research reactors.

46. Of 1100 detonations, 1000 produced yields greater than one ton and are counted as 718 nuclear tests. (T.Cochran and C.Paine, "The Role of Hydronuclear Tests and Other Low–Yield Explosions and Their Status under a Comprehensive Test Ban," NRDC, *Nuclear Weapons Databook*, March 1995, p. 21.)

47. This includes 3,500 tons recovered from irradiated fuel of the three plutonium production reactors shut down in 1992.

48. The reactor–produced isotope U–232 is an occupational safety problem as it decays into Bi–212 and Tl–208, both high–energy gamma emitters. U–236, also produced in a reactor by neutron capture in U–235, is a neutron poison. Reprocessed uranium might be contaminated with traces of fission products and transuranics. Additional contamination with plutonium may have occurred in HEU used in composite warheads due to mutual diffusion of uranium and plutonium. HEU may also be contaminated with alloying metals and other chemical impurities.

49. Remarks by E.Mikerin at the NEI's International Uranium Fuel Seminar, October 8–11, 1995, Williamsburg, Virginia.

50. Dilution with uranium of higher levels of enrichment yields larger quantities of the final product, and in this way, increases the dilution factor.

51. U–234 is a natural isotope of uranium. However, because it is a strong alpha emitter there are restrictions on its concentrations in commercial–grade uranium. U–234 is concentrated in HEU because of its preferential enrichment.

52. E.Mikerin, "The Industrial Process of Blending Russian Weapons HEU into LEU," Presented at Nuclear Energy Institute's International Uranium Fuel Seminar, October 8–11, Williamsburg, Virginia.

53. The estimated inventory of 1300 tons HEU exceeds the 1250 tons suggested by V.Mikhailov. ("Behind the HEU Curtain: A Critical Review of the Atomic Armistice," Nukem Market Report, October 1993, p. 5.)

54. Fuel requirements, enrichment levels are from D. Bradley, K. Schneider, "*Radioactive Waste Management in the USSR: A Review of Unclassified Sources, 1963–1990,*" PNL Volume 1, March 1990, p. 6.3.