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Integration of the Military and Civilian Nuclear Fuel Cycles in Russia

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This paper describes the close integration of the civil and military nuclear fuel cycles in Russia. Individual processing facilities, as well as the flow of nuclear material, are described as they existed in the 1980s and as they exist today. The end of the Cold War and the breakup of the Soviet Union weakened the ties between the two nuclear fuel cycles, but did not separate them. Separation of the military and civilian nuclear fuel cycles would facilitate Russia's integration into the world's nuclear fuel cycle and its participation in international non-proliferation regimes.

INTRODUCTION

In Russia, the military and civilian nuclear fuel cycles are highly integrated. This connection is a liability for the nuclear complex, the public, and the international community for a number of reasons. First, it is a major obstacle to the introduction of Western-style management and the development of commercial activities in the industry. Second, it increases public distrust of the nuclear complex because of increased secrecy. Third, it slows down Western assistance in building a system of modern nuclear safeguards. Finally, it may impede negotiation and implementation of a ban on the production of fissile materials for weapons.[1]

The roots of the integration of the military and civilian nuclear fuel cycles are in the history of the nuclear complex, as well as in the centralized planned economy under which Russia has lived for more than 70 years. The Soviet nuclear program was initiated in the late 1940s as a massive, well coordinated, and redundant effort to produce nuclear weapons. A nuclear power program was started about two decades later by the same institutions that were

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responsible for the production of nuclear weapons. Thus, the civil nuclear power was developed on the basis of the military nuclear fuel cycle, and the civilian and military fuel cycles were integrated at the level of both uranium flows and individual facilities.[2] In other words, uranium was routinely transferred between the two fuel cycles; and many facilities were involved in both military and civil activities. Below, we examine these two levels of integration.

URANIUM FLOWS

Uranium Flows in the 1980s

Figure 1 shows the flows of natural, low-enriched, and highly enriched uranium in the Soviet nuclear complex of the 1980s—the period when the complex was in its prime.

Virtually all uranium produced in the U.S.S.R. and Eastern Europe was shipped to the metallurgical plant in Glazov for final purification and conversion to metal. Metal ingots were fabricated into aluminum-clad natural uranium fuel for plutonium-production reactors at the fuel fabrication plant in Novosibirsk. After irradiation in the reactors at the Mayak (also known as Chelyabinsk-65), Tomsk-7, and Krasnoyarsk-26 material-production sites, fuel was reprocessed at the reprocessing plants co-located with the reactor sites at Tomsk-7 and Krasnoyarsk-26.[3] Plutonium that was extracted from irradiated fuel was transferred to the nuclear weapons program. Recovered uranium was converted to uranium hexafluoride at the conversion facilities (at Angarsk and Tomsk-7) and enriched from 0.66 percent U-235 to different levels of enrichment at the centrifuge plants at Verkh-Neyvinsk, Tomsk-7, Krasnoyarsk-45, and Angarsk.

Hexafluoride of low-enriched uranium was converted to uranium oxide powder and pellets for VVER and RBMK reactors at the fuel fabrication plant at Ust'-Kamenogorsk. The pellets were subsequently fabricated into fuel rods and assemblies at the fuel fabrication facilities at Electrostal (VVER-440 and RBMK) and Novosibirsk (VVER-1000). Irradiated fuel from VVER-1000 and RBMK reactors was placed in storage;[4] and fuel from VVER-440 reactors was reprocessed at Mayak with BN-, naval- and research reactor fuel. Extracted reactor-grade plutonium was stored at Mayak; and reprocessed uranium (in the form of uranyl nitrate, UNH) was sent to Ust'-Kamenogorsk for fabrication into fuel for the RBMK reactors. (Fabrication of reprocessed uranium into RBMK fuel was carried out on a pilot scale between 1981 and 1992 and has never reached the status of commercial application.[5])

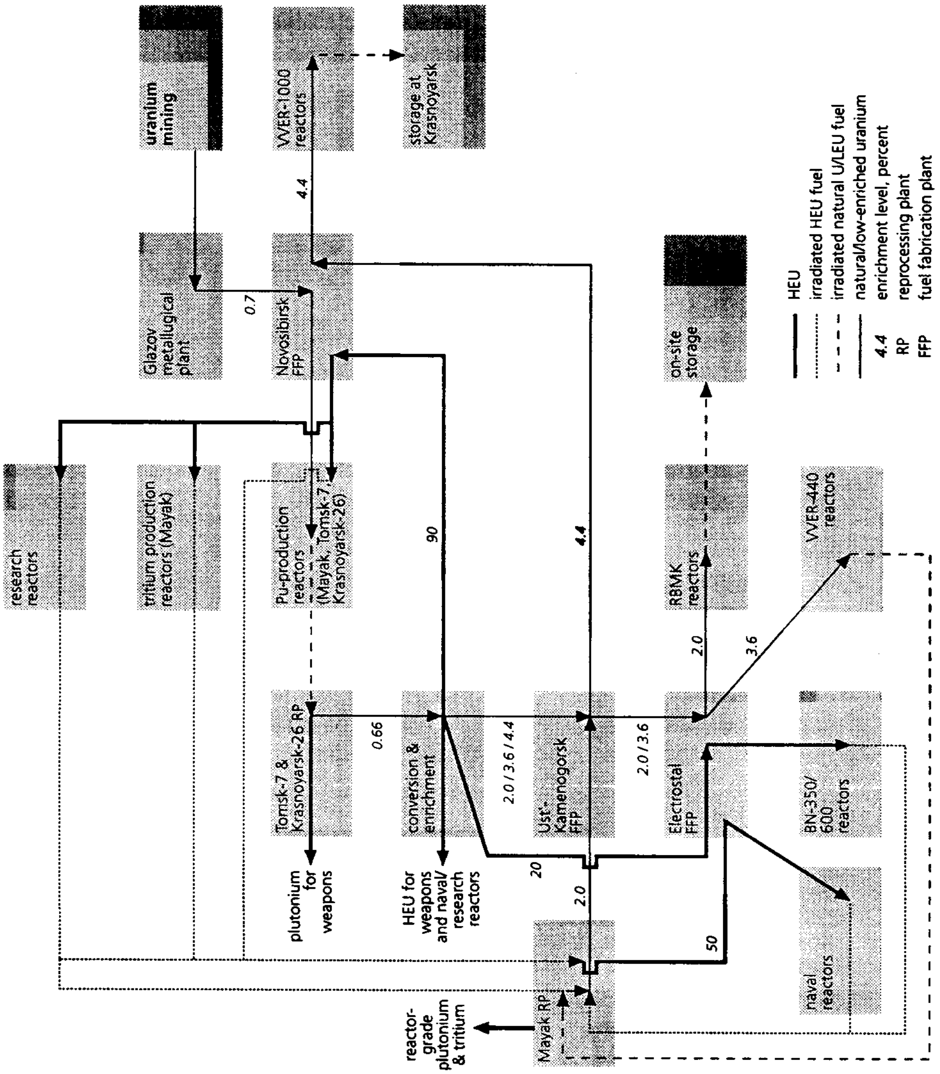

Figure 1: Principal uranium flows in the 1980s.

The flow of natural and low-enriched uranium was closely integrated with that of highly enriched uranium (HEU). Most HEU was produced from uranium recovered from irradiated natural uranium fuel of plutonium-production reactors. Some HEU was used in nuclear weapons and some was fabricated into fuel for HEU-fueled naval and research reactors.[6] The rest was sent to the Novosibirsk plant for fabrication in HEU spike rods for the plutonium-production reactors and HEU cores for two of Mayak's tritium production reactors.[7] HEU fuel, irradiated to burnups of up to 75 percent, was reprocessed at Mayak, and the recovered uranium (about 50 percent enriched) was fabricated into naval reactor fuel at the Electrostal fuel plant.[8] Irradiated fuel from naval reactors was sent back to Mayak where it was reprocessed with irradiated fuel from VVER-440 and other reactors (see above).

Uranium Flows in the Early 1990s

To a certain extent, the above description of the uranium flows in the 1980s holds today. There are, however, some major differences (see figure 2).

The flow of natural uranium to the Russian nuclear complex has been drained because of the termination of uranium mining operations in East European countries (or their re-direction to meet domestic requirements), the disintegration of the Soviet uranium-production complex, and the emergence of individual market-oriented producers. The Ministry of Atomic Power of the Russian Federation (Minatom) is responding to these changes with increased reliance on new sources of uranium, including its enormous stocks of natural and recycled uranium, and uranium recovered from enrichment tailings (see appendix).[9]

The uranium flows have also changed because of dramatic reductions in defense requirements that have occurred since the late 1980s. The number of plutonium-production reactors has been cut from 13 in 1987 to three at present.[10] Assuming that a 2,000 megawatt-thermal (MWt) plutonium-production reactor consumes 1,200 metric tons (MT) uranium per year, the shutdown slashed the natural uranium requirements for plutonium-production reactors from some 15,000 to 3,600 metric tons.[11] The uranium requirements for the Soviet-built commercial power reactors amount to approximately 7,000 metric tons of uranium per year, while only 750 metric tons of natural uranium equivalent is derived from reprocessed uranium of plutonium-production reactors annually (see appendix). Thus, a significant fraction of uranium bypasses the production reactors. Minatom plans to close the uranium fuel cycle of the plutonium-production reactors by recycling recovered uranium into fresh fuel for these same reactors.[12] These reactors are to be shut down by

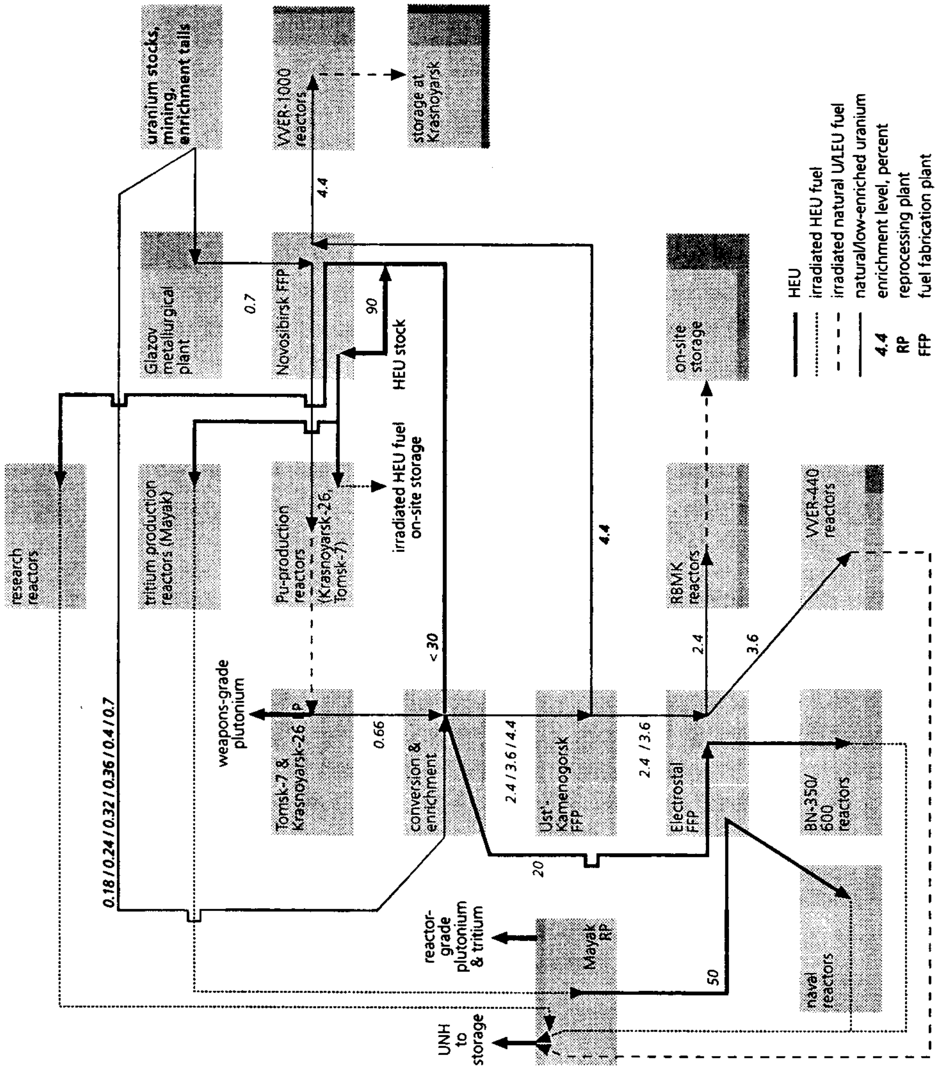

Figure 2: Principal flows of uranium at present.

the year 2000 or earlier.

The shutdown of 10 plutonium-production reactors has reduced the demand for HEU fuel for material-production reactors from about 1,500 kilograms to 900 kilograms 90 percent-enriched uranium per year.[13] The demand for HEU output from the production reactors also dropped following the reductions in maritime activities by the Russian Navy[14] and associated reductions in the demand for naval reactor fuel (fabricated from uranium recovered at Mayak).[15] As a result, Mayak reportedly has been refusing to reprocess HEU driver fuel from the plutonium-production reactors for the past three to four years.

The break-up of the Soviet Union may lead to significant changes in the fuel fabrication complex. Mayak has already stopped sending reprocessed uranium (as UNH) to Ust'-Kamenogorsk (the only fuel cycle facility located outside Russia) for fabrication into RBMK fuel, halting the recycling of uranium recovered from spent fuel of civil reactors. Minatom has also started consolidating fuel fabrication capabilities in Russia by rebuilding production lines to produce uranium oxide powder and pellets for reactors VVER-440 (in Electrostal) and VVER-1000 (in Novosibirsk). As a result, the Ust'-Kamenogorsk plant may lose a substantial part of its fuel fabrication business.[16]

NUCLEAR FUEL CYCLE FACILITIES

Originally, the Soviet nuclear complex was developed as a network of facilities designed to build nuclear weapons. In the early 1970s, however, an ambitious nuclear power program called for the development of industrial capabilities to produce fresh and spent fuel services for civil power reactors. The demand was met through expansion of the existing fuel cycle facilities and diversification of their activities. However, this did not result in demilitarization of military fuel cycle facilities, with the exception of those in the uranium-production and some in the uranium-enrichment industries. The past and present integration of civil and military activities can be seen in the following examples (see figure 3).

Uranium-Production Centers

In the 1970s and 1980s, the uranium demand was met by extensive and well coordinated mining and milling operations in the Soviet republics and by imports of uranium from Hungary, Czechoslovakia, East Germany, Bulgaria, and Mongolia. Approximately 15,000 (out of 16,000 to 17,000 metric tons of

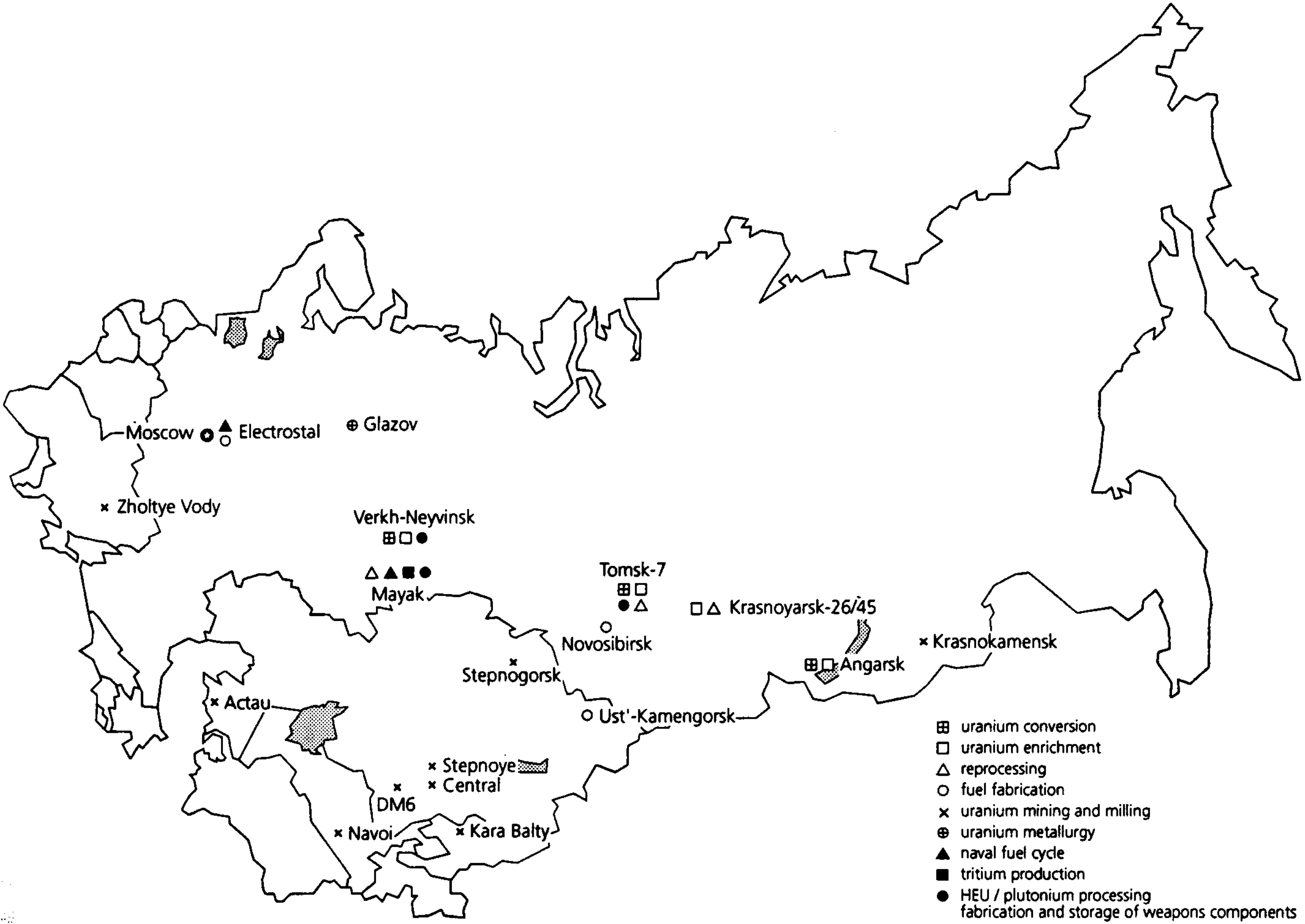

Figure 3: Nuclear facilities in the former Soviet Union.

the total uranium production[17]) was consumed by the material-production reactors annually. A fraction of the production output was placed in a national reserve, and starting in 1988, uranium was exported to the West.[18]

The break-up of the Soviet Union and reductions in the uranium requirements dramatically changed the uranium industry and, to a significant extent, decoupled it from the military fuel cycle. Uranium producers have set up independent uranium businesses (see table 1) with their uranium output destined either for the international market (i.e., Kazakhstan, Uzbekistan, Kyrgyzstan, Russia) or for domestic nuclear power needs (i.e., Ukraine, Russia).

Plutonium- and Tritium-Production Facilities

Production of plutonium for weapons took place at the Mayak, Tomsk-7 and Krasnoyarsk-26 material-production complexes, each featuring production reactors, reprocessing plants and plutonium-processing facilities. Mayak terminated reprocessing of irradiated natural uranium fuel from the production reactors in 1976 (see endnote 3). However, it continues producing tritium for weapons. Both Mayak and Tomsk-7 have been identified as weapons components production sites, and in the future they are likely to become central storage facilities for weapons components from retired warheads.

As time passed, the material-production sites have assumed civil missions as well (see table 2). In 1976, Mayak started reprocessing fuel from BN-350/600 and VVER-440 reactors, and Krasnoyarsk-26 was selected as a central storage and reprocessing site for VVER-1000 fuel.[19] All three sites became involved (or are planned to be involved) in waste management and plutonium utilization activities.

The complexes are looking for opportunities to sell nuclear services to other countries. Mayak has contracts to reprocess VVER-440 spent fuel from Finland, Ukraine, and Hungary.[20] In 1992, Mayak and Amersham International of England announced the formation of a joint venture—Reviss Services. Mayak will produce radioisotopes (Co-60, Cs-137, C-14, Am-241, and Kr-85), and Amersham will fabricate them into finished products and provide marketing worldwide.[21] Mayak has also signed a $6-million contract with the U.S. DOE to supply five kilograms of plutonium-238. (DOE also agreed to buy an additional 35 kilograms in the future.[22]) At Mayak, plutonium-238 is produced by irradiation of neptunium-237 in the tritium-production reactors. Tomsk-7 has signed a contract with Siemens AG of Germany to recover uranium from scrap at its reprocessing plant,[23] and Krasnoyarsk-26 has been negotiating reprocessing contracts with South Korean utilities.

Table 1: Uranium mining and milling operations in former Soviet republics.

Operator of mine/ Republic	**Mine**	**Associated milling center**	**Capacity** *MTU per year*	**Production in 1993**[a] *MTU*
Priargunsky combine/ Russia	Krasnokamensk	Krasnokamensk	4,000	2,300
Tselinny Combine/ Kazakhstan[b]	Kamyshovoye Shokpack Grachevskoye Vostok Zvesdnoye Zaozernoye	Stepnogorsk	1,000	2,700[c]
Kascor/ Kazakhstan	Melovoye Tomak	Actau	1,000	
DM[d] Stepnoye DM Central DM No. 6/ all Kazakhstan	Stepnoye Taukent Chiili	Kara Balty Stepnogorsk	1,900[e]	
Navoi Mining and Metallurgy Combine/ Uzbekistan	Uchkuduk Vostok Zarafabad Nurabad	Navoi	3,060–4,000	2,600
Eastern Combine/ Ukraine	Vatutinsky	Zholtye Vody	2,000	500
Kara Balty Combine/ Kyrgyzia	none[f]	Kara Balty	800	n/a

a. UI News Briefing, 94/13, p. 3.
b. Uranium ore will continue to be shipped for milling to Kara Balty until 1996 or 1997. KATEP has announced the suspension of uranium production at Kascor (UI News Briefing 94/8, p. 1) and is planning to shut down conventional underground mining at Tselinny.
c. Total production in Kazakhstan.
d. DM = Directorate of Mining.
e. Total uranium output from the Directorates of Mining, Stepnoye, Central No. 6.
f. Ore from Kazakhstan.

Table 2: Plutonium- and tritium-production facilities.

Facility/ Location	**Defense activities**	**Civil activities**
Mayak/ Chelyabinsk-65	• Reprocessing of HEU fuel and production of uranium feed for naval reactor fuel • Production of tritium, tritium components, and Pu-238 generators for weapons • Possible storage of fissile materials and tritium components from retired weapons	• Reprocessing of fuel from civil VVER-440, BN-350, BN-600 and research reactors • Production of UNH feed for fabrication into RBMK fuel • Production of radioisotopes in cooperation with a U.K. firm • Waste management • Plutonium utilization (planned)
Siberian Chemical Combine/ Tomsk-7	• Production of plutonium for weapons • Storage and manufacturing (possibly) of weapons components	• Production of heat and electricity for nearby cities • Scrap recovery for foreign companies • Waste management (planned)
Mining and Chemical Combine/ Krasnoyarsk-26	• Production of plutonium for weapons	• Production of heat and electricity for nearby cities • Storage of VVER-1000 spent fuel • Reprocessing of VVER-1000 spent fuel (planned) • Plutonium utilization (planned)

Uranium Conversion and Enrichment Facilities

The Russian enrichment complex consists of four enrichment facilities—Verkh-Neyvinsk, Angarsk, Tomsk-7, and Krasnoyarsk-45 (see figure 3 and table 3)—having a combined capacity of 10- to 18-million SWU per year. The isotope separation technology is based on gaseous centrifuges with gaseous diffusion machines used as a first stage to filter out chemical impurities. In the past, the four sites operated as a single enrichment unit designed to produce HEU. After the Soviet Union discontinued production of HEU in 1987–1989, the sites operated independently producing low- and medium-enriched uranium.[24]

The enrichment complex is supported by two large conversion plants co-located with the enrichment plants at Angarsk and Tomsk-7, and by a smaller facility at Verkh-Neyvinsk which is dedicated to the production of hexafluoride of natural uranium.

A good example of the integration of military and civil activities at the facility level is the Verkh-Neyvinsk site. In the former Soviet enrichment complex, it was a top enrichment stage which produced HEU using the product of other plants as feed. In addition, the site performed HEU processing operations, and was involved in storage and possibly fabrication of HEU components for weapons. Some of these activities are probably still taking place at the site at present.

On the civil side, Verkh-Neyvinsk has been a principal commercial enrichment facility. The complex is operating three enrichment cascades; two of them (totaling approximately three million SWU per year) are dedicated to enrichment of natural (unreprocessed) uranium.[25] Verkh-Neyvinsk is the only site in Russia capable of producing enrichment services and enriched uranium product for the world market. (The rest of the enrichment capacity in Russia has been used for enrichment of uranium recovered from irradiated fuel from plutonium-production reactors and is contaminated with uranium isotope U-232.[26]) The facility, a shareholder of Minatom's marketing agent Tenex, has been involved in export activities since 1973. The third cascade produces medium-enriched uranium (up to 30 percent-enriched) for research and BN-type reactors. Recently, Verkh-Neyvinsk began converting and blending HEU from retired weapons to LEU for fabrication into fuel for power reactors according to the U.S.-Russian HEU agreement.[27] The site is producing hexafluoride of 4.4 percent-enriched uranium for delivery to the U.S.

The enrichment plant at Tomsk-7 is co-located with plutonium-production and processing facilities and may also perform weapons-related HEU-processing activities.[28] The key commercial operation at the Tomsk-7 enrichment facility is the re-enrichment of reprocessed uranium under a long-term con-

Table 2: Plutonium- and tritium-production facilities.

Facility/ Location	Defense activities	Civil activities
Mayak/ Chelyabinsk-65	• Reprocessing of HEU fuel and production of uranium feed for naval reactor fuel • Production of tritium, tritium components, and Pu-238 generators for weapons • Possible storage of fissile materials and tritium components from retired weapons	• Reprocessing of fuel from civil VVER-440, BN-350, BN-600 and research reactors • Production of UNH feed for fabrication into RBMK fuel • Production of radioisotopes in cooperation with a U.K. firm • Waste management • Plutonium utilization (planned)
Siberian Chemical Combine/ Tomsk-7	• Production of plutonium for weapons • Storage and manufacturing (possibly) of weapons components	• Production of heat and electricity for nearby cities • Scrap recovery for foreign companies • Waste management (planned)
Mining and Chemical Combine/ Krasnoyarsk-26	• Production of plutonium for weapons	• Production of heat and electricity for nearby cities • Storage of VVER-1000 spent fuel • Reprocessing of VVER-1000 spent fuel (planned) • Plutonium utilization (planned)

tract with the French firm Cogema.[29] Also, it is expected that Tomsk-7 will be involved in oxidation of HEU metal under the U.S.-Russian HEU agreement. After oxidation, HEU oxide will be transferred to Verkh-Neyvinsk for fluorination and blending to LEU for export to the U.S. The Angarsk and Krasnoyarsk-45 facilities produce LEU for domestic needs and enrich uranium tailings to the level of natural uranium. In addition, some enrichment facilities separate non-uranium isotopes, including iron, tungsten, molybdenum, xenon, and sulfur.

Fuel Fabrication Facilities

Fabrication of reactor fuel takes place at the fuel-production complexes at Electrostal, Novosibirsk, and Ust'-Kamenogorsk. All three facilities became a part of the Soviet nuclear weapons program in the late 1940s. The Electrostal and Ust'-Kamenogorsk plants started as nuclear materials metallurgical facilities. The Electrostal plant, for example, produced HEU metal for the first Soviet weapons. Later, the plant became a principal fabricator of naval reactor fuel. The Ust'-Kamenogorsk plant was involved in fabrication of beryllium-HEU alloys for naval reactors fuels as well. Its primary defense mission, however, was to satisfy beryllium requirements for the Soviet nuclear-weapons and aerospace programs. After the break-up of the U.S.S.R., the Ust'-Kamenogorsk plant became the property of sovereign Kazakhstan and lost virtually all military orders for beryllium from Russia.[30] The Novosibirsk plant was started in 1949 as a fabricator of fuel for weapons-materials production and research reactors and has been performing this function ever since.

In the early 1970s, all three facilities expanded to fabrication of fuel for power reactors. Originally, this capability was developed at Electrostal and Novosibirsk. In 1974, the first stage of fuel fabrication process (production of uranium oxide powder and fuel pellets) was consolidated at the Ust'-Kamenogorsk plant; the Novosibirsk and Electrostal sites retained responsibility for fabrication of fuel rods and assemblies.[31] Defense and civilian activities of the fuel fabrication sites are summarized in table 4.

Table 4: Fuel fabrication facilities.

Facility/ Location	**Defense activities**	**Civil activities**
Chimconcentrate Plant/ Novosibirsk[a]	• Production of fuel for weapons-materials-production reactors	• Production of fuel for VVER-1000 reactors • Production of fuel for research reactors
Machine-Building Plant/ Electrostal	• Production of fuel for naval reactors	• Production of fuel for VVER-440, RBMK, and BN reactors
Ulbinsky Metallurgical Plant/ Ust'-Kamenogorsk[b]	• Beryllium production	• Production of uranium oxide powder and pellets for VVER and RBMK reactors • Production of beryllium and tantalum

a. The Novosibirsk complex consists of three major plants producing fuel for: research reactors (uranium oxide fuel in an aluminum matrix), VVER-1000, and for material-production reactors.

b. The Ust'-Kamenogorsk complex consists of four major plants: beryllium plant, tantalum and semiconductor plant, VVER fuel plant, and RBMK fuel plant.

CONCLUSIONS

There are still many links between the civil and military nuclear fuel cycles in Russia. This analysis suggests that breaking the connection might require the following:

- Termination of the production of tritium at Mayak and plutonium at Tomsk-7 and Krasnoyarsk-26.
- Termination of reprocessing HEU fuel at Mayak and identification of an alternative source of enriched uranium for naval reactors (if needed).
- Establishment of physical and institutional separation of weapons-related and civil activities at the Mayak, Tomsk-7, and Verkh-Neyvinsk sites.

Implementation of these steps is feasible. Indeed, there is a national conversion program to stop the production of plutonium for weapons by the year 2000. The remaining three plutonium-production reactors may be shut down or converted to terminate production of weapon-grade plutonium even before 2000. The problem is currently being studied jointly by U.S. and Russian experts. The issue of recycling HEU from material-production reactors into fuel for naval reactors may be moot given the already reduced HEU discharge from the production reactors (with further cuts expected) and the lack of demand for it. Finally, weapons-related facilities, although co-located with civilian facilities within the common protected areas, sites are likely to be surrounded by additional protective barriers.

Drawing a clear line between military and civil nuclear activities would speed up integration of the Russian nuclear complex into the international nuclear fuel cycle. It would also facilitate implementation of non-proliferation regimes, including international safeguards and a ban on the production of fissile materials for weapons.

APPENDIX A: RUSSIAN URANIUM SUPPLY AND DEMAND

Tables A-1 presents sources of uranium, and table A-2 presents the uses of uranium product. Most estimates are drawn (directly or by normalization to natural uranium equivalent) from Minatom's *Program of Development of Nuclear Power in the Russian Federation for the Period until 2010* (Moscow: Minatom, 1992). Tables A-3 and A-4 present our estimates of natural uranium and SWU requirements for Soviet-designed power reactors (table A-5), based on parameters of reactor design and performance (fuel enrichment, burnup, load factor). The difference between the values in tables 1 and 2 and the estimates in tables 3 and 4 can be partially explained by Minatom's accounting for forward fuel requirements, technological and economic optimization of fuel cycle and reactor services, and internal inconsistencies of the Program.

Table A-1: Uranium supply, 1994.

Sources of uranium	**Natural uranium equivalent** *metric tons per year*
E. Europe	1,300
Ukraine	1,000[a]
Uranium mining in Russia	2,300[b]
Stockpile of natural uranium	1,000[a]
Uranium tailings	1,600[c]
UNH from Pu-production reactors	750[d]
Stockpile of enriched uranium	700[e]

a. The Program, p. 27.
b. The 1993 production at the Priargunsky Combine. UI News Briefing, Uranium Institute, London, 1994.
c. 10,560 metric tons 0.20 percent-enriched tails will be enriched in 1994; this corresponds to 1,600 metric tons 0.7 percent-enriched uranium at a tails assay of 0.11 percent. In the future, tailings of enrichment 0.24 percent and 0.36 percent will be enriched, according to the Program; some 4,000 metric tons 0.7 percent-enriched uranium are to be produced annually between 2006 and 2010. (The Program, p. 27.).
d. This corresponds to 800 metric tons 0.66 percent-enriched uranium (The Program).
e. This corresponds to 100 metric tons 4.4 percent-enriched uranium (The Program, p. 28).

Table A-2: Uranium use, 1994.[a]

Uranium use	**Natural uranium equivalent** *metric tons per year*
Nuclear power in E. Europe	1,600[b]
Nuclear power in Ukraine	1,700
Nuclear power in Kazakhstan	80[c]
Nuclear power in Lithuania	298
Nuclear power in Russia	2,370[d]
Natural uranium exports	2,200 (mining) + 1,000 (tailings enrichment)[a]
Enriched uranium product exports	n/a

a. About 1,000 metric tons and 1,300 metric tons of natural uranium comes to Russia annually from Ukraine and Eastern Europe, respectively. The material is enriched, fabricated into reactor fuel and sent back. Russia covers the deficit by providing 700 and 300 metric tons of natural uranium for Ukraine and Eastern Europe, respectively (*The Program of Development of Nuclear Power in Russian Federation for the Period until 2000.*)
b. The Program, p. 26.
c. This corresponds to 41.81 and 11.15 metric tons 4.4 percent-enriched uranium in the Program. (Ibid, p. 28.).
d. This corresponds to 332.03 metric tons 4.4 percent-enriched uranium in the Program. (Ibid, p. 28.) In the period 1996 to 2000, the reactor requirements will amount to 2,564 metric tons 0.7 percent uranium annually (Ibid).

Table A-3: Estimated natural uranium and SWU requirements per reactor for Soviet-designed power reactors.

Reactor type	Enrichment	Amount of fuel	SWU requirement	Equivalent of natural uranium requirement
	percent	*MT/year*[a]	*million SWU/year*[b]	*MT/year*[c]
RBMK-1000	2.4	37.8[d]	0.154	144
VVER-440	3.6	12.7[e]	0.095	73.8
VVER-1000	4.4	18.5	0.181	132.1
BN-350	20	6.2	0.359	205
BN-600	25	7.4	0.428	244
Pu-production reactors	0.7	1,200	0	1,200

a. Assuming burnup of 20 MWday per kilogram uranium and an average load factor of 0.66, a 1,000-MWe RBMK reactor consumes about 36 metric tons 2.4 percent-enriched uranium per year. With burnups of 40 MWday per kilogram uranium, VVER-440 and VVER-1000 reactors consume 18.1 and 10.6 MTU per year.

b. Assuming 0.11 percent tail assay.

c. Neglecting conversion and enrichment losses, which are on the order of 0.5 percent.

d. Assuming burnup of 20 MWday per kilogram uranium and an average load factor of 65.3 percent, a 1,000-MWe RBMK reactor consumes slightly more than 36 metric tons 2.4 percent-enriched uranium per year.

e. Assuming burnup of 30 MWday per kilogram uranium and an average load factor of 0.653, a VVER-440 consumes about 10.6 MTU per year. Currently, VVER-440s are being transferred from a three to a four-year fuel life with increase in burnup to 40 MWday per kilogram.

Table A-4: Natural uranium and SWU requirements for countries operating Soviet-designed reactors.

Country	Natural uranium requirements *MT/year*	Enrichment requirements *million SWU/year*
Russia (power reactors)	3,196	3.959
Russia (Pu-production reactors)	3,600	
Ukraine	1,757	2.308
Kazakhstan	205	0.359
Lithuania	360	0.385
Outside former U.S.S.R.	1,460	1.891
Total without Pu-production reactors	**6,978**	**8.875**
Total with Pu-production reactors	**10,578**	**8.875**

Table A-5: Soviet-designed power reactors operating and under construction.[a]

	VVER-440	VVER-1000	RBMK	Others	Under construction[b] (% complete)
Russia					
Novovoronezh	2	1			
Kola Peninsula	4				
Balakovo		4			
Tver'		2			1 VVER-1000 (70)
Kursk			4		1 RBMK-1000 (60)
St. Petersburg			4		
Smolensk			3		
Beloyarskaya				BN-600	
Bilibino				4 × 12 MW_e[c]	
Ukraine					
Rovno	2	1			1 VVER-1000 (70)
Zaporozhye		5			1 VVER-1000 (90)
South Ukraine		3			
Khmel'nitsky		1			1 VVER-1000 (90)
Chernobyl			2		
Lithuania					
Ignalina			2 × 1,250 MW_e		
Kazakhstan					
Actau				BN-350	
Bulgaria	4	2			
Hungary	4				
Czechoslovakia	8				2 VVER-440 2 VVER-1000
Finland	2				

[a] The acronyms are Russian name. English translations of the reactor names are as follows: VVER — "Vodo-Vodyanoy Energetichesky Reactor" (water-water power reactor); RBMK — "Reactor Bolshoy Moschnosti Kipyaschiy" (high power boiling reactor); BN — "(reactor na) Bystrykh Neitronakh" (fast neutron reactor).

[b] Construction of some reactors (not included in the table) has been stopped. Among them are a 30 percent-complete Tver' 4 unit (the local government voted to allow operation of a Tver' 3 unit but to stop construction of Tver' 4); Rostov 1 and Rostov 2 units; Voronezh 1 and 2 AST-500 units (AST — "Atomnaya Stantcia Teplovaya" (heat atomic station)); and the fast reactor South Ural project. The prospects for completion of these reactors are uncertain.

[c] Heat and electricity graphite-moderated pressurized-water reactors.

NOTES AND REFERENCES

1. On 2 September 1993, the U.S. and Russia signed an agreement on U.S. assistance in developing a national nuclear safeguards system in Russia. Effectiveness of the program depends on the level of access by foreign safeguards experts to nuclear fuel cycle facilities in Russia. A ban on the production of fissile materials for weapons, as proposed by U.S. President Clinton in the fall of 1993, would require on-site inspections at uranium-enrichment and reprocessing facilities.

2. Military nuclear fuel cycle activities include production of nuclear materials for weapons, fabrication of weapons components, and support of naval reactor program.

3. Between 1976 and 1990, fuel from plutonium-production reactors at the Mayak complex at Chelyabinsk was reprocessed at the Tomsk plant. Five plutonium-production reactors were brought into operation at the Mayak site between 1949 and 1952 and were decommissioned between 1987 and 1990. (T. Cochran and R.S. Norris, "Russian/Soviet Nuclear Warhead Production," NWD 93-1, pp. 49–51.)

4. RBMK fuel has been stored on-site; VVER-1000 fuel has been transported (after a period of on-site storage) to a central storage facility at Krasnoyarsk-26.

5. Interview with plant officials at Ust'-Kamenogorsk, November 1993. The principal problem of commercialization of the technology was related to the presence of the uranium isotope U-232, which presents an occupational safety problem. U-232 decays to Bi-212 and Tl-208, both high-energy gamma-emitters.

6. Some 1.5 metric tons HEU are used as fuel for naval and research reactors each year. The material is drawn from the HEU stockpile. (E. Mikerin, Workshop in Rome in June 1992 and interview in Moscow in May 1992.) Although most naval reactors use non-weapon-grade uranium (non-WgU), some reactors (e.g., liquid-metal reactors) use WgU. Also, WgU is used in reactors on commercial nuclear-powered vessels (ice-breakers, etc.).

7. HEU fuel is cermet fuel made of uranium oxide particles in an aluminum matrix. Plutonium-production reactors use a ring of HEU rods to levelize the power output throughout the core. Tritium production reactors use a driver-target configuration and are fueled with HEU.

8. A burnup of 75 percent means that 75 percent of the fissile content (atoms U-235) have been fissioned. Remaining uranium, 42.3 percent of the original amount of 90 percent-enriched uranium, is about 53 percent-enriched in U-235 and contains about 23 percent U-236 (ignoring formation of plutonium in U-238 and assuming capture-to-fission ratio of 0.169).

9. Some 1,000 metric tons uranium is drawn annually from the Russian stocks, and an additional 1,000 metric tons is generated through enrichment of past tailings to the level of natural uranium. (The tailings are stripped from 0.4, 0.36, 0.32, 0.24, 0.20, and 0.18 percent U-235 to 0.11 percent.) See *The Program of Development of Nuclear Power in the Russian Federation for the Period until 2010* (Moscow: Minatom, 1992). Interview with Russian officials (December 1993).

10. During the 1980s, five plutonium- and two tritium-production reactors operated at Mayak; five and three plutonium-production reactors operated at Tomsk-7 and Krasnoyarsk-26, respectively. Tritium-production reactors are 1,000 MWt light-water reactors; plutonium-production reactors are graphite-moderated pressurized-water reactors with a capacity of 2,000 MWt (with the exception of the first two reactors at Mayak which had capacities of 500 and 68 MWt). At present, one 2,000 MWt pluto-

nium-production reactor operates at Krasnoyarsk-26, two operate at Tomsk-7, and two tritium-production reactors operate at Mayak.

11. Report at Working Group on Nuclear Reactors, Joint Study on Plutonium Production Reactor Replacement, USDOE, 14–16 March 1994.

12. Presently, the reactors are fueled with natural uranium. *The Program of Development of Nuclear Power in the Russian Federation for the Period until 2010* (Moscow: Minatom, 1992).

13. At a load factor of 0.7, HEU burnup of 75 percent, and HEU energy value of 1.05 grams per MWt-day, production of one MWt-year requires 0.36 metric tons 90 percent-enriched uranium. Thus, a 1,000 MWt HEU reactor consumes 362.5 kilograms HEU per year. According to U.S. sources, three plutonium-production reactors consume about 200 kilograms HEU per year (or 33 kilograms HEU per 1,000 MWt-year). Thus, with the combined capacity of about 22,600 MW, 13 plutonium-production reactors consume about 750 kilograms HEU per year.

14. At present, Russia keeps only a single SSBN on patrol at sea at any given time (*Bulletin of the Atomic Scientists*, November 1993, p. 56.)

15. At a burnup of 75 percent, 1,478 and 925 kilograms 90 percent-enriched uranium would yield approximately 620 and 390 kilograms 53 percent-enriched uranium, respectively.

16. Interviews with officials from the Ust'-Kamenogorsk plant (November 1993).

17. D. Bradley and K. Schneider "Radioactive Waste Management in the U.S.S.R.: A Review of Unclassified Sources, 1963–1990," PNL, March 1990, pp. A.23–A.24.

18. The size of the reserve is estimated to be at least 227 metric tons uranium (D. Bradley and K. Schneider, "Radioactive Waste Management in the U.S.S.R.: A Review of Unclassified Sources, 1963–1990," PNL, March 1990, p. A.24.)

19. In 1975, it was resolved to build RT-2 storage and a reprocessing plant for VVER-1000 fuel. Construction of the storage facility started in 1976 and it began operation in 1985. Construction of the reprocessing plant has been delayed and it is unlikely to be completed until after 2000. (T. Cochran and R.S. Norris, "Russian/Soviet Nuclear Warhead Production," NWD 93-1, p. 101.)

20. *NuclearFuel*, 19 July 1993, 27 September 1993, and 3 January 1994.

21. *Nuclear Engineering International*, December 1992, pp. 38–39.

22. Frank von Hippel, "Limiting Stockpiles of Separated Civil Plutonium," (draft).

23. According to an agreement signed by Siemens AG and Tomsk-7 in 1993, about 140 metric tons of contaminated uranium scrap (accumulated at the fuel fabrication plant at Hanau, Germany) will be brought to Tomsk-7 for recovery of uranium in 1994. In return, Siemens will receive about 70 metric tons UF_6. (*NuclearFuel*, 17 January 1994.)

24. The Verkh-Neyvinsk plant is licensed to enrich uranium to up to 30 percent (interview with Russian officials, 18 December 1993). All the other facilities are licensed to enrich uranium to less than five percent.

25. Personal correspondence with T. Neff of M.I.T. (February 1994).

26. Personal correspondence with T. Neff (December 1993).

27. The U.S. will purchase approximately 550 metric tons of HEU recovered from Russian weapons—at least 10 metric tons per year the first five years and 30 metric tons per year during the subsequent 15 years.

28. It is possible that the enrichment facility at Tomsk-7 may have capabilities for HEU processing and storage as well as for fabrication of HEU components for weapons.

29. Under the contract signed in March 1991 by Tenex and Cogema the Tomsk-7 plant enriches reprocessed uranium from France to some four percent U-235 at a rate of up to 500 metric tons reprocessed uranium per year. The contract will be in effect until the year 2000. (T. Cochran and R.S. Norris, "Russian/Soviet Nuclear Warhead Production," NWD 93-1, pp. 94–95.)

30. Interviews with Ust'-Kamenogorsk plant officials (November 1993).

31. Interviews with nuclear industry officials in Russia and Kazakhstan (1993).